



MAPBIOMAS  
PERÚ

**Land cover and land use**

General manual

Theoretical basis document on algorithms (ATBD)

**Collection 4.0**

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## Executive Summary

The Institute for the Common Good (IBC) is a Peruvian non-profit civil association founded in 1998 that works to promote the stewardship of common goods. By common goods, we mean resources and spaces that are jointly owned or used, such as rivers, lakes, forests, fisheries, protected natural areas, and community territories. Because these resources and spaces are crucial for the well-being of Amazonian peoples, particularly in the current era of climate change, our work promoting their conservation and sustainable use contributes to the well-being of these communities and all Peruvians.

The IBC is the Peruvian member of the Amazonian Network of Georeferenced Socio-Environmental Information (RAISG), where this type of information is generated in coordination with other countries in the basin to achieve the same objectives. Since 2009, within the framework of its work with RAISG, the IBC has been developing deforestation maps of the Peruvian Amazon using increasingly advanced satellite data processing tools. Seeking new alternatives for automating processes and generating timely information, in March 2017, RAISG, in agreement with the General Coordination of the MapBiomass Network, created the MapBiomass Amazonia initiative, of which the IBC is a member.

MapBiomass is an initiative of a collaborative network made up of non-governmental organizations, universities and companies in Brazil, organized with the objective of using quality and lower cost technology to produce annual series of land cover and land use maps (from 1985 onwards).

As part of the work with RAISG and MapBiomass, the IBC presents its *Collection 4.0 of Annual Land Cover and Land Use Maps* from all over Peru. Thanks to this collaborative effort, these maps will be available on an interactive platform for the country through the MapBiomass Peru initiative.

The objective of this Theoretical Algorithm Base Document (ATBD) is to provide users with an understanding of the methodological steps and computational algorithms for producing the *Coverage and Use Collection 4.0*, which includes 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 land cover and land use maps from 1985 to 2025 of Collection 4.0 of Annual Land Cover and Land Use Maps of MapBiomass Peru.

This document covers the Landsat image classification methods (L4, L5, L7, L8, L9), the image processing architecture, and the approach to integrating the biomes and regions present in the country. It also presents historical context and background, as well as an overview of the satellite image dataset and the accuracy assessment method applied.

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

## 1.2. Overview

The MapBiomass Peru project began in July 2021 with the aim of supporting the understanding of land cover and land use (LULC) dynamics across the country. The project is made possible by: i) technological advancements that allow for the cloud-based processing of large amounts of spatial data using algorithms hosted on the Google Earth Engine platform; ii) the implementation of image processing methods focused on monitoring MapBiomass LULC; iii) the multidisciplinary technical team whose expertise enables the mapping of the territory; and iv) the support of visionary institutions and funders who back the project.

MapBiomass Peru's products consist of annual thematic maps with a spatial resolution of 30 meters for the entire country. Their methodology uses annual mosaics of satellite images made up of information layers (spectral bands, derived indices, physical variables). They also obtain statistics derived from the maps by department, province, district, biome, watershed, indigenous territories, conservation units, among others.

MapBiomass Peru's mapping project has now released its first collection of annual maps; this collection will evolve in methodology, analysis period, detail of mapped land cover over time, and an improvement in map quality.

**Collection 4.0:** Mapping of land cover and land use between the years **1985 and 2025**. The methodology used was *machine learning (Random Forest)* with 156 layers of information (original Landsat bands, fractional and texture information derived from them, and indices). Landsat C images were used, which present the most up-to-date version of the reprocessed Landsat files. The generated maps have a total of **25 classes**.

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 land cover and land use maps. All data, classification maps, statistical codes, and other analyses are freely accessible through the MapBiomass Peru platform (<http://peru.mapbiomas.org>)

The products in Collection 4.0 are as follows:

- Annual classification rasters of the entire Peruvian territory;
- Rasters of annual transitions between classes and years chosen by the user;
- Preprocessed mosaics generated from Landsat file collections (Landsat 4, Landsat 5, Landsat 7, Landsat 8 and Landsat 9);
- Image processing infrastructure and algorithms (scripts in Google Earth Engine and source code);
- LULC annual and transitional statistics with various units of analysis;
- Landsat mosaic quality assessment. Each scene may have a proportion of clouds and other interference. Thus, each pixel for a given year is rated according to the number of available observations, ranging from 0 to 40 observations per year. The Landsat mosaic quality assessment is available on the MapBiomass website.
- Wall map of Land Cover and Land Use in Peru to 2025;
- National infographic on land cover and land use;
- Document of key findings in the analysis of the results;
- Technical documents for understanding the processes by topic.

### **1.3. Study Area**

The scope of work is the entire territorial extension of Peru, excluding the insular surface (0.01%). This encompasses an approximate area of 1,294,306.15 km<sup>2</sup>. Within this area, four biomes were defined: the Amazon biome, the Andes biome, the Coastal Desert biome, and the Equatorial Dry Forest biome. (Figure 1).



**Figure 1.**Limit of identified biomes for Peru.

For this purpose, technical criteria regarding ecosystem distribution were used, based on national reference maps and the experience of previous collections. The land cover types used were:

- Vegetation cover map (MINAM, 2015)
- Map of Ecoregions of Peru (SIGMINAM-DGOTA, 2017)
- Physiographic Map of Peru (INRENA, 2002)
- Map of Hydrographic Regions of Peru (MINAM-ANA)
- Map of the Remaining Natural Vegetation of the Northern and Central Andes (Andean Community - CAN)
- SRTM 90m Digital Elevation Model
- Map of wetlands of Peru (MINAM, 2010)

**Table 1.** Characteristics of land cover and land use in Peruvian biomes.

| Biome                        | Area (km <sup>2</sup> )<br>(% country) | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | Threats                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |
|------------------------------|----------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Equatorial dry forest</b> | 46,026.95<br>(3,55%)                   | The extent of this biome is defined primarily by the spread of dry forest, both lowland and mountainous, along the country's northwest coast. Approximating Brack's "Equatorial Dry Forest" ecoregion, it is subject to the influence of the Tropical Sea and warm ocean currents, related to the El Niño phenomenon. The biome is characterized by a mixed tropical/subtropical climate with broadleaf dry forest vegetation, and it also contains Peru's only mangrove forests. | Dry forests face significant pressure that has gone largely unnoticed at the national level due to a lack of information. They are subject to logging (the felling of carob trees for firewood and charcoal), overgrazing (primarily by goats), and increasing deforestation to allow for agricultural expansion, especially by the agro-export industry. Pressure on groundwater is also increasing due to the growing number of wells being drilled for agriculture. At the same time, years of drought threaten dry forests, whose regeneration is linked to the El Niño phenomenon and rainfall. |
| <b>Coastal desert</b>        | 84,991.20<br>(6,57%)                   | Heavily influenced by the cold Humboldt Current from Chile, the arid subtropical climate of the south-central Peruvian coast supports sparse vegetation, with desert predominating. Despite this, fog often forms, fostering unique ecosystems such as the coastal hills (Fog oasis) and tillandsia scrublands. Most of the vegetation and agricultural activity is concentrated in the river valleys, which are fed by rivers originating in the high Andes.                     | In the desert region, ecosystems such as coastal wetlands, coastal hills, and tillandsia forests face significant pressure from the uncontrolled urban sprawl of cities along the coast. Another constant threat is the lack of water for agriculture in river valleys, due both to decreased rainfall caused by climate change affecting water reserves and to the growing demand resulting from the expansion of agribusiness.                                                                                                                                                                     |
| <b>Andes</b>                 | 378,533.71<br>(29,25%)                 | This geographic region divides Peru into two watersheds: the Atlantic (eastern) and the Pacific (western). On the western slope, the Andes rise from approximately 750 meters above sea level to 6,788 meters above sea level, then descend along the eastern slope to 3,500 meters above sea level, giving way to the High Jungle, also known as the Yungas. Herbaceous vegetation predominates, with small inclusions of shrublands                                             | It is severely threatened by soil compaction caused by livestock farming, as well as peat extraction from high-altitude Andean wetlands and extensive agriculture that supplies essential goods to the country's main population centers and cities. Agricultural burning and forest fires are frequent occurrences in a biome where the predominant ecosystems are characterized by climates with low relative humidity and vegetation with high fuel potential.                                                                                                                                    |

and small forests. Glaciers are a prominent feature of this biome, serving as the main water source for the Atlantic and Pacific watersheds of Peru. They also create lakes and flooded high-Andean ecosystems such as bofedales (high-altitude wetlands). The inter-Andean valleys, known for their high agricultural productivity, are also noteworthy.

|               |                         |                                                                                                                                                                                                                                                                          |                                                                                                                                                                                                                                                                                                                                                                                 |
|---------------|-------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Amazon</b> | 784,754.29<br>(60,63 %) | According to Brack's ecoregions, this biome mostly encompasses the extensions of the High Jungle and Low Jungle; characterized by a variety of forest landscapes that differ in their composition depending on their location, altitude, relief, climate and vegetation. | Primarily due to extensive agriculture, livestock farming, logging, and open-pit mining. Industrial crops such as oil palm are expanding in the northern and central parts of the biome, leading to the clearing of primary forests. Meanwhile, the southern part of the country is mainly affected by the expansion of gold mining in the large rivers of the Amazonian plain. |
|---------------|-------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

Source: Own elaboration

## 1.4. Applications

Scientific applications can be derived from an annual time series history of the LULC maps produced, including:

MapBiomass Peru's products show potential for the annual monitoring of areas threatened by land cover conversion and at risk of deforestation. Likewise, the time series maps can be useful as a complement to studies estimating greenhouse gas emissions from land cover and land use change in the country. Other application examples include characterizing land use dynamics, quantifying land cover and land use transitions, forest loss and gain, monitoring regeneration, changes in water resources, urban and agricultural expansion, regional planning, and the management of protected areas.

MapBiomass Peru not only complements existing national and global efforts, but also brings additional advantages such as: 1) MapBiomass Peru maps have been constructed using the complete Landsat data collection (41 years) with an annual timeframe; 2) the entire product shares the same methodology, legend, and temporal and spatial resolution, thus allowing comparisons between regions; 3) the product is prepared by experts familiar with the national context, generating a product with a view to local applications; 4) MapBiomass Peru 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

#### 2.1.1. *Institute for the Common Good - IBC*

The Institute for the Common Good is a Peruvian non-profit civil association founded in 1998 that works to promote the stewardship of common goods. By common goods, we mean resources and spaces that are jointly owned or used, such as rivers, lakes, forests, fisheries, protected natural areas, and community territories. Because these resources and spaces are crucial for the well-being of Amazonian peoples, particularly in the current era of climate change, our work promoting their conservation and sustainable use contributes to the well-being of these communities and all Peruvians.

All information about IBC projects and publications generated since the institution's inception is available on the website <https://ibcperu.org/>.

#### 2.1.2. *MapBiomias*

The MapBiomias Global Network currently comprises six initiatives mapping land cover and land use in Brazil, the Amazon, the Chaco, the Trinational Atlantic Forest, the Trinational Pampas, and Indonesia. These initiatives are multi-institutional collaborative networks made up of NGOs, universities, and technology companies that use cloud processing and automated classifiers developed and operated with the Google Earth Engine platform to contribute to the understanding of changes in land cover and land use. All data and methods generated by the project are public, transparent, and available on the platforms <https://mapbiomas.org/>.

In 2025, the network expanded to include the initiative in Chile and extended its reach to Argentina, Bolivia, Colombia, Paraguay, Ecuador, Peru, and Venezuela, all involving local institutions. The main objective is to produce annual collections of land cover and land use maps that reflect the dynamics of land-use changes in different biomes in South America and other tropical and subtropical regions.

The objective of the Red Global MapBiomias es pTo produce and promote the use of qualified information for land use and land cover stewardship in South America and other tropical and subtropical regions. This Network presents a series of common practices across all its MapBiomias initiatives and products:

- User-friendly data platform, easy to access and use for applications
- Transparency in methodology and technology
- Open and free data
- Local experience and thematic knowledge of Land Use and Land Cover
- Cloud processing (Google Earth Engine platforms)
- Technical knowledge in remote sensing and programming
- Independence in data publication
- Collections that allow for constant evolution and improvement
- Distributed and decentralized networks
- Collaborative spirit
- Committed to technical and scientific rigor
- Promoting capacity building



## 2.2 Remote Sensing Data

The mapping data for Collection 4.0 were obtained from satellite images from the period 1985 to 2025 from the Landsat Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), Operational Land Imager and Thermal Infrared Sensor (OLI-TIRS) and Operational Land Imager 2 and Thermal Infrared Sensor 2 (OLI-2 - TIRS 2) sensors, aboard the Landsat 4 (L4, for coverage of information gaps at the beginning of the series and mainly in 1988), Landsat 5 satellites (L5, for the years 1985-2012 of the series), Landsat 7 (L7, for the years 2000-2021), Landsat 8 (L8, 2013 onwards) and Landsat 9 (L9, 2021 onwards).

The images dThe surface reflectance values belong to the Landsat data catalog.<sup>1</sup> C2 with Tier 1 correction level, These images underwent radiometric calibration, orthorectification based on ground control points, and digital elevation modeling to ensure pixel-level recording and atmospheric correction. The catalog of Landsat images with a spatial resolution of 30 meters was 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-based platform for the scientific analysis of global geospatial datasets. The main components of GEE are: 1) publicly available remote sensing data catalogs, 2) petabyte-scale cloud computing infrastructure, 3) APIs for JavaScript and Python to interact with GEE servers, and 4) an online integrated development environment (IDE) that enables application development using scripts.<sup>2</sup> called the Code Editor<sup>3</sup>.

The aforementioned components make GEE the ideal tool for processing the large amounts of data required for classifying satellite images for land cover, land use, and land use change mapping. Additionally, GEE provides an environment that facilitates collaboration among regional teams (as in the case of RAISG) and the application of shared methodologies to the same dataset, as well as the replication of processes by third parties interested in evaluating concepts or methodologies.

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

## 2.4. Other mapping initiatives

In recent years, various tools have been developed for mapping land cover and land use in the Amazon, some of them global in scope, with increasingly robust approaches. They all share a common interest in contributing to one of today's most pressing issues: understanding the current state of land cover types and monitoring changes in them. These initiatives have contributed to detecting deforestation, monitoring terrestrial and aquatic ecosystems, and strengthening the detection of

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<sup>1</sup> <https://developers.google.com/earth-engine/datasets/catalog/landsat/>

<sup>2</sup> <https://developers.google.com/earth-engine/>

<sup>3</sup> [code.earthengine.google.com](https://code.earthengine.google.com)

forest degradation, conservation efforts, hotspots, and more. Below, we list the most relevant initiatives.

#### **2.4.1. Global 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 European Commission's Joint Research Centre, with the aim of producing a global land cover database for 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 a coherent legend.
- Intact Forest Landscapes (IFL) is a global spatial database at a scale of 1:1,000,000, showing the extent of intact forest landscapes (IFL) for the years 2000, 2013, and 2016. The first global IFL map, for the year 2000, was prepared in 2005–2006 under the leadership of Greenpeace, with contributions from the Biodiversity Conservation Center, the International Socio-Ecological Union, and Transparent World (Russia), Luonto Liitto (Finnish Nature League), Forest Watch Indonesia, and Global Forest Watch, a network initiated by the World Resources Institute. The 2013 version was subsequently generated, and the map was finally updated to 2016 with support from the University of Maryland, the Wildlife Conservation Society, Greenpeace, and Transparent World.
- Global Forest Watch (GFW) – A collaboration between the GLAD (Global Land Analysis & Discovery) laboratory at the University of Maryland, Google, USGS, and NASA, measures areas of tree cover loss across the Earth (excluding Antarctica and other Arctic islands) at a 30 × 30 meter resolution. Their project focuses on developing global tree cover change data products based on Landsat satellite imagery, available on the Global Forest Watch 4.0 web platform. It includes annual forest cover change (gains and losses) from 2000 to 2020.
- GlobeLand30, an initiative of the National Geomatics Center of China, comprises spatial datasets collected at a resolution of 30 meters. This collection considers ten land cover types, including forests, artificial surfaces, and wetlands, for the years 2000 and 2010. The data was extracted from more than 20,000 satellite images from Landsat and the Chinese HJ-1 satellite.
- ESA CCI Land Cover, a joint project of the European Space Agency (ESA) and the Climate Change Initiative (CCI), provides annual global land cover maps, which describe the Earth's surface in 22 classes. The series of annual global land cover maps spans the period from 1992 to 2018.
- The CORINE Land Cover (CLC) inventory was initiated in 1985 (reference year 1990). Updates were carried out in 2000, 2006, 2012, and 2018. It consists of a land cover inventory in 44 classes. CLC uses a Minimum Mapping Unit (MMU) of 25 hectares (ha) for area features and a minimum width of 100 m for linear features. Time series data are supplemented with change layers, which highlight land cover changes with an MMU of 5 ha.
- ESRI 2020 Global Land Use/Land Cover from Sentinel-2: This layer displays a global land use/land cover (LULC) map for 2020. The map is derived from ESA Sentinel-2 imagery with a 10-meter resolution and contains 10 classes. This map was produced by a deep learning model trained on over 5 billion hand-labeled Sentinel-2 pixels sampled from more than 20,000 sites distributed across the world's major biomes.
- ESA WorldCover 2020 and 2021: This is a reference global land cover product with a spatial resolution of 10 m, generated from Sentinel-2 and Sentinel-1 imagery with 10 land cover classes and an overall accuracy of 75%. The legend includes 11 generic classes that adequately describe the land surface: "Tree cover", "Shrubland", "Grassland", "Cropland", "Built-in", "Bare/sparse vegetation", "Snow and ice", "Permanent water bodies", "Herbaceous wetland", "Mangroves", and "Mosses and lichens".

- Dynamic World is a near real-time, 10-meter resolution global land cover dataset generated from Sentinel-2 imagery using deep learning. It is freely available and openly licensed. The legend presents the probabilities per pixel for nine land cover classes: Water, Forest, Shrub and Bush, Grassland, Floodplain Vegetation, Cropland, Buildings, Bare Soil, Snow, and Ice. This data is the result of a partnership between Google and the World Resources Institute to produce a dynamic dataset of the physical material on 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 for ecological systems. These systems represent recurring groups of biological communities found in similar physical environments and 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 readily 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.
- Land Cover Map of South America. Digital map of land cover in South America based on satellite imagery 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 - "GLC 2000" project.
- The Land Cover Map of Latin America and the Caribbean, developed within the framework of the SERENA project, 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 Monitoring and Study of Natural Resources (SERENA) project. The SERENA land cover map for LAC integrates: 1) the local experience of SERENA network members in generating training and validation data, 2) a land cover mapping methodology based on decision trees using MODIS time series, and 3) class membership estimates to account for pixel heterogeneity issues.
- Deforestation in the Amazon, a study conducted by RAISG, analyzes historical and recent deforestation trends by five-year period from 2000 to 2015. The deforestation data was produced by RAISG members using their own standardized methodology, which allowed for regional analysis while still accounting for national differences. The study examines the issue at various levels: the entire Amazon region, the Amazon region within each country, Protected Natural Areas, Indigenous Territories, and at the river basin level.
- Mapbiomas Amazonia Land Cover and Land Use Collections is a study based on Landsat satellite imagery that generates annual land cover and land use maps of the Amazon region, with a spatial resolution of 30 meters. The project was developed by the RAISG network and its partners in the Amazonian countries. Currently, it uses the Landsat C2 image catalog and includes a legend of 27 mapped land cover classes.

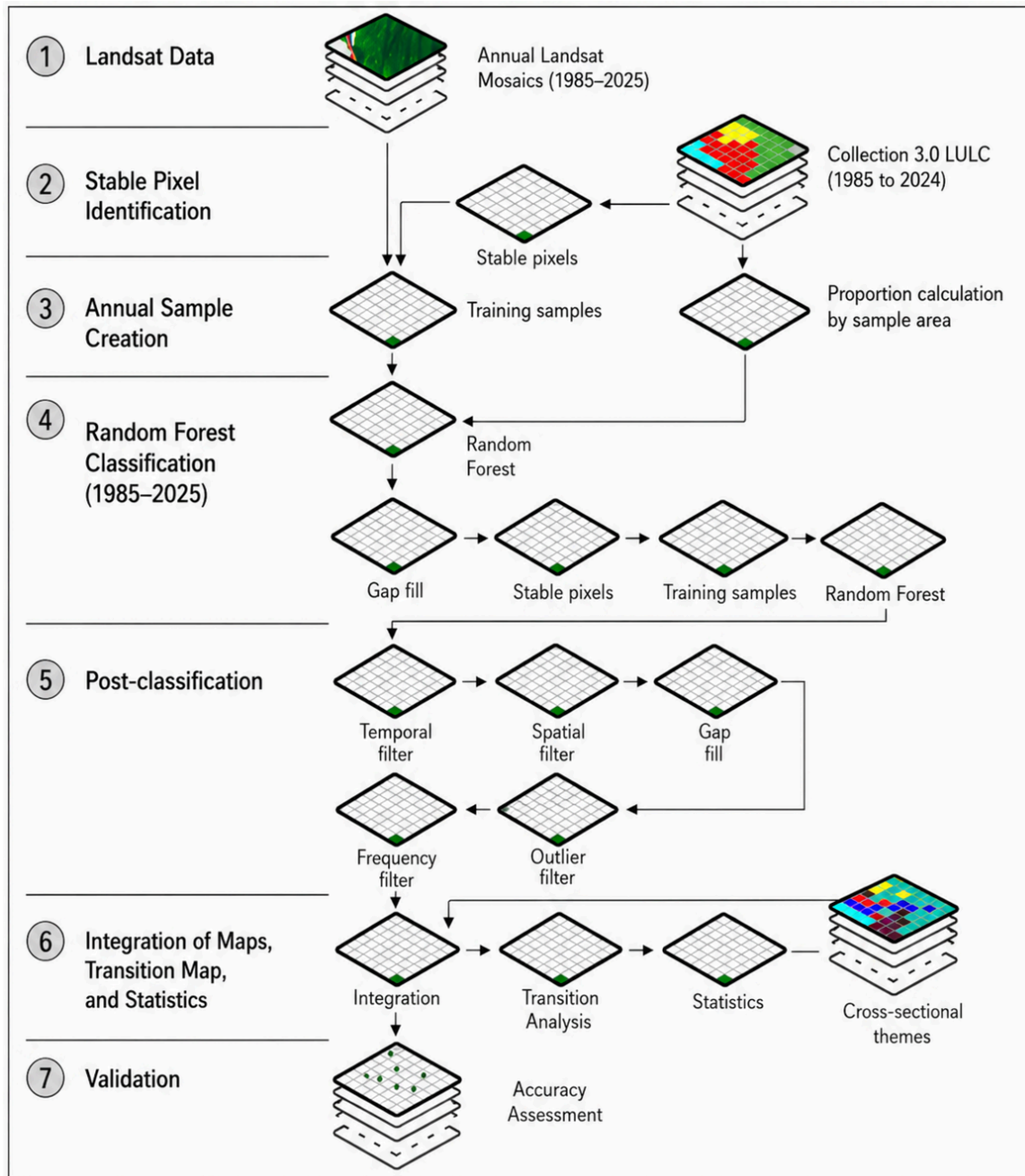
#### **2.4.3. Sources for the national territory**

- Physiographic Map of Peru (2002) by the National Institute of Natural Resources - INRENA. A legend of 21 classes is used. Publication scale: 1:250,000.
- Ecosystem Map of the Northern and Central Andes. Bolivia, Colombia, Ecuador, Peru, and Venezuela (2009) General Secretariat of the Andean Community, ECOBONA Regional Program, CONDESAN-Andean Páramo Project, BioAndes Program, EcoCiencia, NatureServe, LTA-UNALM, IAvH, ICAE-ULA, CDCUNALM, RUMBOL SRL. Lima. Remaining natural vegetation units, transformed areas, and protected natural areas at the national level in the Northern and Central Andes designated by the Andean Community. Publication scale: 1:4,100,000

- Map of wetlands in Peru (2010) from the Ministry of the Environment - MINAM. The map shows national information on the distribution of wetlands in Peru, comprising four main units: 1) Swamps and marshes; 2) Mangroves; 3) High-altitude wetlands; and 4) Coastal wetlands. The scale is 1:1,000,000.
- Map of the National Forest Heritage (2010) of the Ministry of the Environment - MINAM. The map was prepared by the Ministry of the Environment through the Directorate of Evaluation, Valuation and Financing of Natural Heritage and the General Directorate of Territorial Planning. It has a publication scale of 1:2,000,000.
- The Forest-Non-Forest and Amazon Rainforest Loss Map 2000-2014 (2015), produced by the National Forest Conservation Program for Climate Change Mitigation, shows the areas and percentages of forest-non-forest and forest cover loss at the national level. It features a 4-class legend and a publication scale of 1:6,000,000.
- Vegetation cover map (2015) from the Ministry of the Environment - MINAM, which includes a legend of 76 classes and a publication scale of 1:100,000
- Land Use and Land Use Change Maps 2000-2005, 2005-2011, 2011-2013, 2013-2016, prepared by the National Forest Conservation and Climate Change Mitigation Program. Available on the Ministry of the Environment's GeoBosques platform in raster and vector formats. They use the IPCC classification at a first level and a more detailed level called Subclasses.
- National Ecosystem Map (2018) prepared by the Working Group for the National Ecosystem Map and the Directorate of Monitoring and Evaluation of Natural Resources of the Territory (DMERNT) at a publication scale of 1:2,000,000.
- Map of Seasonally Dry Forest (2018). Baseline of the dry forests of the northern coast of Peru, prepared by Geobosques and the Ministry of the Environment.
- Mapa de Fog oasis (2020) obtenido de Moat et al., "Seeing through the clouds - Mapping desert fog oasis ecosystems using 20 years of MODIS imagery over Peru and Chile".
- National agricultural area (2020). Prepared by the Ministry of Agrarian Development and Irrigation. GEOMIDAGRI
- Rice crop monitoring (2021). Prepared by the Ministry of Agrarian Development and Irrigation. GEOMIDAGRI.

### 3. Methodology

The processing chain adopted for the generation of Collection 4.0. MapBiomass Peru is summarized in Figure 2 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).



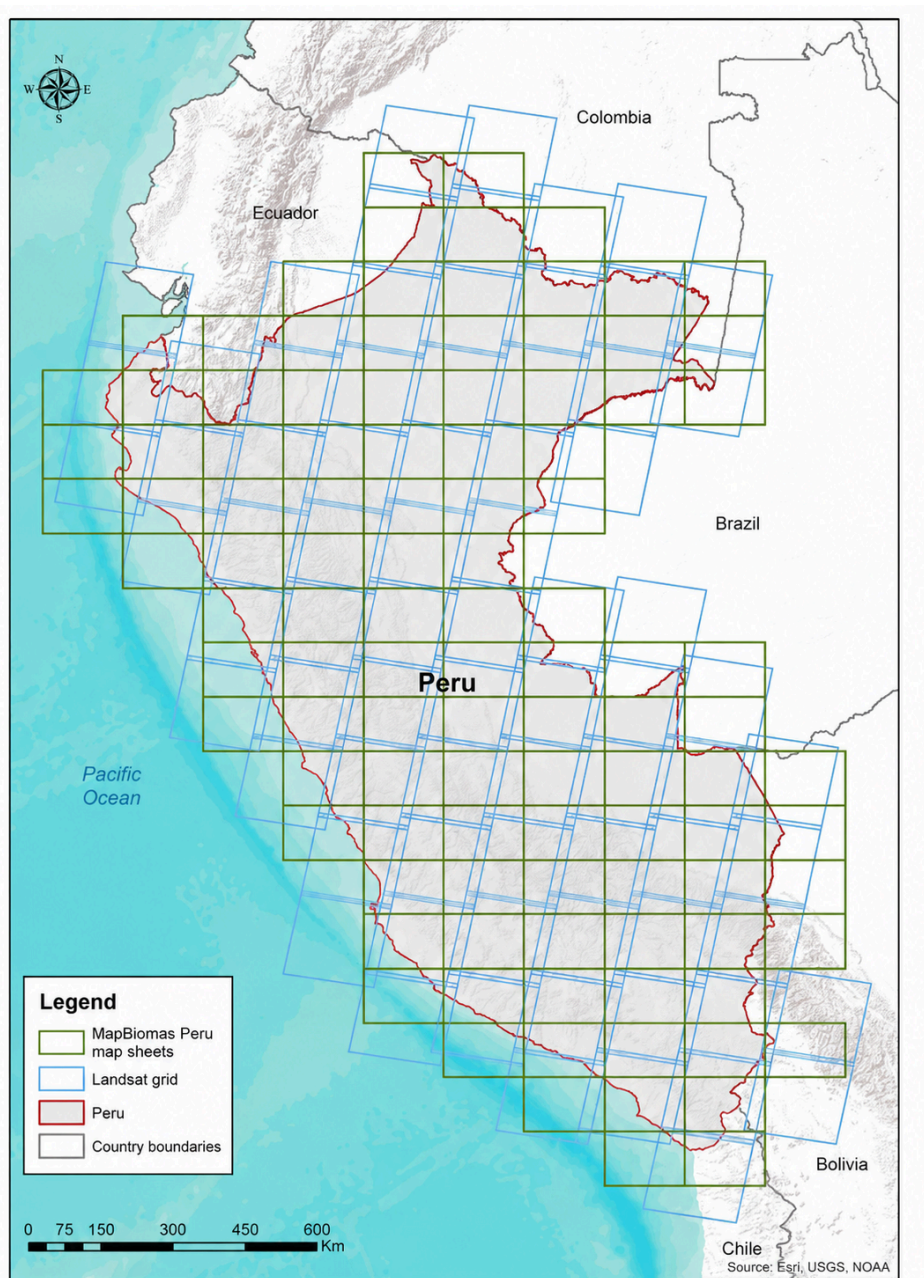
**Figure 2.**Methodological synthesis of Collection 4.0.

### 3.1 Generation of annual mosaics

#### 3.1.1. Division of the analysis space into charts

The MapBiomass methodology divides the project area into a grid of regular maps defined based on the grid of the International Maps of the World to the Millionth, at a scale of 1:250,000. Each rectangular map covers an area of 1°30' longitude by 1° latitude. A total of 107 maps cover the Peruvian territory.

The regular division of space resulting from the application of the International Charts grid implies that each chart requires a total or partial combination of Landsat images, given that the Landsat image grid is oblique to the MapBiomass chart grid (Figure 3).



**Figure 3.** MapBiomass Peru chart grid (green) and Landsat image grid (blue) and national boundary (red).

It was essential to subdivide the cards by mosaic regions.<sup>4</sup>(Figure 4) to facilitate the construction of the mosaics through parameterization tailored to the specificities of each portion. As a result, annual mosaics of independent Landsat image pixels were generated for each map or subdivision, each of which was processed separately. Table 2 summarizes the number of existing maps at the country level (without subdivision), the final number of subdivisions (maps/region), and the total number of mosaics processed and generated.

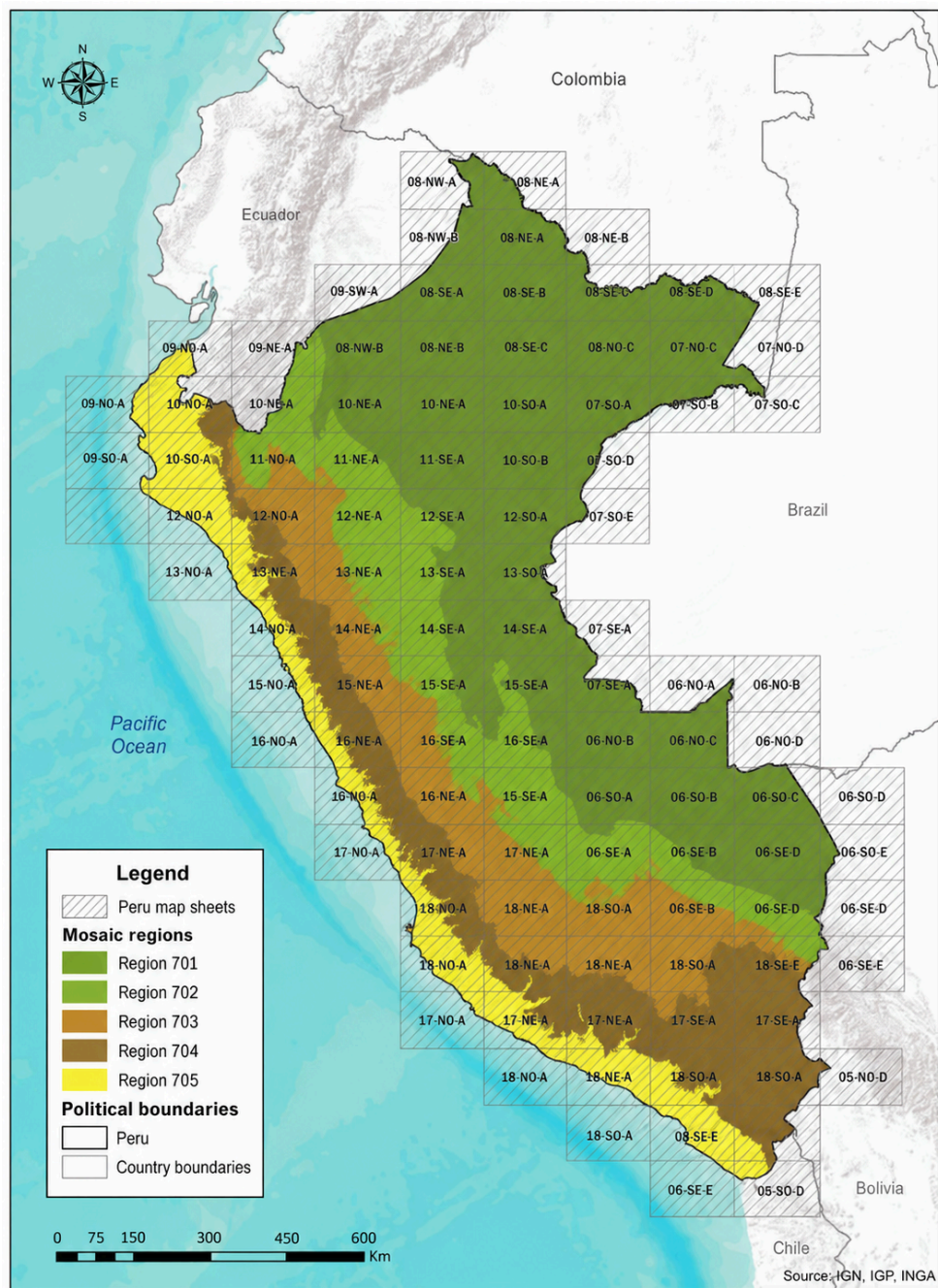
**Table 2.**Summary of the number of MapBiomass Peru maps by region and country.

| Mosaic region | Biomes that it encompasses                | Cards/Mosaic Region | Total number of tiles (x41 years) |
|---------------|-------------------------------------------|---------------------|-----------------------------------|
| Region 701    | Amazon (high jungle mountain range)       | 31                  | 1240                              |
| Region 702    | Amazonia (lowland rainforest plains area) | 59                  | 2360                              |
| Region 703    | Andes (Atlantic basin)                    | 32                  | 1280                              |
| Region 704    | Andes (Pacific and Titicaca basins)       | 35                  | 1400                              |
| Region 705    | Equatorial dry forest and coastal desert  | 35                  | 1400                              |
| Total         |                                           | 192                 | 7680                              |

Source: Own elaboration

<sup>4</sup> The "**mosaic regions**"are used specifically in the construction of mosaics and are different from the "**classification regions**"that are used specifically for the sorting process."





**Figure 4.** Map of the region charts for the generation of image mosaics for Peru.

### 3.1.2. Parameterization of annual mosaics

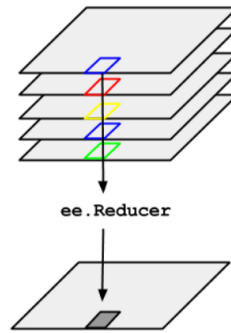
An annual mosaic is the aggregation of pixels from several Landsat images from which a representative mosaic for a year is generated, constructed from the following parameters:

- ID: Unique identifier of the letter-region unit
- Year: Year of the series (1985 to 2025) to which the mosaic corresponds.
- Letter: Letter identifier code
- Start Date/ End Date: Period of the year (start and end date) for the selection of images from the Google Earth Engine Landsat image data catalog.



- Sensor: The satellite and its respective sensor: Landsat 4 TM, Landsat 5 TM, Landsat 7 ETM+, Landsat 8 OLI or a combination of Landsat 5 and Landsat 7, Landsat 9 OLI-2 TIRS-2.
- Cloudiness: The maximum percentage of cloud cover accepted for each Landsat image that will be used to construct the image mosaic. This data comes from the Landsat image metadata.
- Probability of clouds:
- shadowSum: This is a TDOM parameter for cloud shadow detection. A lower number masks fewer pixels with cloud.
- cloudThresh: This is a CloudScore parameter for cloud detection. Lower numbers increase masking, while higher numbers decrease it. Decreased masking can be useful in areas of bare ground where high reflectance leads to false cloud detection.
- Blacklist: Images that, due to their quality, are excluded from the mosaic construction. Some quality issues are related to snow pixels in non-glacial regions and clouds that have not been masked.

The parameters for constructing annual mosaics are defined by the interpreter and represent the criteria for selecting images available in the Landsat data catalog from which the annual mosaic is constructed. The images selected for each year were *reduced* to an individual image, or annual mosaic, using operators called *reducer*s existing in Google Earth Engine, as illustrated in Figure 5.



**Figure 5.**Diagram of the application of a reducer to a set of images (Google, 2020)<sup>5</sup>.

When parameterizing the mosaics, it was considered that higher accuracy values could be achieved by using satellite image mosaics with minimal noise. Therefore, each mosaic was designed to have the least possible cloud cover and interference, as well as the largest possible coverage of available Landsat data within the defined period. In exceptional cases where images were unavailable for the selected period, the image search period was extended.

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

Table 3 presents a summary of the most frequently used parameters for each region by biome.

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

| Region     | Satellite | Year                 | Period                | Max % cloud |
|------------|-----------|----------------------|-----------------------|-------------|
| Region 701 | L5        | 1985-1999, 2003-2011 | June 15 - November 15 | 20 - 90     |

<sup>5</sup>Taken from: [https://developers.google.com/earth-engine/guides/reducers\\_image\\_collection](https://developers.google.com/earth-engine/guides/reducers_image_collection)

|                                                     |       |                            |                         |         |
|-----------------------------------------------------|-------|----------------------------|-------------------------|---------|
| Amazon<br>(zone<br>mountainous<br>high jungle)      | L7    | 2002, 2012                 | June 1 - October 31     | 10 - 80 |
|                                                     | L5/L7 | 2000-2001                  |                         |         |
|                                                     | L8    | 2013-2021                  |                         |         |
|                                                     | L9    | 2022-2025                  |                         |         |
| Region 702                                          | L5    | 1985-1999, 2000, 2003-2011 | April 1 - August 30     | 30 - 95 |
| Amazon<br>(zone<br>of plains<br>lowland jungle)     | L7    | 2002, 2012                 |                         |         |
|                                                     | L5/L7 | 2001                       |                         |         |
|                                                     | L8    | 2013-2021                  |                         |         |
|                                                     | L9    | 2022-2025                  |                         |         |
| Region 703                                          | L5    | 1985-2001,2003-2011        | April 1 - August 30     | 30 - 95 |
| Andes<br>(basin)<br>of the Atlantic)                | L7    | 2002,2009,2010,2012        |                         |         |
|                                                     | L8    | 2013-2021                  |                         |         |
|                                                     | L9    | 2022-2025                  |                         |         |
| Region 704                                          | L5    | 1985-2001,2003-2011        | April 1 - August 30     | 30 - 95 |
| Andes<br>(basin)<br>of the Pacific and<br>Titicaca) | L7    | 2002,2009,2010,2012        |                         |         |
|                                                     | L8    | 2013-2021                  |                         |         |
|                                                     | L9    | 2022-2025                  |                         |         |
| Region 705                                          | L5    | 1985-1999                  | January 1 - December 31 | 20-90   |
| (Equatorial B.S. and<br>coastal desert)             | L7    | 2000-2012                  |                         |         |
|                                                     | L8    | 2013-2021                  |                         |         |
|                                                     | L9    | 2022-2025                  |                         |         |

Source: Own elaboration

### 3.2. Classification variables or feature space

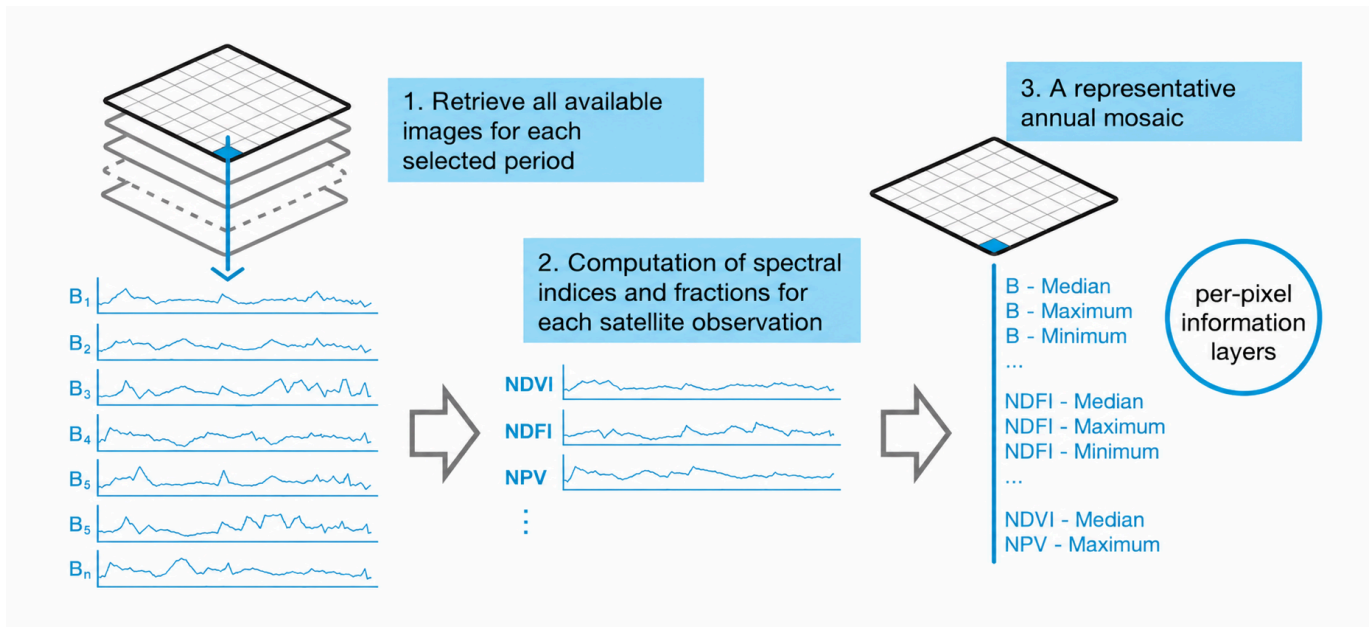
Variables were calculated (*feature space*) from the annual mosaic representing the inputs of the classification process. The Landsat bands, along with the classification variables, are consolidated into raster files composed of 156 bands in total.<sup>6</sup>which include: spectral landsat bands, spectral indices, fractional and texture information derived from them, and indices of spectral fractions.

Additionally, 7 static variables were used: HAND, shademask2, slppost, altitude, slope, latitude and longitude; which helped to classify classes that are spectrally very similar but are differentiated by these topographic aspects.

<sup>6</sup>Available for download on the MapBiomass Peru platform.

The calculation was applied to the images available each year. Statistical reducers are used to generate the values for each pixel. The process is represented in Figure 6. These reducers are:

- Median: Median<sup>7</sup> of all available values in the annual mosaic for that location (pixel).
- Median dry season: Calculation of the statistical median applied to the pixels of the 25th quartile (with the lowest values) of NDVI (proxy of dry season).
- Median wet season: Calculation of statistical median applied to the pixels of the 75th quartile (with the highest values) of NDVI (proxy of rainy season).
- Amplitude: Extent of variation between all available pixels in the annual mosaic.
- Standard deviation: Standard deviation of the values of all available pixels in the annual mosaic for a given location.
- Minimum: Lowest value of all available pixels in the annual mosaic in a location determined.
- Maximum: Highest value of all available pixels in the annual mosaic in a location determined.
- Minimum of the dry period: Calculation of the lowest value of all available pixels from the images in the quartile with the lowest NDVI values (dry season proxy).
- Minimum of the wet period: Calculation of the lowest value of all available pixels from the images of the quartile with the highest NDVI values (rainy season proxy).
- Maximum of the dry period: Calculation of the highest value of all available pixels from the images of the quartile with the lowest NDVI values (dry season proxy).
- Maximum of the wet period: Calculation of the highest value of all available pixels from the images in the quartile with the highest NDVI values (rainy season proxy).
- 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.



**Figure 6.** Process of calculating bands that make up the annual Landsat image mosaics.

Table 4 shows the complete list of bands for the final mosaics or *feature space*. Each band represents a training variable of the classifier.

<sup>7</sup> The median is the value that separates the upper half from the lower half of a data sample or population. [Documentation](#) of the tool in Google Earth Engine.

**Table 4.** Description of bands and variables used for Collection 2 MapBiomass Peru.

| Type    | Name          | Formula                                                 | Description                                                                                             | Reducer <sup>8</sup> |            |            |     |        |     |     |         |         |         |         |         | Quality Band <sup>9</sup> |  |
|---------|---------------|---------------------------------------------------------|---------------------------------------------------------------------------------------------------------|----------------------|------------|------------|-----|--------|-----|-----|---------|---------|---------|---------|---------|---------------------------|--|
|         |               |                                                         |                                                                                                         | 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 y L7); B2 (L8)                                   | Blue visible spectrum                                                                                   | X                    |            |            |     |        |     |     |         |         |         |         |         |                           |  |
|         | green         | B2 (L5 y L7); B3 (L8)                                   | Green visible spectrum                                                                                  | X                    | X          |            |     |        | X   |     |         |         | X       |         | X       | X                         |  |
|         | red           | B3 (L5 y L7); B4 (L8)                                   | Red visible spectrum                                                                                    | X                    | X          | X          |     |        | X   |     | X       | X       |         | X       | X       |                           |  |
|         | nir           | B4 (L5 and L7); B5 (L8)                                 | Near infrared                                                                                           | X                    | X          | X          |     | X      | X   |     |         |         |         |         | X       | X                         |  |
|         | swir1         | B5 (L5 y L7); B6 (L8)                                   | Shortwave infrared 1                                                                                    | X                    | X          | X          |     |        | X   |     |         | X       | X       | X       | X       | X                         |  |
|         | swir2         | B7 (L5); B8 (L7); B7(L8)                                | Shortwave infrared 2                                                                                    | X                    | X          | X          |     |        | X   |     | X       |         |         | X       | X       | X                         |  |
| Indices | ndvi          | (nir - red)/(nir + red)                                 | Normalized Difference Vegetation Index                                                                  | X                    | X          | X          | X   | X      |     |     |         |         |         |         |         |                           |  |
|         | evi2          | (2.5 * (nir - red)/(nir + 2.4 * red + 1))               | Modification of the Enhanced 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   |        |     |     |         |         |         |         |         |                           |  |
|         | ccv           | (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                    |            |            |     |        |     |     |         |         |         |         |         |                           |  |

<sup>8</sup> Each product calculated with the statistical reducers makes up a band of the integrated product.<sup>9</sup>It combines all the images in a collection, using a quality band (evi2) as the pixel sorting function.

|        |                                                                                                     |                                                                   |   |   |   |  |   |   |   |  |  |   |  |  |  |  |
|--------|-----------------------------------------------------------------------------------------------------|-------------------------------------------------------------------|---|---|---|--|---|---|---|--|--|---|--|--|--|--|
| at     | (blue - green)/(blue + green)                                                                       | Photochemical reflectance index (Photochemical Reflectance Index) | X | X |   |  |   |   |   |  |  |   |  |  |  |  |
| clay   | (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 |   |   |  |   |   |   |  |  |   |  |  |  |  |
| nuance | $UNTl * (1 - \sqrt{(NDWI - aNDWI)^2 + (NDVI - aNDVI)^2 + (NDBI - aNDBI)^2})$                        | Normalized Composite Index of Urban Areas                         | X |   |   |  |   |   |   |  |  |   |  |  |  |  |
| ndsi   | (green-swir1)/(green+swir1)                                                                         | Normalized Differential Snow Index                                | X |   |   |  |   | X |   |  |  |   |  |  |  |  |
| water  | (swir2 / 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 |  |  |   |  |  |  |  |
| man    | (green - nir) / (green + nir)                                                                       | Normalized Difference Water Index                                 | X | X | X |  |   |   | X |  |  |   |  |  |  |  |
| ndbi   | (swir1 - nir) / (swir1 + nir)                                                                       | Cumulative normalized difference index                            | X | X |   |  |   | X | X |  |  |   |  |  |  |  |
| ndgb   | (green - blue) / (green + blue)                                                                     | Normalized difference Green Blue                                  | X | X | X |  | X |   | X |  |  |   |  |  |  |  |
| ndmi   | (nir - swir1) / (nir + swir1)                                                                       | Normalized Humidity Difference Index                              | X | X |   |  |   |   | X |  |  |   |  |  |  |  |
| mdmir  | (swir1 - swir2) / (swir1 + swir2)                                                                   | Normalized difference mean infrared index                         | X |   | X |  | X | X | X |  |  |   |  |  |  |  |
| ndrb   | (red - blue) / (red + 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 |  |  |  |  |  |  |
| Fraction MOTHER <sup>10</sup> | teacher |                                                                                                                         | 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 abundance of shadow within the pixel                        | x |   |   |   |   |   |   |  |  |  |  |  |  |
|                               | snow    |                                                                                                                         | Fractional abundance of snow within the pixel                          | x |   |   |   |   | x |   |  |  |  |  |  |  |
|                               | cloud   |                                                                                                                         | Fractional abundance of clouds within the pixel                        | x |   |   |   |   |   |   |  |  |  |  |  |  |
| MEM Index                     | gvs     | $\text{gv} / (\text{gv} + \text{npv} + \text{soil} + \text{cloud})$                                                     | Green vegetation normalized by shade                                   | x | x | x |   | x |   |   |  |  |  |  |  |  |
|                               | money   | $(\text{gvs} - (\text{npv} + \text{soil})) / (\text{gvs} + (\text{npv} + \text{soil}))$                                 | Normalized difference fraction index                                   | x | x | x | x | x |   |   |  |  |  |  |  |  |
|                               | heads   | $(\text{gv} + \text{npv} - \text{soil}) / (\text{gv} + \text{npv} + \text{soil})$                                       | Savanna ecosystem fraction index                                       | x | x |   |   | x |   |   |  |  |  |  |  |  |
|                               | wefi    | $((\text{gv} + \text{npv}) - (\text{soil} + \text{shade})) / ((\text{gv} + \text{npv}) + (\text{soil} + \text{shade}))$ | Wetland ecosystem fraction index                                       |   |   | x | x | x |   |   |  |  |  |  |  |  |
|                               | UN      | $((\text{gv} + \text{shade}) - \text{soil}) / ((\text{gv} + \text{shade}) + \text{soil})$                               | Index based on gv, shade, and                                          |   | x |   |   | x |   |   |  |  |  |  |  |  |

<sup>10</sup>MME = Spectral Mixture Model

|                                     |                                             |                                                                                                                                               |                                        |     |  |  |   |  |  |  |  |  |  |  |  |  |  |
|-------------------------------------|---------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------|-----|--|--|---|--|--|--|--|--|--|--|--|--|--|
|                                     |                                             | + soil)                                                                                                                                       | soil fractions                         |     |  |  |   |  |  |  |  |  |  |  |  |  |  |
|                                     | ndfib                                       | 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                                       |                                                                                                                                               | Earring                                |     |  |  |   |  |  |  |  |  |  |  |  |  |  |
|                                     | latitude                                    |                                                                                                                                               | Latitude                               |     |  |  |   |  |  |  |  |  |  |  |  |  |  |
|                                     | longitud e                                  |                                                                                                                                               | Length                                 |     |  |  |   |  |  |  |  |  |  |  |  |  |  |
|                                     | HAND<br>(Height Above the Nearest Drainage) | hand30_100<br>hand30_1000<br>hand30_5000<br>hand90_1000<br>water_HAND_0m<br>water_HAND_10m<br>water_HAND_1m<br>water_HAND_2m<br>water_HAND_5m | Index - Height above the nearest drain |     |  |  |   |  |  |  |  |  |  |  |  |  |  |

Source: Own elaboration.

### 3.3 Classification

#### 3.3.1. Legend

The semi-automated classification was developed using a random forest methodology. The collection specifically maps 25 classes: 1.1. Forest (ID 3), 1.2. Dry forest (ID 4), 1.3. Mangrove (ID 5), 1.4. Flooded forest (ID 6), 2.1.1. Lowland floodplain grassland (ID 51), 2.1.2. High Andean floodplain grassland (ID 82), 2.2. Herbaceous formation (ID 12), 2.3.1. Scrubland and other shrublands (ID 66), 2.3.2. Coastal hill (ID 70), 3.1. Mosaic of agriculture and pasture (ID 21), 3.2. Forest plantation (ID 9), 3.3. Oil palm (ID 35), 3.4. Rice (ID 40), 3.5. Pasture (ID 15), 4.1. Urban infrastructure (ID 24), 4.2. Mining (ID 30), 4.1. Beach (ID 23), 4.4. Rocky surface (ID 92), 4.5. Coastal saline surface (ID 52), 4.6. Salt flat surface (61), 4.7. Other natural area without vegetation (ID 68), Other anthropogenic area without vegetation (ID 25), 5.1. River, lake or ocean (ID 33), 5.2. Aquaculture (ID 31), 5.3. Glacier (ID 34).

**Table 5.**General legend of land cover and land use in Collection 4.0.

| ID | Class                                            | Hexadecimal code | Color | Natural/anthropogenic |
|----|--------------------------------------------------|------------------|-------|-----------------------|
| 1  | 1. Forest formation                              | #1f8d49          |       |                       |
| 3  | 1.1. Forest                                      | #1f8d49          |       | Natural               |
| 4  | 1.2. Dry forest                                  | #7dc975          |       | Natural               |
| 5  | 1.3. Mangrove                                    | #04381d          |       | Natural               |
| 6  | 1.4. Flooded forest                              | #026975          |       | Natural               |
| 10 | 2. Non-forested natural formation                | #d6bc74          |       |                       |
| 11 | 2.1. Floodable herbaceous formation              | #519799          |       | Natural               |
| 51 | 2.1.1 Lowland floodable grassland                | #5faf92          |       | Natural               |
| 82 | 2.1.2. High-Andean flooded grassland             | #26abab          |       | Natural               |
| 12 | 2.2. Herbaceous formation                        | #d6bc74          |       | Natural               |
| 13 | 2.3. Shrub formations and others                 | #d89f5c          |       | Natural               |
| 66 | 2.3.1. Scrubland and other shrublands            | #a89358          |       | Natural               |
| 70 | 2.3.2. Coastal hill (beta)                       | #be9e00          |       | Natural               |
| 14 | 3. Agricultural area                             | #ffefc3          |       |                       |
| 21 | 3.1. Mosaic of agriculture and pasture           | #ffefc3          |       | Anthropogenic         |
| 9  | 3.2. Forest plantation                           | #7a5900          |       | Anthropogenic         |
| 35 | 3.3. Oil palm                                    | #9065d0          |       | Anthropogenic         |
| 40 | 3.4. Rice                                        | #c71585          |       | Anthropogenic         |
| 15 | 3.5. Pasture                                     | #edde8e          |       | Anthropogenic         |
| 22 | 4. Area without vegetation                       | #d4271e          |       |                       |
| 24 | 4.1. Urban infrastructure                        | #d4271e          |       | Anthropogenic         |
| 30 | 4.2. Mining                                      | #9c0027          |       | Anthropogenic         |
| 23 | 4.3. Beach                                       | #ffa07a          |       | Natural               |
| 92 | 4.4. Rocky surface                               | #d98a45          |       | Natural               |
| 52 | 4.5. Coastal saline area                         | #f0b4a8          |       | Natural               |
| 61 | 4.6. Salt flat                                   | #f5d5d5          |       | Natural               |
| 68 | 4.7. Other natural area non-vegetated-area       | #e97a7a          |       | Natural               |
| 25 | 4.8. Other anthropogenic area non-vegetated-area | #db4d4f          |       | Anthropogenic         |
| 26 | 5. Body of water                                 | #2532e4          |       |                       |
| 33 | 5.1. River, lake or ocean                        | #2532e4          |       | Natural               |
| 31 | 5.2. Aquaculture                                 | #091077          |       | Anthropogenic         |
| 34 | 5.3. Glacier                                     | #93dfe6          |       | Natural               |
| 27 | 6. Not observed                                  | #ffffff          |       | Not defined           |



Source: Own elaboration.

As part of the process of describing the land cover classes for each country, a table was created to correlate the MapBiomas legend classes with the Vegetation Cover Map (MINAM, 2015). A workshop was also held with various state and/or educational entities to facilitate the exchange of information and the approval of the legend. The following descriptive report and interpretation criteria (Table 6) for each class in the MapBiomas Peru legend, within the context of Peru's land cover, are presented.

**Table 6.** Descriptive report for the MapBiomass Peru legend.

| MapBiomass<br>CLASS (ID) | Biome              | Approval<br>VEGETATION COVER<br>MAP<br>(MINAM, 2015)                                                                                 | Class description                                                                                                                                                                                                                                                                                                                                           | Interpretation criteria<br>(RGB 543)                                                                                        |
|--------------------------|--------------------|--------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------|
| 1                        | Forest<br>(ID:3)   | Lowland and montane forests; Forest plantation                                                                                       | Dense evergreen tree cover with trees up to 45 m tall in the Lower Amazon (up to 500 m above sea level), decreasing in height to 3800 m above sea level in the Upper Amazon. It occupies terraces, hills, and mountains. It includes bamboo thickets (pure or mixed) and forest plantations; it excludes Flooded forests on poorly drained soils.           | - In dense forests: high roughness; dark green hue;<br>- In sparse forests: low roughness; light green tone;                |
|                          |                    | Low and high terrace forests; White sand sclerophyllous vegetation (varillal); High and low hill forests; Pacales; Forest plantation |                                                                                                                                                                                                                                                                                                                                                             |                                                                                                                             |
|                          |                    | Relict forests; Dry mountain forests; Subhumid mountain forests;                                                                     | Tree cover of two types: very humid, evergreen, dense forests in the north, up to 20 m tall; and relict forests in the center and south, with scattered, low-growing trees (up to 10 m). The latter are located on mountain slopes that are difficult to access, between 2800 and 3800 meters above sea level, or at the edge of the agricultural frontier. | - In sparse forests: low roughness; light green tone;<br>- In semi-deciduous forests: medium roughness; green-purple tones. |
|                          |                    | B. S. subhumid mountain forest                                                                                                       | Reduced tree cover in the highlands of Tumbes (600 to 1200 m above sea level). Mixture of species from the dry forest and Amazonian forest, with a predominance of evergreen vegetation over deciduous vegetation.                                                                                                                                          | - High roughness; dark green hue in wet periods or dark purple in dry periods;                                              |
|                          | Dry forest (ID: 4) | Amazon Semi-deciduous mountain forests, mountain forest                                                                              | Tree and shrub vegetation with a discontinuous canopy, adapted to a marked climatic seasonality with deciduous species. It stands out for its high biological diversity and level of endemism.                                                                                                                                                              | - Sparse forests, of medium roughness, when they lose their leaves tend to have a fuchsia-orange hue.                       |
|                          |                    | Andes Inter-Andean xeric savannas; Inter-Andean xeric forests;                                                                       | Inter-Andean dry forest of scattered trees or shrubs (< 8 m), located in deep valleys and slopes. Its species are deciduous during the dry season.                                                                                                                                                                                                          | - Sparse forests, varying in texture and color according to latitude. To the north they tend                                |

|   |                                                            |                                                         |                                          |                                                                                                                                                                     |                                                                                                                                                                                                                                                                                                                                                                                                   |                                                                                                                                                                                                         |
|---|------------------------------------------------------------|---------------------------------------------------------|------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 2 |                                                            |                                                         | B. S.<br>Ecuatorial                      | Dry savanna forest;<br>Riparian dry forest;<br>Piedmont dry forest;<br>Hillside dry forest; Low hill<br>dry forest; High hill dry<br>forest; Mountain dry<br>forest | Low and mostly deciduous tree cover with<br>shrubby-herbaceous undergrowth. Includes: a)<br>dry savanna-type forests dominated by carob<br>trees (5-8 m) up to 800 m above sea level; b)<br>semi-dense dry hill and mountain forests (up<br>to 12 m) between 400 and 2000 m above sea<br>level; and c) dense (up to 12 m) dry riparian<br>carob forests due to the moisture from<br>watercourses. | towards a<br>brownish-green tone,<br>towards the center and<br>south, brownish-pink<br>tones.                                                                                                           |
|   |                                                            |                                                         | Coastal<br>desert                        | Riparian dry forest                                                                                                                                                 | Tree cover located in the areas adjacent to<br>watercourses, dominated by "algarrobo" type<br>trees (up to 12 m high) in a dense manner due<br>to the better humidity conditions.                                                                                                                                                                                                                 | - In sparse savanna<br>forests: low roughness;<br>pinkish-purple hue;<br>- In semi-dense hill and<br>mountain forests: high<br>roughness; green hue<br>in wet periods or dark<br>purple in dry periods: |
|   | <b>Mangrove (ID: 5)</b>                                    |                                                         | B. S.<br>Ecuatorial                      | Mangrove                                                                                                                                                            | Dense evergreen tree cover that grows in<br>saline or brackish coastal waters.                                                                                                                                                                                                                                                                                                                    | - Areas near the water<br>with a deep green to<br>dark green-purple hue.<br><br>- Uniform texture and<br>color characteristics,<br>from dark green to light<br>green.                                   |
|   | <b>Flooded forest (ID:6)</b>                               |                                                         | Amazon                                   | Floodplain palm forest<br>(aguajal); Basimontan<br>and flood terrace forests;<br>Meandering plain forest                                                            | Tree cover of the floodplain and floodable<br>terraces (seasonal or permanent). Developed in<br>poorly drained soils with abundant organic<br>matter, it is dominated by palm trees along<br>with species such as "renacales" and<br>"pungales".                                                                                                                                                  | - They have uniform<br>texture and color<br>characteristics, tending<br>towards green-purple.                                                                                                           |
|   | <b>Floodable<br/>herbaceous<br/>formation<br/>(ID: 11)</b> | <b>Lowland<br/>floodable<br/>grassland<br/>(ID: 51)</b> | Amazon                                   | Hydrophytic grassland;<br>Hydrophytic palm<br>savanna                                                                                                               | Floodplain vegetation cover (grasslands and<br>hydrophytic savannas) on hydromorphic soils.<br>After prolonged flooding recedes, a dense,<br>low-lying herbaceous carpet emerges. Includes<br>the palm savannas of the Pampas del Heath.                                                                                                                                                          | - Natural wetlands with<br>variations in edge and<br>color (presence of<br>sediments); Proximity to<br>watercourses.                                                                                    |
|   |                                                            |                                                         | B. S.<br>Ecuatorial<br>Coastal<br>desert | Lagoon; Estuary; Virillá<br>Estuary; Coastal Wetland                                                                                                                | Herbaceous vegetation subject to periodic<br>flooding with fresh, brackish, or salt water.<br>Includes marshy areas temporarily flooded by<br>El Niño.                                                                                                                                                                                                                                            | - Annual variations in<br>extent, colors vary<br>according to humidity<br>between bright<br>green-purple-brown.                                                                                         |

|                                                                                                                                                                                                               |                       |                                                                                      |                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                                                                                                                                                                                                   |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------|--------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <div> <div>High-Andean flooded grassland (ID: 82)</div> <div>Herbaceous formation (ID: 12)</div> <div> <div>Shrub formations and others</div> <div>Scrubland and other shrublands (ID:66)</div> </div> </div> | Andes                 | Bofedal                                                                              | Evergreen, compact and cushion-like vegetation, located in valley bottoms, volcanic cones and high Andean plains (>3800 m above sea level) on permanently flooded and poorly drained soils.                                                                                                                                                                                                                                                                 | <ul style="list-style-type: none"> <li>- Natural wetlands near bodies of water (lagoons).</li> <li>- Annual variations in extent.</li> <li>- They tend towards green-purple.</li> </ul>           |
|                                                                                                                                                                                                               | Amazon                | Jalca;Páramo;Pajonalandino                                                           | In the Upper Amazon region, the vegetation is considered herbaceous. At the transitional boundary with the Andes, it includes high-Andean grass vegetation in jalca and páramo ecosystems.                                                                                                                                                                                                                                                                  | <ul style="list-style-type: none"> <li>- Bright pink color</li> <li>- Low roughness</li> <li>- Color difference per period (dry: fuchsia / wet: green).</li> </ul>                                |
|                                                                                                                                                                                                               | Andes                 | Andean grassland                                                                     | Grasslands composed of vigorous, low-growing grasses and puna turf, almost at ground level. This vegetation is found approximately between 3000 and 4800 meters above sea level.                                                                                                                                                                                                                                                                            | <ul style="list-style-type: none"> <li>- Intense pink, it blends in with bare soil (dry grass).</li> <li>- Near the wetland area it is a very light green or yellow.</li> </ul>                   |
|                                                                                                                                                                                                               | Amazon                | Area without Amazon rainforest                                                       | Vegetation cover with a predominance of shrubs and dwarf trees with leathery leaves, located on the plateaus of the Cordillera del Cóndor (>1800 m above sea level) and in high mountain areas (>3500 m above sea level) in contact with the Andean grassland.                                                                                                                                                                                              | <ul style="list-style-type: none"> <li>- Low to medium roughness. Intense pink color. May have color differences between dry and rainy periods. Low tree density or only small shrubs.</li> </ul> |
|                                                                                                                                                                                                               | Andes                 | Shrubby scrubland; High-altitude shrubby scrubland; Montane sclerophyllous scrubland | Predominantly shrubby vegetation (dense or sparse) with herbaceous layers and grasses, located between 1500 and 3800 meters above sea level, with specialized flora. It includes northern scrublands (from 1500 meters above sea level) on arid soils; mid- and high-level (2500–3800 meters above sea level) deciduous and evergreen sub-humid scrublands; and upper-level inter-Andean (2000–3800 meters above sea level), which are more humid and cold. | <ul style="list-style-type: none"> <li>-Low to medium roughness. Intense pink color. May have color differences in dry and rainy periods. Low density of trees or only small shrubs.</li> </ul>   |
|                                                                                                                                                                                                               | Equatorial dry forest | Shrubby scrub                                                                        | The predominant vegetation is xeric scrubland, with open (30-60%) vegetation consisting of thorny, stunted shrubs and columnar cacti (up                                                                                                                                                                                                                                                                                                                    |                                                                                                                                                                                                   |

|   |                                            |                           |                                |                                                                                                                                                                                                                                                                                                                                                                                                    |                                                                                                                                                                                                                                                                                                                                                                                                                                   |
|---|--------------------------------------------|---------------------------|--------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 3 | (ID:13)                                    |                           |                                | to 4 m tall) interspersed with ephemeral grasslands. It has low biodiversity but high endemism. It is found in valleys and on steep slopes between 300 and 2000 meters above sea level.                                                                                                                                                                                                            |                                                                                                                                                                                                                                                                                                                                                                                                                                   |
|   |                                            | Coastal Desert            | Cardonal                       | It comprises xeric scrubland to the south (shrubs, cacti and ephemeral grassland on slopes up to 2000 m above sea level) and coastal tillandsias (monogeneric, with creeping plants of the genus Tillandsia).                                                                                                                                                                                      | <ul style="list-style-type: none"> <li>- Low to medium roughness. Intense pink color. May have color differences between dry and rainy periods. Low tree density or only small shrubs.</li> <li>- Tillandsial displays purple colors in desert areas.</li> <li>- The hills have dark colors of purple-burgundy-brown-green tones with medium roughness.</li> <li>- Tillandsial displays purple colors in desert areas.</li> </ul> |
|   | Coastal hill (beta) (ID:70)                |                           |                                |                                                                                                                                                                                                                                                                                                                                                                                                    |                                                                                                                                                                                                                                                                                                                                                                                                                                   |
|   |                                            | Coastal desert            | Fog oasis                      | a) Hills, seasonal vegetation (tree, shrub and herbaceous) arising from winter fogs between 100 and 1000 meters above sea level; and b) Tillandsial, monogeneric formation scattered on the coast (greater density to the south) composed of creeping plants (Tillandsia).                                                                                                                         |                                                                                                                                                                                                                                                                                                                                                                                                                                   |
|   |                                            |                           |                                |                                                                                                                                                                                                                                                                                                                                                                                                    |                                                                                                                                                                                                                                                                                                                                                                                                                                   |
| 3 | Mosaic of agriculture and pasture (ID: 21) | Amazon                    | Area without Amazon rainforest | Undifferentiated agricultural areas encompassing both agriculture and pastureland, as well as urban green spaces. Depending on the biome, the predominant crops are: in the Equatorial Dry Forest and Coastal Desert, cereals, vegetables, and fruit trees; in the Amazon, livestock, cereals, and oil palm; and in the Andes, livestock, cereals, tubers, and vegetables in inter-Andean valleys. | <ul style="list-style-type: none"> <li>- They feature mixed colors of fuchsia, burgundy and green with light tones.</li> <li>- Agro-industrial plantations of light green color similar to the fallow land and young secondary forests.</li> <li>- Small size.</li> </ul>                                                                                                                                                         |
|   |                                            | Ecuatorial Coastal desert | Coastal and Andean agriculture |                                                                                                                                                                                                                                                                                                                                                                                                    |                                                                                                                                                                                                                                                                                                                                                                                                                                   |
|   | Forest plantation (ID: 9)                  | Andes                     | Forest plantation              | Plantations of exotic species (Pinus sp. and Eucalyptus sp.) with specific design and purposes (such as production), located in forestry-suitable lands of the Andean region between 3000 and 3800 meters above sea                                                                                                                                                                                | <ul style="list-style-type: none"> <li>- Light green color.</li> </ul>                                                                                                                                                                                                                                                                                                                                                            |

|   |                                          |                |                                               |                                                                                                                                                                                                                              |                                                                                                                    |
|---|------------------------------------------|----------------|-----------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------|
| 4 |                                          |                |                                               | level.                                                                                                                                                                                                                       |                                                                                                                    |
|   | <b>Oil palm<br/>(ID: 35)</b>             | Amazon         | Area without Amazon rainforest                | Areas where the original cover has been modified or replaced by permanent oil palm crops, mainly of the species <i>Elaeis guineensis</i> .                                                                                   | - Intense light green colors of delimited geometric structures.                                                    |
|   | <b>Rice (beta)<br/>(ID:40)</b>           | Amazon         | Area without Amazon rainforest                | Areas where the original cover has been modified or replaced by permanent rice crops, mainly of the species <i>Oryza sativa</i> .                                                                                            | - Delimited geometric structures,                                                                                  |
|   |                                          | Coastal desert | Coastal and Andean agriculture                |                                                                                                                                                                                                                              | intermittency between light greens and bodies of water.                                                            |
|   | <b>Pasture (beta)<br/>(ID: 15)</b>       | Amazon         | Area without Amazon rainforest                | Areas of pasture, planted or natural, linked to livestock activity.                                                                                                                                                          | - In the lower Amazon region, it displays intense orange and yellow colors.                                        |
|   |                                          | Andes          | Coastal and Andean agriculture                |                                                                                                                                                                                                                              | - In the high Amazon and Andes it presents low green colors and shades of yellow, melon.                           |
|   | <b>Urban infrastructure<br/>(ID: 24)</b> | Amazon         | Urban area; Infrastructure                    | This unit consists of the spaces covered by Urban infrastructure and all associated green areas and communication routes. Excludes small-scale rural infrastructure that is not visible at the resolution of Landsat images. | - Intense pink. In some cases white (reflective infrastructure).                                                   |
|   |                                          | Andes          |                                               |                                                                                                                                                                                                                              |                                                                                                                    |
|   | <b>Mining<br/>(ID: 30)</b>               | B.S.           | Mining center; area without Amazon rainforest | It includes the areas where materials are extracted or accumulated from open-pit mining and river mining.                                                                                                                    | They feature intense fuchsia, burgundy, and purple colors, as well as turquoise bodies of water (salt extraction). |
|   |                                          | Ecuatorial     |                                               |                                                                                                                                                                                                                              |                                                                                                                    |
|   | <b>Beach<br/>(ID: 23)</b>                | Coastal desert | Sandbar                                       | Areas with sandy cover or no vegetation that is transported by rivers.                                                                                                                                                       | - Pink-purple in different shades                                                                                  |
|   |                                          | Amazon         |                                               |                                                                                                                                                                                                                              |                                                                                                                    |
|   | <b>Rocky surface<br/>(ID:92)</b>         | Andes          | Area with little or no vegetation;            | Naturally exposed rocks without soil cover, with rock-dwelling vegetation and steep slopes. They are found mainly in periglacial zones or stone forests.                                                                     | -Pinkish-purple in different shades, strong presence of shadows due to the slopes                                  |
|   |                                          | Andes          |                                               |                                                                                                                                                                                                                              |                                                                                                                    |
|   | <b>Coastal salt flat<br/>(ID: 52)</b>    | Coastal desert | Coastal Wetland                               | Stationary natural areas resulting from the accumulation of salts due to evaporation and/or infiltration of seawater on the coast.                                                                                           | - Light blue or turquoise tones                                                                                    |

|   |                                                        |  |                                                      |                                         |                                                                                                                                                                                                                              |                                                                                                                 |
|---|--------------------------------------------------------|--|------------------------------------------------------|-----------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------|
| 5 | <b>Salt flat (ID:61)</b>                               |  | Andes                                                | Not applicable                          | High Andean wetland (>3000 m above sea level) where evaporation exceeds precipitation, accumulating salts transported by runoff, wind, or groundwater. It may contain lagoons or springs.                                    | - Light blue and blue coloration with the presence or absence of water respectively                             |
|   | <b>Other natural non-vegetated-area (ID:68)</b>        |  | Amazon                                               | Areas without Amazon rainforest         | Natural areas with little or no vegetation. This includes landslides on hillsides caused by tectonic activity, heavy rains, etc.                                                                                             | - Pinkish-purple in different shades, including white areas in drier zones                                      |
|   |                                                        |  | Andes                                                | Areas without Amazon rainforest         | Natural areas with little or no vegetation not mapped in other classes. Includes exposed soils, alluvial fans, riverbanks, volcanic deposits, etc.                                                                           | - Pinkish-purple in different shades, including white areas in drier zones                                      |
|   |                                                        |  | B.S. Ecuatorial                                      | Arena benches                           | Natural areas with little or no vegetation not mapped in other classes. This includes deserts, alluvial fans, arid hills, etc.                                                                                               | - Pinkish-purple in different shades, including white areas in drier zones                                      |
|   |                                                        |  | Coastal desert                                       | Arena benches<br>Coastal Desert         | Natural areas with little or no vegetation not mapped in other classes. On the coast, this includes sandbanks, alluvial fans, dunes, desert, foothills located in the transition between the coastal and Andean biomes, etc. | - Pinkish-purple in different shades, including white areas in drier zones                                      |
|   | <b>Other anthropogenic non-vegetated-area (ID: 25)</b> |  | Amazon<br>Andes<br>B.S. Ecuatorial                   | Area without Amazon rainforest          | Anthropogenic areas with little or no vegetation. This includes crop transition areas, clearing, exposed rock/soil in areas of anthropogenic intervention, urban and road expansion areas, and dirt roads.                   | - Pinkish-purple in different shades, including white areas in drier zones. Variation in roughness.             |
|   |                                                        |  | Coastal desert                                       | Not applicable                          | It includes facilities intended for the breeding and intensive production of birds, mainly chickens and hens, characterized by elongated and regularly arranged structures associated with poultry activities.               | - White tones, including black to grayish shades depending on the material of the ceiling. Smooth texture       |
|   | <b>River, lake or ocean (ID: 33)</b>                   |  | Amazon<br>Andes<br>B.S. Ecuatorial<br>Coastal desert | Lagoons, lakes and oxbow lakes<br>River | It is any body of water found on the Earth's surface, whether natural or artificial. It includes rivers, lakes, dams, reservoirs, and other bodies of water.                                                                 | - Depending on the sediment content and the depth of the source, they could be black, dark blue, or light blue. |

|                                 |                    |                                   |                                                                                                                                                                                                                                                                                                                       |                                                                                                                                             |
|---------------------------------|--------------------|-----------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Aquaculture<br/>(ID: 31)</b> | B.S.<br>Ecuatorial | Lagoons, lakes and<br>oxbow lakes | <p>Artificial bodies of water intended for shrimp farming using seawater. This structure consists of a series of adjacent pools and is therefore characterized by a regular geometric pattern.</p>                                                                                                                    | <p>- Typically black, but depending on the time of use they could also present different shades of blue or, in years without use, pink.</p> |
| <b>Glacier<br/>(ID: 34)</b>     | Andes              | Glacier                           | <p>The ice and/or snow cover that forms in the Andes Mountains from 4,800 to 6,768 meters above sea level. It is a large mass of ice resulting from the accumulation, compaction, and recrystallization of snow over thousands of years. It is the main source of water resources for the country's river basins.</p> | <p>- Light blue and turquoise tones</p>                                                                                                     |

Source: Own elaboration



### 3.3.2. Classification Regions

To facilitate the mapping of the diverse landscapes within the study area, sixty-one (61) mapping or classification regions were defined. Each region was mapped independently for each year of the time series.

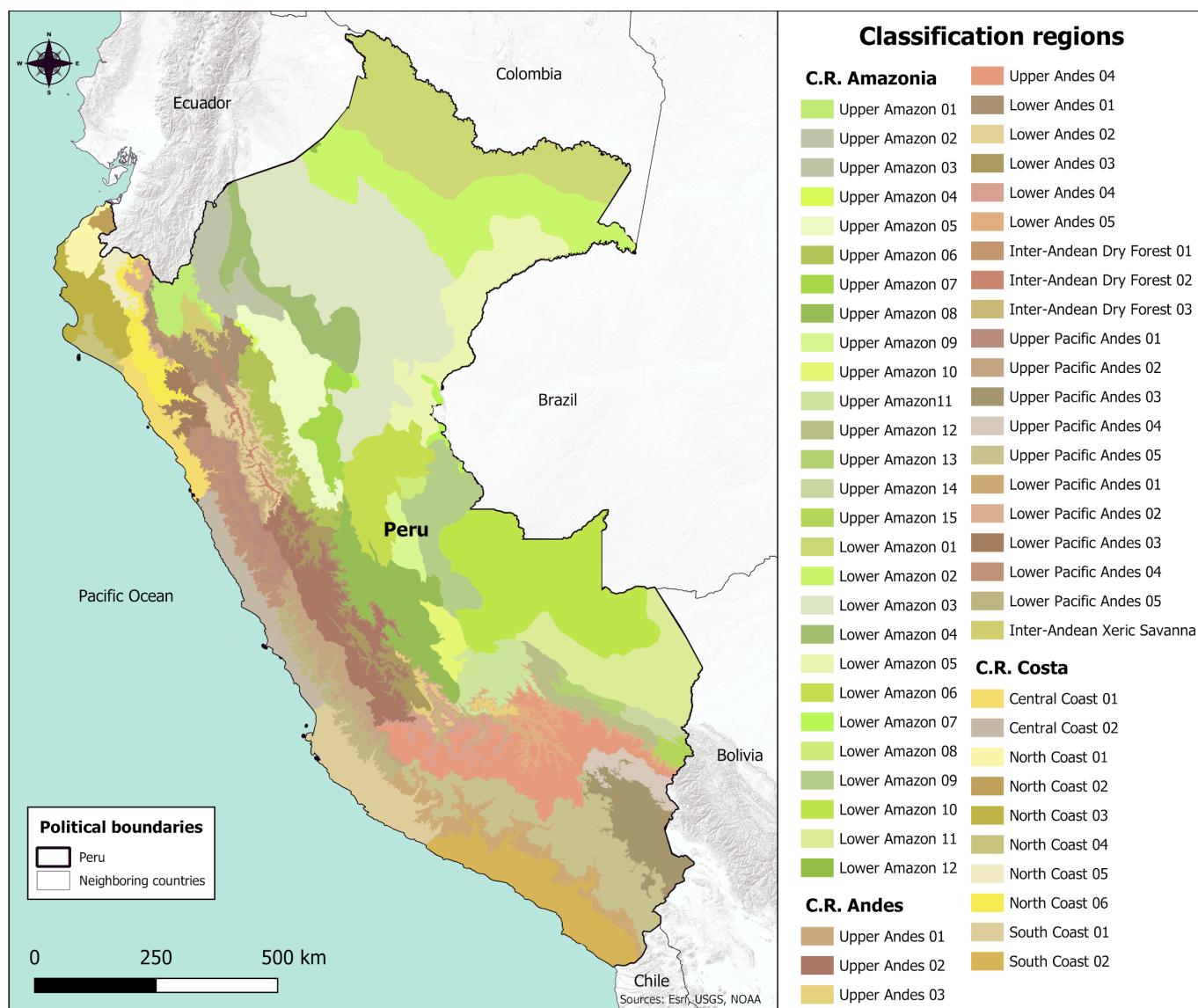
The regions were defined following ecosystem criteria and the occurrence of anthropogenic intervention, based on reference maps such as those mentioned in the section '*Other national mapping initiatives*'. The resulting regions are shown in Figure 7 and detailed in Table 7.

**Table 7.** Classification regions defined within the framework of the MapBiomass Peru project.

| Mosaic region | Mosaic region | Identifier | Codes | Reason for separation                                                                                                               |
|---------------|---------------|------------|-------|-------------------------------------------------------------------------------------------------------------------------------------|
| Region 701    | Upper Amazon  | 1          | 70101 | Northern transition zone with medium intervention, around Cajamarca                                                                 |
|               |               | 2          | 70102 | Northern area of medium intervention around Amazonas                                                                                |
|               |               | 3          | 70103 | Northern low-intervention zone around the Amazon                                                                                    |
|               |               | 4          | 70104 | Northern zone of little intervention around Alto Mayo and Colán                                                                     |
|               |               | 5          | 70105 | Central zone of high intervention along San Martín, Huánuco, Pasco and Junín                                                        |
|               |               | 6          | 70106 | Central transition zone with little intervention. San Martín, Huánuco and Pasco                                                     |
|               |               | 7          | 70107 | Central zone with little intervention and many landslides                                                                           |
|               |               | 8          | 70108 | Central transition zone with little intervention in Junín                                                                           |
|               |               | 9          | 70109 | Central zone of high intervention in Junín                                                                                          |
|               |               | 10         | 70110 | Central area of medium intervention in Pasco                                                                                        |
|               |               | 11         | 70111 | Central transition zone with high intervention                                                                                      |
|               |               | 12         | 70112 | Central transition zone with little intervention around Otishi                                                                      |
|               |               | 13         | 70113 | Southern zone of high intervention around Quincemil and Pillcopata                                                                  |
|               |               | 14         | 70114 | Southern zone of little intervention around Manu and Bahuaja Sonene                                                                 |
|               |               | 15         | 70115 | Southern transition zone with high intervention in Puno                                                                             |
| Region 702    | Lower Amazon  | 1          | 70201 | Northern low-intervention zone around the Putumayo River                                                                            |
|               |               | 2          | 70202 | Northern area of medium intervention around the Amazon and Nanay rivers                                                             |
|               |               | 3          | 70203 | Northern zone of little intervention around the Pastaza and Pacaya Samiria rivers                                                   |
|               |               | 4          | 70204 | Northern high intervention zone in Yurimaguas                                                                                       |
|               |               | 5          | 70205 | Central zone with little intervention due to Sierra del Divisor                                                                     |
|               |               | 6          | 70206 | Central zone with little intervention and many landslides                                                                           |
|               |               | 7          | 70207 | Pachitea high intervention central zone                                                                                             |
|               |               | 8          | 70208 | Central zone of minor intervention around the Imiria                                                                                |
|               |               | 9          | 70209 | Central zone of high intervention in Ucayali                                                                                        |
|               |               | 10         | 70210 | Southern area of low intervention near Purús                                                                                        |
|               |               | 11         | 70211 | Southern zone of high intervention around Tambopata                                                                                 |
|               |               | 12         | 70212 | Northern zone of non-forested vegetation in continuity with Ecuador.                                                                |
| Region 703    | High Andes    | 1          | 70301 | North-central area of the Atlantic slope above approximately 3800 meters above sea level, presence of glaciers and wetlands.        |
|               |               | 2          | 70302 | Central zone of the Atlantic slope at approximately 3800 meters above sea level, presence of glaciers and wetlands.                 |
|               |               | 3          | 70303 | South-central area of the Atlantic slope at approximately 3800 meters above sea level, presence of glaciers and wetlands.           |
|               |               | 4          | 70304 | Southern zone on the slope of Lake Titicaca (east) at approximately 3800 meters above sea level, presence of glaciers and wetlands. |
|               | Lower Andes   | 1          | 70305 | Northern area of the Atlantic slope, humid forests with intervention.                                                               |
|               |               | 2          | 70306 | North-central area of the Atlantic slope below approximately 3800 meters above sea level.                                           |
|               |               | 3          | 70307 | Central zone of the Atlantic slope below approximately 3800 meters above sea level.                                                 |

|                    |                                  |       |                                                                                                                                          |                                                                                                                                                                    |
|--------------------|----------------------------------|-------|------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Region 704         | Andes<br>Inter-Andean Dry Forest | 4     | 70308                                                                                                                                    | Southern zone of the Atlantic slope below approximately 3800 meters above sea level.                                                                               |
|                    |                                  | 5     | 70309                                                                                                                                    | Southern zone of the Atlantic slope below approximately 3800 meters above sea level.                                                                               |
|                    |                                  | 1     | 70310                                                                                                                                    | Northern area of the Atlantic slope of dry forests and thorny mountains                                                                                            |
|                    |                                  | 2     | 70311                                                                                                                                    | Northern area of the Atlantic slope that combines humid forests, scrubland and heavy human intervention                                                            |
|                    |                                  | 3     | 70312                                                                                                                                    | Central-southern area of the Atlantic slope, dry forests and scrubland                                                                                             |
|                    | Inter-Andean Xeric Savannah      |       | 70313                                                                                                                                    | Southern area of the Atlantic slope, dry forests and thorny steppes                                                                                                |
|                    | High Pacific Andes               | 1     | 70401                                                                                                                                    | North-central zone on the Pacific slope, at approximately 800 meters above sea level, with glaciers and wetlands.                                                  |
|                    |                                  | 2     | 70402                                                                                                                                    | Central zone of the Pacific slope at approximately 3800 meters above sea level, presence of glaciers and wetlands.                                                 |
|                    |                                  | 3     | 70403                                                                                                                                    | Southern zone on the Titicaca slope (west) at approximately 3800 meters above sea level, with high levels of human intervention                                    |
|                    | Lower Pacific Andes              | 1     | 70404                                                                                                                                    | Southern zone of the Pacific slope below approximately 3800 meters above sea level. It borders the coast (Tacna, Moquegua, Arequipa).                              |
| 2                  |                                  | 70405 | Northern area of the Pacific slope, presence of dry forests, borders the Equatorial Dry Forest.                                          |                                                                                                                                                                    |
| 3                  |                                  | 70406 | Northern area of the Pacific slope, area of regular agricultural intervention.                                                           |                                                                                                                                                                    |
| High Pacific Andes | 4                                | 70407 | Central zone of the Pacific slope below approximately 3800 meters above sea level.                                                       |                                                                                                                                                                    |
|                    | 5                                | 70408 | South-central area of the Pacific slope below approximately 3800 meters above sea level.                                                 |                                                                                                                                                                    |
|                    | 4                                | 70409 | Southern area of the Titicaca slope (west) at approximately 3800 meters above sea level. Presence of grasslands and wetlands             |                                                                                                                                                                    |
|                    | 5                                | 70410 | Southern area of the Titicaca slope (west) at approximately 3800 meters above sea level. Presence of grasslands, wetlands, and glaciers. |                                                                                                                                                                    |
|                    |                                  |       |                                                                                                                                          |                                                                                                                                                                    |
| Region 705         | North Coast                      | 1     | 70501                                                                                                                                    | Northern coastal area bordering Ecuador with mangroves and dry forests.                                                                                            |
|                    |                                  | 2     | 70502                                                                                                                                    | Northern zone bordering Ecuador with the presence of tropical rainforest of Tumbes.                                                                                |
|                    |                                  | 3     | 70503                                                                                                                                    | Northern coastal area with dry forests and high urban and agricultural intervention.                                                                               |
|                    |                                  | 4     | 70504                                                                                                                                    | Sechura Desert with the presence of lagoons, salt flats and wetlands that emerge seasonally from the temporary impacts of the El Niño phenomenon on the area.      |
|                    |                                  | 5     | 70505                                                                                                                                    | Border area with Ecuador with the presence of dry forests and regular agricultural intervention.                                                                   |
|                    |                                  | 6     | 70506                                                                                                                                    | Transition zone from dry forest to the Andean region, with regular agricultural intervention.                                                                      |
|                    | Central Coast                    | 1     | 70507                                                                                                                                    | Central-northern coastal area, sporadic presence of dry forests and high agricultural intervention                                                                 |
|                    |                                  | 2     | 70508                                                                                                                                    | Central coastal area, little natural vegetation but high urban and agricultural intervention.                                                                      |
|                    | Costa Sur                        | 1     | 70509                                                                                                                                    | Southern coastal area, little natural vegetation but high agricultural intervention. Presence of scrubland in transition zones towards the Andean region.          |
|                    |                                  | 2     | 70510                                                                                                                                    | Southern coastal area: little natural vegetation but high urban and agricultural development. Presence of scrubland in transition zones towards the Andean region. |

Source: Own elaboration.



**Figure 7.** Map of classification regions for Collection 4.0.

### 3.3.3. Classification Algorithm

*Random forest*<sup>11</sup> It is a classification method that uses a machine learning algorithm (*machine learning*) and which reports high accuracy values, even in complex scenarios due to their heterogeneity. The conceptual basis of Random Forest is based on what Turner and Ghosh (1996) found when demonstrating that the product resulting from the combination of multiple classifiers achieves high accuracy. Random Forest uses training data to build multiple decision trees from which a class is assigned to each pixel. Random Forest has gained importance in recent years due to its robustness against noise and outliers. The Random Forest algorithm is part of the classifier package of *machine learning* available on the Google EE platform. The methodology applies a pixel-based classification criterion.

One of the parameters that Random Forest requires is a defined number of trees. It also requires a list of variables (see the "Variables" section) and training data (see the "Spectral Collection" section). For

<sup>11</sup> Leo Breiman, "Random Forests," *Machine Learning* 45, no. 1 (October 1, 2001): 5–32, <https://doi.org/10.1023/A:1010933404324>

Collection 4.0, the number of trees varied according to the needs and characteristics of each classification subregion.

### 3.3.4. Sample collection

The classification method used was random forest and used different sample sources depending on the region to be classified.

For mosaic regions 701, 702 and 703, a collection of stable samples (same class throughout the time series) was carried out for each of the categories of the legend that was being sought. The data was extracted from the MapBiomass Amazonia products. A preliminary classification was then generated for the 41 years. Stable samples (for 41 years) were extracted from this product to be used as input for a new classification. The interpreter contributes by excluding and/or including samples to improve them.

For mosaic regions 704 and 705, available national references were used. The process began with the homologation of MapBiomass classes with the classes of the national ecosystem map. Then, a random selection of samples per class was made within each classification region, assuming a false stability of these points over the years of analysis, to obtain a preliminary classification. Based on this preliminary result, and with the participation of the interpreter, unstable samples were excluded. As in the first case, the random selection of points was balanced according to the extent of each class within that classification region. Optionally, additional samples were manually included and designated as *supplementary samples*, using the geometry creation tools directly in Google EE.

Table 8 presents the summary of stable samples used by region as input for the 40 to 60 trees applied to the classifier.

**Table 8.** Parameters used in the Random Forest classifier.

| Mosaic region | Classification region | Number of stable samples exported |                       | Number of trees Random Forest |
|---------------|-----------------------|-----------------------------------|-----------------------|-------------------------------|
|               |                       | Minimum                           | Maximum               |                               |
| Region 701    | 70101 a 70115         | Between 800 and 3000              | Between 4000 and 5000 | 50                            |
| Region 702    | 70201 a 70211         | Between 500 and 2500              | Between 3000 and 5000 | 50                            |
| Region 703    | 70301 a 70314         | Between 300 and 500               | Between 4000 and 5000 | 50 and 60                     |
| Region 704    | 70401 a 70408         | Between 300 and 500               | Between 4000 and 5000 | 60                            |
| Region 705    | 70501 a 70510         | Between 100 and 500               | Between 3000 and 5000 | 50                            |

Source: Own elaboration

### 3.3.5. Cross-cutting themes

During the various classification tests, certain classes were identified whose differentiation using the general map presented limitations, primarily related to their spectral or spatial characteristics, or their specific distribution within certain biomes. For this reason, an independent classification strategy was established for these classes, called Cross-Cutting Themes, using binary classification algorithms. This strategy considered one class of interest and one "Not Observed" class. This approach allowed for the

development of specific models for those classes that required a different approach compared to the general map classification process.

The application of this strategy was not necessarily uniform across the country. Depending on the characteristics of each land cover class and the specific features of the biomes, some were classified using the cross-sectional approach only in certain areas, while in others they were obtained using the general map. This differentiation allowed for the selection of the most appropriate methodological strategy for each class and biome, considering its spectral and spatial characteristics, as well as the specific conditions for representing each land cover type.

Within the scope of MapBiomass Peru, the following classes were considered as cross-cutting themes:

- Mangrove (ID = 5);
- Flooded forest (ID = 6);
- Forest plantation (ID = 9);
- Swampy area or floodable grassland (ID = 11);
- Pasture (ID = 15);
- Mosaic of agriculture and pasture (ID = 21);
- Beaches (ID = 23);
- Urban infrastructure (ID = 24);
- Mining (ID = 30);
- Aquaculture (ID = 31);
- Coastal saline surface (ID = 52);
- Oil palm (ID = 35);
- River, Lake and Ocean (ID = 33)\*;
- Glacier (ID = 34)\*;
- Rice (ID = 40);
- Salt flat (ID = 61);
- Fog oasis (ID = 70);
- Other anthropogenic non-vegetated-area (ID = 25).

The application of these strategies presented particularities depending on the biome and, in some cases, involved subsequent integration and subdivision processes. For example, Flooded forest (ID = 6) was classified using a cross-sectional approach, following the methodological criteria established in the specific ATBD for Floodplains. Similarly, Coastal Saline Area (ID = 52) was addressed using a cross-sectional classification in the Coastal Desert, while in the Amazon and Andes its representation was obtained using the general map.

A particular case corresponds to the Swampy Zone or Floodplain (ID = 11). During the initial classification stage, this class was addressed using different strategies depending on the biome. In the Coastal Desert, its classification was carried out using a cross-cutting approach, while in the other biomes it was obtained using the general map. Subsequently, the results of both strategies were integrated to obtain a national representation of class 11.

Once this integration was completed, a topographic subdivision criterion based on altitude was applied, using a threshold of 3000 m a.s.l. Pixels belonging to class 11 located at altitudes greater than or equal to 3000 m a.s.l. were assigned to class 81, High Andean Floodplain Grassland, while those located at altitudes below 3000 m a.s.l. were assigned to class 51, Lowland Floodplain Grassland. Therefore, classes 51 and 81 correspond to a subsequent subdivision of class 11, carried out after the integration of the initial classifications using a topographic criterion, and not to independent classes during the initial stage of the process.

Additionally, Other anthropogenic non-vegetated-area (ID = 25) was classified using the cross-sectional approach in the Coastal Desert and Equatorial Dry Forest, according to the

methodology established in the specific ATBD for this class. In these areas, the cross-sectional mapping was aimed at identifying specific anthropogenic surfaces associated with certain productive activities, including facilities for intensive poultry farming. In contrast, in the Andes and Amazon, class 25 was represented by the general map, which encompasses a broader set of anthropogenic surfaces without vegetation cover and not necessarily associated with the specific facilities considered in the cross-sectional mapping.

These differences demonstrate that the term "cross-cutting theme" refers to the methodological strategy applied to a specific classification class and area, and does not necessarily imply that the class has been processed using a cross-cutting model in all biomes. Consequently, the same class may exhibit different classification strategies depending on the biome, being obtained through a cross-cutting model in one area and through the general map in another.

Finally, the results obtained through the different approaches were integrated to form the national representation of the corresponding classes, applying, when necessary, subsequent processes of remapping, integration and subdivision according to the methodological criteria defined for each topic.

Details of the specific methodologies, algorithms used, and criteria established to determine the scope of application of each cross-cutting theme are presented in the respective ATBDs for each class.

\*Cross-cutting classes that have been mapped in other initiatives such as MapBiomás Agua.

### **3.4. Post-classification**

The preliminary classification result was subjected to the application of a sequence of filters in order to reduce temporal inconsistencies and reduce classification noise smaller than the minimum mapping unit.<sup>12</sup> and fill information gaps. The post-classification process in this collection does not follow a specific order in the application of filters; their sequence was determined by the needs of each classification region, and repeated use of filters was even facilitated. Exceptions were also included within each filter, such as excluding certain years and classes. All these tools were implemented on the Google EE platform using scripts written in JavaScript. Each of these tools is presented in greater detail below. A description of how these filters were adapted by country can be found in the national appendices.

#### **3.4.1 Gap Filling**

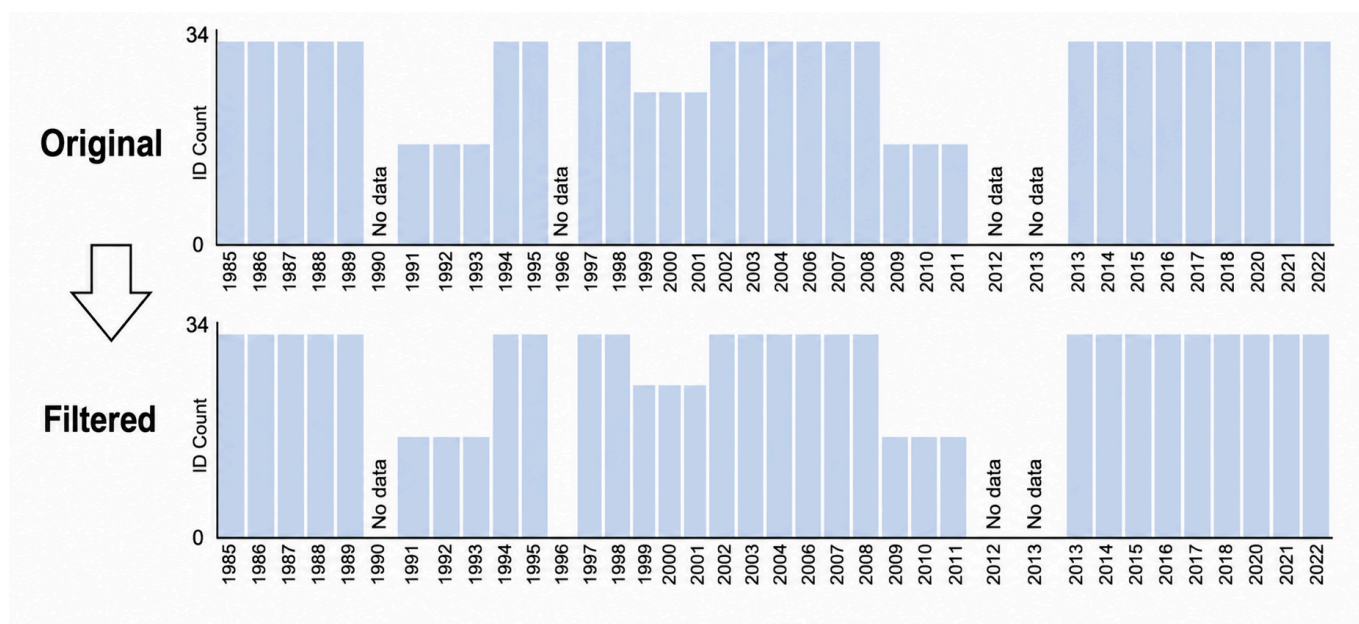
Certain areas of Peruvian territory are characterized by atmospheric and climatic conditions that result in an almost permanent presence of clouds throughout the year in various parts of the territory. As a result, the composition of annual mosaics contains pixels without observations or data (*No data*).

The gap fill filter has the ability to reduce these residual gaps by assigning values to pixels without data due to absences of satellite observation ("gaps").

Pixels in classifications with missing data ("gaps") are replaced with the nearest temporally available value. When a "future" pixel lacks a value (no data), the Gap Fill filter assigns it the value of the year closest to it. This filter reviews the series, first filling gaps by scanning from "back to front," where gaps are filled with data from the years immediately preceding the missing data year. If any gaps remain, they are filled with data from the immediately preceding year. For each pixel whose value was filled using this filter, the change is recorded in a metadata file, which records the pixel's year (history) (see Figure 8).

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<sup>12</sup> 5 pixels = approximately half a hectare.



**Figure 8.**Gap Fill filter functionality diagram.

### 3.4.2 Temporal Filter

The temporal filter examines the value of each classified pixel in relation to its value in consecutive temporal classifications. It does this using a one-way moving window that considers classification sequences of 3 to 5 years and identifies disallowed temporal transitions. The temporal filter is applied to every pixel in every year of the collection.

Depending on the year the rule will modify, there are three types of rules:

- General Rules (GR). Applied to pixels in intermediate positions within 3- to 5-year sequences. This rule applies only in cases of temporal inconsistency; for example, when sequences of consecutive years have identical values except for the central pixel. In these cases, the filter will modify the value of the central pixel to maintain consistency with the preceding and following pixels. For 3-year sequences, there is only one central position or intermediate year option. For 4- or 5-year sequences, there are two or three central position alternatives. This rule modifies the classification values for the years 1986 to 2023.
- First-year rules (PR). Applied only to the first year of the time series. This rule modifies the classification values for the year 1985.
- Last-Year Rules (RU). Applied to the last year of the ranking. This rule modifies the ranking values for the year 2025.

In this way, temporal filters reduce information gaps and temporal inconsistencies or changes that are not possible or permitted (see Figure 9). For example, if in three consecutive years a pixel has the following values: Forest Formation > Non-Vegetated Area > Forest Formation, the filter will correct the intervening year. This case is a typical classification error due to the presence of cloud haze in the mosaic of the intervening year.

The decision to choose the size of the time window was made by each country according to the needs and characteristics of its land cover and land use by subregion and/or cross-cutting theme. See more details in the respective country appendices.

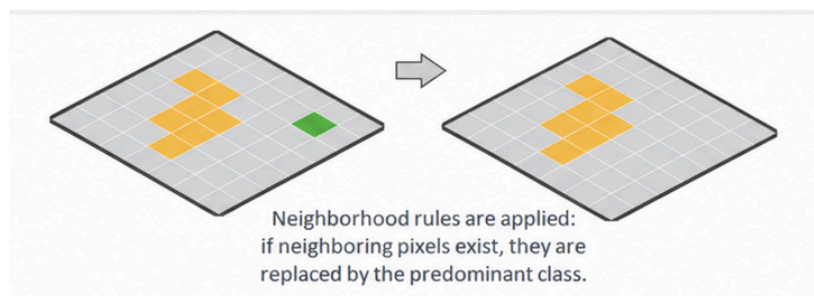




**Figure 9.**Time filter functionality diagram.

### 3.4.3 Spatial Filter

The spatial filter is based on the GEE's native "connectedPixelCount" function. This function locates connected pixels (neighbors) that share the same value using a moving window. Only pixels that do not share a connection with a predefined number of identical neighbors are considered isolated pixels. In the case of MapBiomass Amazonia, the minimum mapping unit was defined as 0.5 ha (5 pixels). Consequently, at least five connected pixels were required to meet the minimum connection criterion. Thus, the spatial filter smooths out local differences by eliminating isolated or edge pixels smaller than 0.5 ha, increasing the spatial consistency of the ratings (see Figure 10). It should be noted that some classification regions had exceptions to the 3-pixel minimum unit.



**Figure 10.**Spatial filter functionality diagram.



### 3.4.4 Frequency Filter

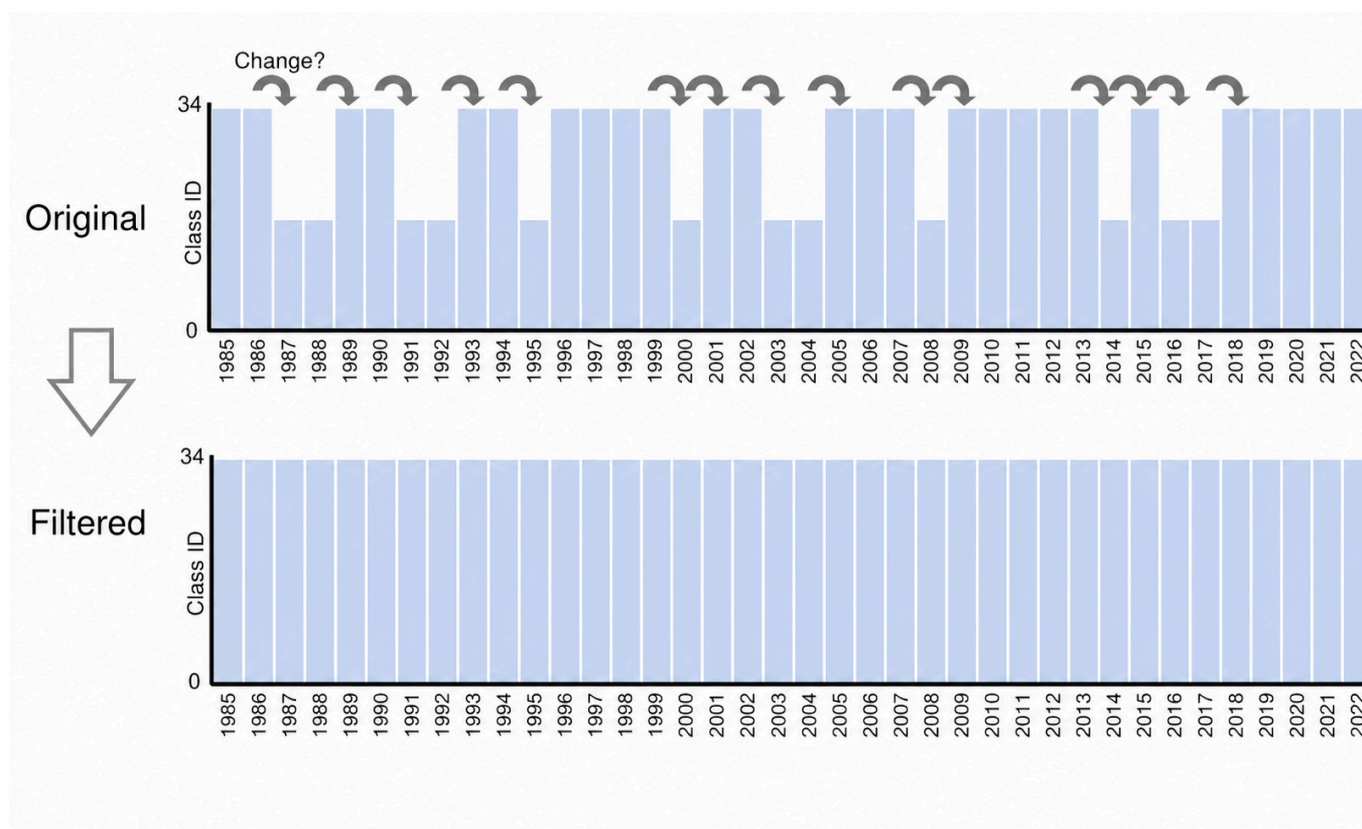
This filter takes into account the frequency of occurrence of natural classes throughout the time series. Therefore, classes with occurrences below a percentage defined by the interpreter are replaced by the value of the most frequent class. This mechanism helps reduce the temporal oscillation associated with a natural class, decreasing the frequency of false positives and preserving established trends (Figure 11). The filter criteria were adapted by classification region according to the needs of each subregion and/or cross-cutting theme. Its application was ruled out in several subregions and/or countries. See the respective country appendices for more details.



**Figure 11.**Frequency filter functionality diagram.

### 3.4.5 Incident Filter

The incidence filter stabilizes the value of natural-class pixels that changed class too many times over the 41-year time series. All pixels that change more than a user-defined number of times and are connected to at least Pixels were replaced by the mode class value for that pixel. This reduces changes along class edges and helps stabilize transitions disrupted by noise. The filter criteria were adapted to the needs of each subregion and/or cross-cutting theme (Figure 12). Its application was ruled out in several subregions and/or countries. See the respective country appendices for more details.



**Figure 12.** Incident filter functionality scheme.

### 3.4.6. Reclassification

In very particular cases, where there was no class continuity between countries, it was decided to verify with reference layers or secondary information which country had the correct classification and thus reclassify the erroneous class and obtain a correct continuity between biomes or countries.

### 3.5. Integration

The results of the annual classifications obtained for each of the classification regions constitute sectors of the general base map, which need to be integrated into a single annual regional map with the cross-cutting themes; following rules of prevalence or order of integration that define the prevalence of classes where overlap of different values occurs.

The integration for Peru was carried out by classification region with specific prevalence rules for each region, as shown in Table 9. Layers with a lower prevalence order (numbers close to one (1)) are those with a smaller classification area and will be the top layer in the integration. These prevalence orders vary according to the biome. The product consists of annual land cover and land use maps by country.

**Table 9.**Prevalence rules by biome for the integration phase.

| Collection 4.0. | CLASS ID | FOUNTAIN | ORDER OF PREVALENCE |
|-----------------|----------|----------|---------------------|
|-----------------|----------|----------|---------------------|

|                                                   |    |             | AMAZONIA | ANDES | EQUATORIAL<br>DRY FOREST | COASTAL<br>DESERT |
|---------------------------------------------------|----|-------------|----------|-------|--------------------------|-------------------|
| Forest Plantation                                 | 9  | General     | -        | 2     | -                        | -                 |
| Forest Plantation                                 | 9  | Transversal | -        | 2     | -                        | -                 |
| Beach                                             | 23 | Transversal | 1        | 4     | 9                        | 11                |
| Beach                                             | 23 | General     | 2        | 4     | 10                       | 16                |
| Aquaculture                                       | 31 | Transversal | -        | -     | -                        | 6                 |
| Water                                             | 33 | General     | 3        | 5     | 1                        | 1                 |
| Mining                                            | 30 | Transversal | 4        | 6     | 3                        | 4                 |
| Urban Infrastructure                              | 24 | Transversal | 5        | 7     | 4                        | 5                 |
| Fog oasis                                         | 70 | Transversal | -        | -     | -                        | 12                |
| Coastal salt flat                                 | 32 | Transversal | -        | -     | -                        | 15                |
| Salt flat                                         | 61 | Transversal | -        | 3     | -                        | -                 |
| Rocky surface                                     | 29 | General     | -        | 17    | -                        | -                 |
| Other natural non-vegetated-area                  | 68 | General     | 6        | 16    | -                        | 17                |
| Another human-modified area<br>without vegetation | 25 | Transversal | -        | 17    | 6                        | 3                 |
| Another human-modified area<br>without vegetation | 25 | General     | 7        | 17    | 7                        | 14                |
| Herbaceous formation                              | 12 | General     | 8        | 15    | -                        | -                 |
| Floodable herbaceous formation                    | 11 | General     | 9        | 8     | -                        | -                 |
| Floodable herbaceous formation                    | 11 | Transversal | 10       | 8     | -                        | 9                 |
| Shrub formations and others                       | 66 | General     | 11       | 14    | 8                        | 13                |
| Oil palm                                          | 35 | Transversal | 12       | -     | -                        | -                 |
| Rice                                              | 40 | Transversal | 13       | 11    | -                        | 8                 |
| Pasture                                           | 15 | Transversal | 14       | 12    | -                        | -                 |
| Pasture                                           | 15 | General     | -        | 12    | -                        | -                 |
| Mosaic of agriculture and pasture                 | 21 | Transversal | 15       | 13    | -                        | -                 |
| Mosaic of agriculture and pasture                 | 21 | General     | 16       | 13    | 5                        | 10                |
| Flooded forest                                    | 6  | Transversal | 17       | -     | -                        | -                 |
| Flooded forest                                    | 6  | General     | 18       | -     | -                        | -                 |
| Mangrove                                          | 5  | General     | -        | -     | -                        | -                 |
| Mangrove                                          | 5  | Transversal | -        | -     | -                        | 7                 |
| Dry forest                                        | 4  | General     | -        | 9     | 11                       | 18                |
| Dry forest                                        | 4  | Transversal | 19       | 9     | -                        | -                 |
| Forest                                            | 3  | General     | 20       | 10    | 12                       | 12                |
| Water                                             | 33 | Transversal |          |       |                          | 2                 |
| Glacier (MAPBIOMAS WATER)                         | 34 | Transversal | -        | 1     | -                        | -                 |
| Water (MAPBIOMAS WATER)                           | 33 | Transversal | 21       | 5     | 2                        | 2                 |

### 3.6 Transition Maps

Based on the integrated annual land cover and land use maps, transitions are calculated. These represent the changes between pairs (2) of maps, that is, between two periods. The results are available on the MapBiomás Amazonia platform. Transitions are calculated for different periods, such as:

- (A) consecutive years, annual (for example, from 2001 to 2002, or from 2013 to 2014, etc.)
- (B) five-year periods (for example, 2000-2005)
- (C) ten-year periods (e.g., 2000-2010)
- (D) complete time series (1985 - 2025)
- (E) special periods (for example, 2000-2025)

### 3.7 Statistics

Based on the integrated annual land cover and land use maps, area statistics in hectares (Ha) are calculated for both zonal and annual areas of the mapped classes. The spatial units considered for calculating the statistics are:

- Country
- Biome
- Department
- Province
- District
- River basin
- Indigenous territories
- Protected natural areas
- Geographic region

## 4. Validation

Map validation is performed every three collections. The validation process for collection 1.0 of annual land cover and land use maps of Peru, which only covers the period 1985–2021, is detailed below.

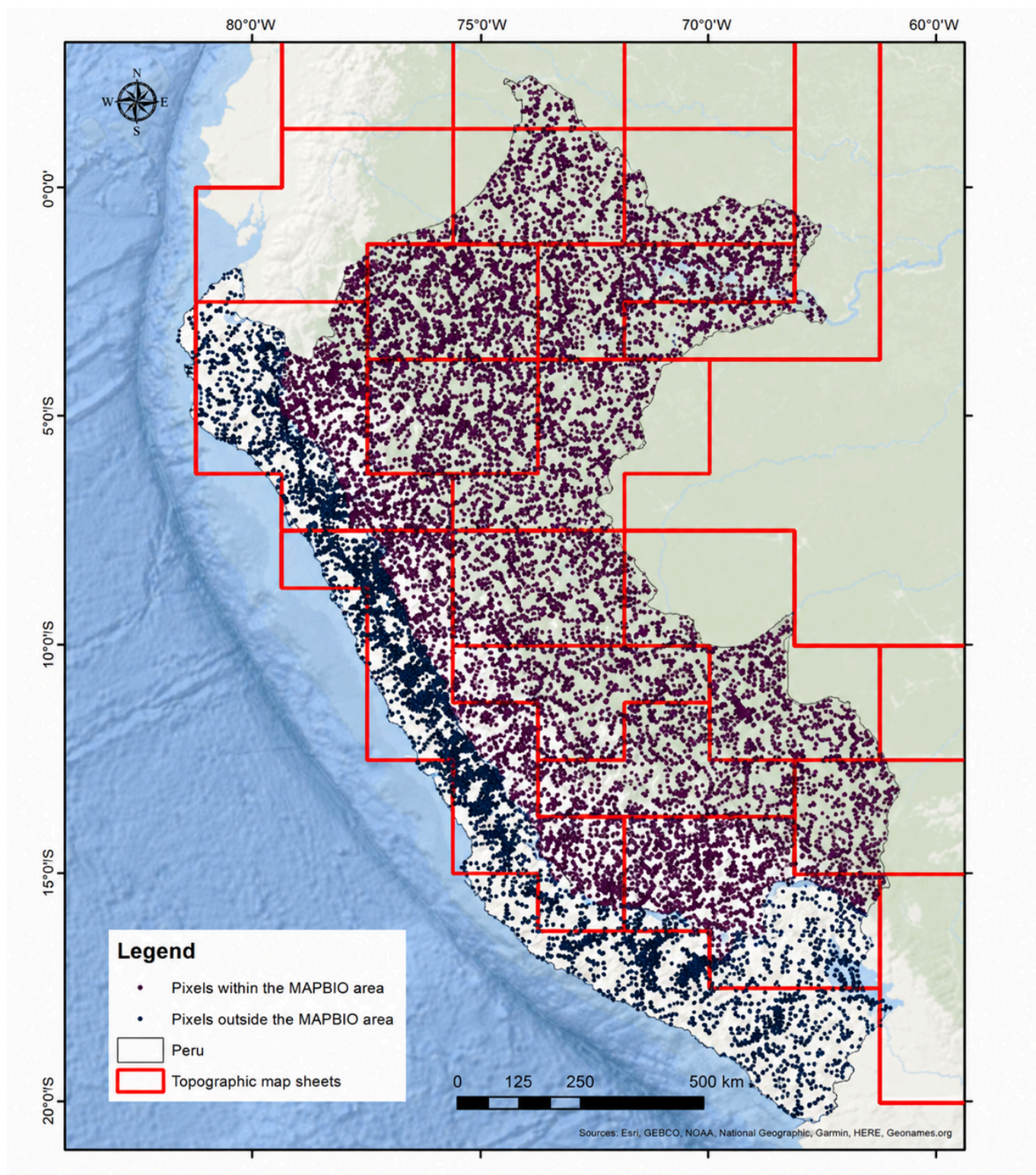
The accuracy analysis evaluates the quality of the resulting maps. This analysis was conducted by an institution external to the map's authors and includes results on the overall map accuracy by class and year, as well as errors of omission and commission for each of the classified categories.

The accuracy analysis considered a sampling method in which the population (i.e., the total number of pixels) was divided into two domains in Peru, inside and outside the RAISC boundary. Within the RAISC boundary, subdomains were created by constructing maps.<sup>13</sup>grouped ([ATBD link](#)). Nineteen maps were constructed, grouped by region of Peru (Figure 14), each with an area of approximately 70,000 km<sup>22</sup>For each domain, a one-stage proportional stratified random sampling was carried out, where stratification was defined by division into six slope levels, and within each stratum, a simple random sampling of the primary sampling units (pixel) was carried out.

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<sup>13</sup>Corresponding to the charts of the International Map of the World to the Million (CIM) at scales of 1:250,000. See section 3.1.1.





**Figure 14.** Distribution of sample points in domains inside and outside the RAISG boundary.

In each domain, the precision and reliability of the estimates were controlled so that the sample size would guarantee a maximum standard error of 5% in the grouped maps and 2.5% in the rest of Peru, with a 95% confidence level. From this perspective, the maximum expected error for the entire study area is 0.5%. Considering the feasibility of time and interpreters for the inspection process, a minimum of 500 points was defined for each domain. The sample size calculation also considered information on variability and the number of classes in each grouped map. Thus, the sample size was

established as an increasing function in relation to the number of classes and/or the variability. The variability information was derived from the maximum variance of the land cover classes, and the Bonferroni correction (Dunn, 1959) was applied to account for the information on the number of classes.<sup>14</sup> which corrects the quantile value of the standard normal distribution. The total number of samples extracted for the entire study area corresponded to 7,839 pixels within the RAISG boundary and 3,450 outside of RAISG.

The formula for calculating the sample size for each domain is shown below.

$$n = \max_{p \cdot q} \left( \frac{N z_{\gamma}^2 p q}{(N - 1) E^2 + z_{\gamma}^2 p q} \right),$$

where  $n$  is the sample size;  $N$  is the total number of points;  $E$  is the maximum margin of error;  $p = 1 - q$  is the proportion to be estimated (for outside RAISG, the maximum proportion of 0.25 was used); and  $z$  is the factor of the standard normal distribution corresponding to the adjusted confidence level  $1 - g$  calculated by the Bonferroni correction, where  $g = k - 1$  and  $1 -$  is the desired confidence level;  $k$  is the number of land use and land cover classes (Cochran, 1977).<sup>15</sup>

Each sample was classified annually (i.e., 1985–2021) by three independent interpreters. In this study, we considered the class with the most votes in each observation. This process involved a group of 14 people and the validation of 18 classes present in Collection 1.0.

Visual inspections were conducted using the Temporal Visual Inspection (TVI - [tvi.lapig.iesa.ufg.br](http://tvi.lapig.iesa.ufg.br)) tool, developed by the Image Processing and Geoprocessing Laboratory (Lapig) at the Federal University of Goiás (UFG). Each year under evaluation, the interpreter had access to two Landsat images (SWIR-NIR-RED composite). Auxiliary information, such as coordinates and region, was also provided, along with the option to view high-resolution images using Google Earth. It is worth noting that Google Earth was used to enhance understanding of the landscape context and its spectral response in Landsat images.

Meetings were also held between the group of interpreters and a group of experts from each country. These meetings led to the creation of an interpretation key with different criteria for interpreting Landsat images (e.g., color, tone, texture, homogeneity, shape, and context). This action enhanced the understanding of different land cover types in the region.

Accuracy was assessed using metrics that compare the assigned class with the class evaluated by the validating technicians on the reference data. The metrics used were: User accuracy (commission error), which is associated with the reliability of each assigned class; Producer accuracy (omission error), which is associated with the classifier's sensitivity, i.e., its ability to correctly distinguish one class from others; and finally, overall accuracy, which is the estimate of the classifiers' overall accuracy rate.

The validation results are available on the MapBiomass platform.

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<sup>14</sup> Olive Jean Dunn "Estimation of the Medians for Dependent Variables," *The Annals of Mathematical Statistics*, Ann. Math. Statist. 30(1), 192-197, (March, 1959)

<sup>15</sup> William Gemmell Cochran, *Sampling Techniques*, 3d ed, Wiley Series in Probability and Mathematical Statistics (New York: Wiley, 1977).

## 5. Practical considerations and challenges

The 4.0 collection of annual land cover and land use maps for Peru is a strategic monitoring tool that reflects the country's history over more than three decades. The production of this volume of multi-year information has led to applications for estimating trends in land cover change, as well as for understanding the factors that modify land cover dynamics.

For the development of this project, with its unprecedented spatial and temporal scope, a standardized methodology was used that can be replicated in other areas of the world. The use of Google Earth Engine's cloud-based work platforms and open-source technology has shown promise for large-scale data accessibility and processing.

Through the learning and experience gained from producing the previous collection, along with the exchange of ideas with the teams from the various MapBiomass initiatives, it was possible to achieve greater efficiency in terms of time and processes. Through the collaborative and networked work of a multidisciplinary team, it was possible to develop a methodology tailored to the specific needs of each region.

The use of the Random Forest algorithm as a classifier, combined with a flexible mapping protocol, allows each country in the various initiatives to define its feature space and samples.

Applying post-classification filters reduced the effects associated with the low quality and limited availability of satellite imagery, which are most prevalent at the beginning of the time series. Furthermore, the inclusion of new, hierarchically integrated cross-cutting themes made it possible to provide greater thematic detail in the land use and land cover maps.

The next step in this project is to expand the level of detail in the legend, increase the accuracy of the mapping, and use new remote sensing technologies and tools to obtain a higher quality product.

## 6. References

National Water Authority. n.d. Map of Hydrographic Units. Lima, Peru.  
<https://sinia.minam.gob.pe/repositorio-de-mapas?page=11>

Andean Community. Map of Ecosystems of the Northern and Central Andes. 2009  
<https://sinia.minam.gob.pe/mapas/mapa-vegetacion-natural-remanente-andes-norte-centro>

DGOTA-MINAM. National Ecosystem Map.  
2018 <http://geoservidor.minam.gob.pe/recursos/intercambio-de-datos/>

DGOTA-MINAM. Map of Ecoregions of Peru.  
2017 <http://geoservidor.minam.gob.pe/recursos/intercambio-de-datos/>

Fosnight, E. A., Shaw, J., Masek, J. G., and Roy, D. P. (2016). The global Landsat archive: Status, consolidation, and direction. *Remote Sensing of Environment*, Vol. 185, 271-283.

Google (2019, March 1). Landat Collections. Accessed at <https://developers.google.com/earth-engine/datasets/catalog/landsat/>

Google (2019, March 1). Google Earth Engine API. Retrieved from <https://developers.google.com/earth-engine/>



- Gorelick, Noel; Hancher, Matt; Dixon, Mike; Ilyushchenko, Simon; Thau, David; Moore, Rebecca. (2017). Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment*, Vol. 202, 18-27.
- National Institute of Natural Resources - Office of Intersectoral Environmental Management, Evaluation and Information of Natural Resources. 2000. Map of natural regions of Peru. Lima. Peru.
- National Institute of Natural Resources. 2002. Physiographic map of Peru. Lima. Peru.
- Kalliola, R., Puhakka, M. and Danjoy, W. (ed.) (1993). Peruvian Amazon: Tropical humid vegetation in the sub-Andean plain. Amazon Project University of Turku-National Office of Natural Resources Assessment.
- LAMPRECHT, H. 1990. Silviculture in the tropics. Forest ecosystems in tropical forests and their tree species; possibilities and methods for sustainable use. Translated by Antonio Carrillo. Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ). 335 pp.
- Ministry of Agrarian Development and Irrigation. 2020. Official National Agricultural Area. <https://siea.midagri.gob.pe/portal/index.php/normas>
- Ministry of Agrarian Development and Irrigation. 2021. Rice crop monitoring. GEOMIDAGRI. <https://minagri-geoespacial.users.earthengine.app/view/monitoreoarrozv1>
- Ministry of the Environment. 2009. Map of wetlands of Peru. Lima, Peru. <https://sinia.minam.gob.pe/repositorio-de-mapas?page=11>
- Ministry of the Environment. 2015. Map of Vegetation Cover of Peru. Descriptive Report - Peru. 108p. <https://sinia.minam.gob.pe/repositorio-de-mapas?page=11>
- Ministry of the Environment. 2022. Forest Conservation and Climate Change Mitigation Program. Map of Forest and Non-Forest 2000. Forest Loss 2001-2021. Lima, Peru.
- Ministry of the Environment. 2018. Forest Conservation and Climate Change Mitigation Program. Mapping of seasonally dry and non-seasonally dry forests on the northern coast of Peru. Tumbes · Piura · Lambayeque. Descriptive Report. [http://www.bosques.gob.pe/archivo/Memoria-descriptiva\\_Bosques-secos-interiores-final.pdf](http://www.bosques.gob.pe/archivo/Memoria-descriptiva_Bosques-secos-interiores-final.pdf)
- Moat et al. 2020. Seeing through the clouds - Mapping desert fog oasis ecosystems using 20 years of MODIS imagery over Peru and Chile. Consulte el mapa en Earth Engine: <https://gist.in/users/earthengine.app/view/fogoasis> See the article at: <https://www.sciencedirect.com/science/article/pii/S0303243421001756>
- Nature Server, IIAP, CDC-UNALM (2007). Ecological systems of the Amazon basin of Peru and Bolivia. Classification and mapping. Lima: Nature Server, IIAP, CDC-UNALM.
- Olson, David; Dinerstein, Eric; Wickramanayake, Eric; Burgess, Neil; VN Powell, George; C. Underwood, Emma; A. D'Amico, Jennifer; Itoua, Illanga; E. Strand, Holly; Morrison, John; J. Loucks, Colby; F. Allnutt, Thomas; Ricketts, Taylor; New, Yumiko; Lamoreux, John; W. Wettengel, Wesley; Hedao, Prashant ; Kassem, Kenneth. (2001). Terrestrial Ecoregions of the World: A New Map of Life on Earth. *BioScience*. Vol 51, No 11. 933-938.
- National Program for Forest Conservation and Climate Change Mitigation. 2016. Land use and land change rasters in the Amazon. Peru.
- Souza, Carlos; Roberts, Dar A.; Cochrane Mark A. (2005). Combining spectral and spatial information to map canopy damage from selective logging and forest fires. *Remote Sensing of Environment*, Vol. 98, p329-343.
- Souza, Carlos; Siqueira, J.V.(2013). ImgTools: a software for optically remotely sensed data analysis. *Proceedings of the XVI Brazilian Symposium on Remote Sensing*. 1571-1578.



