Appendix – Mangroves

Cross-cutting theme in Collection 3.0

Version 1

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1. Introduction

Mangroves are highly important land cover types for coastal ecosystems (Peters et al., 1997), providing a variety of ecosystem services related to provisioning, regulation, support, and culture (Carvajal-Oses et al., 2019; Marlianingrum et al., 2019). Among these ecosystem services, carbon sequestration stands out, as mangroves can capture up to four times more carbon than the average of other terrestrial forest covers (Spalding & Leal, 2021). They are also recognized as the "nursery grounds" for numerous species of fish, mollusks, amphibians, and birds, offering refuge, feeding, and breeding/nesting sites (Dirección General de Ecosistemas, 2002). In addition, they play an important supporting role as natural barriers against marine erosion, stabilizing coastlines and protecting nearby communities from strong waves.

To establish effective measures for mangrove management, mapping and monitoring gains and losses over time is essential. In this regard, Global Mangrove Watch (GMW) is one of the platforms dedicated to providing geospatial information on the global extent of mangroves and the changes occurring since 1996 through remote sensing, though not continuously. At the national level, the Ministry of Environment, Water and Ecological Transition (MAATE) is responsible for generating geospatial information for Ecuador through vegetation cover and ecosystem maps, which include mangroves; however, this information applies only to the continental territory. Additionally, mangrove mapping in Guayas for the years 2018, 2020, and 2022 by the EcoCiencia Foundation has been used as a reference. In the case of the Galápagos Archipelago, there is no official state-generated geospatial information; therefore, national reference layers from the Charles Darwin Foundation (FCD) and EcoCiencia were used.

One of the main challenges of MapBiomas Ecuador Collection 3.0 was to map mangrove ecosystems continuously over a 40-year time series, from 1985 to 2024. Based on the methodology proposed by Diniz et al. (2019) and used by MapBiomas Brazil in its mangrove mapping collections, adjustments and adaptations were made to replicate the method using the tools available to the interpretation team. Specific working areas were delineated (Figure 1), and national reference maps were used for comparison and validation of results.

The entire process was divided into three main stages: (I) processing of satellite mosaics, (II) sample collection and classification from satellite mosaics, and (III) application of post-classification filters. Each stage involved several steps, including the compilation of reference data, the definition of sampling areas, and preliminary test classifications. The complete classification process is illustrated in Figure 2.

It is important to highlight that the Landsat mosaics used for mangrove mapping differ from those used for the general land cover classification and other cross-cutting themes included in MapBiomas Ecuador Collection 3. The data used correspond to annual mosaics built from Landsat Tier 1 (Top of the Atmosphere) imagery from Google Earth Engine Collection 3. TOA data were selected to preserve as much terrestrial surface as possible along coastal areas while minimizing cloud interference. From all available variables, those most representative for distinguishing mangrove cover from other classes within the mask were selected (including Landsat bands, spectral indices, and topographic variables, using median and 25th percentile reducers) to train the Random Forest classifier.

Finally, the resulting mangrove classification proposed by MapBiomas Ecuador is based on the spectral response characteristics of this land cover.

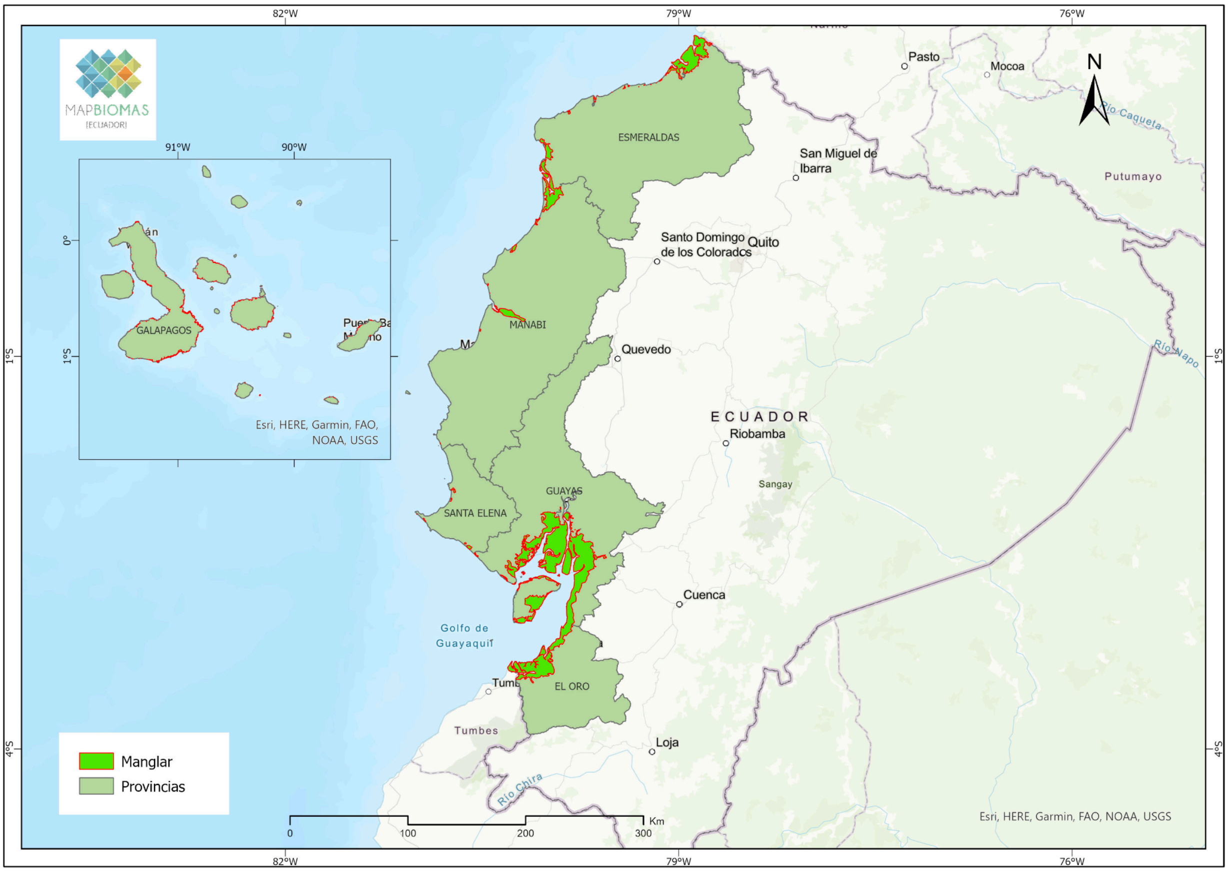

Figure 1. *Location of the classification regions for the Mangroves cross-cutting theme, Collection 3.0, MapBiomas Ecuador. Source: EcoCiencia, 2025*

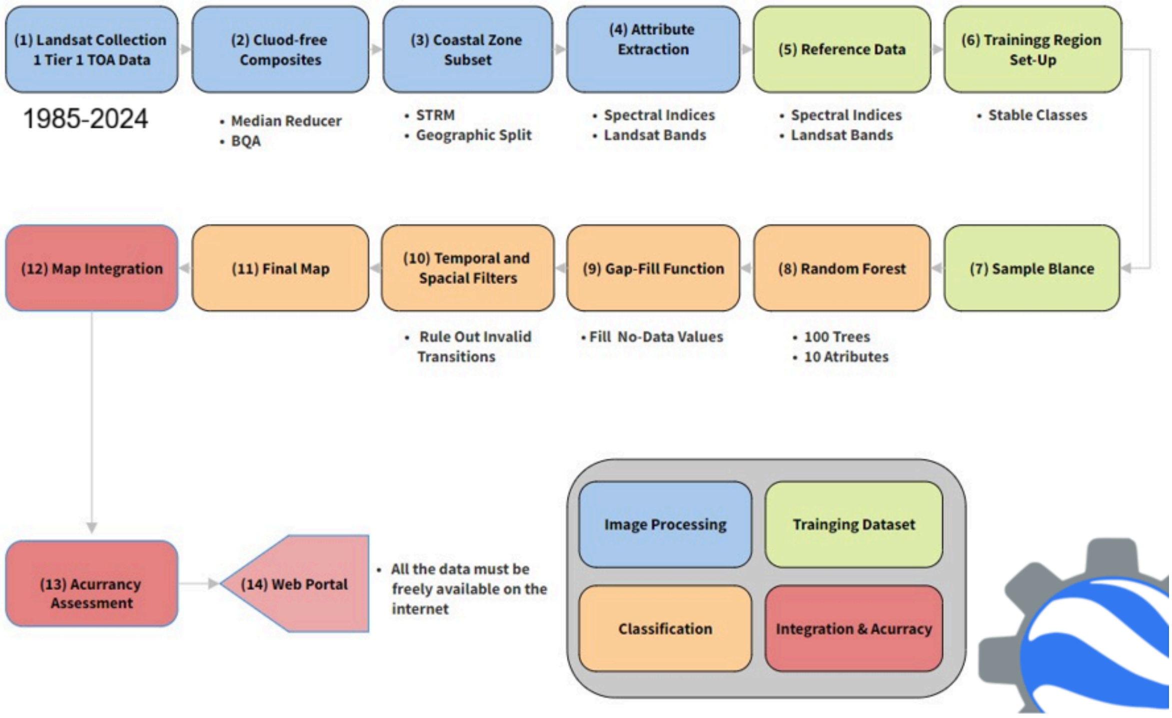

Figure 2. *Methodological diagram for the classification of the Mangroves cross-cutting map. Source: MapBiomas, adapted by EcoCiencia, 2025.*

2. Satellite image mosaics

In the identification and classification of the mangrove class, Landsat TOA (Top of Atmosphere) data were used, which apply radiometric rescaling coefficients to produce annual cloud-free mosaics. These mosaics were generated from the Landsat image collections available on Google Earth Engine (Diniz et al., 2019). Accordingly, annual mosaics were created for the area covered by the 13 Landsat scenes corresponding to Ecuador's Pacific coastal zone and the insular areas where mangroves are present (Table 1).

Table 1. Landsat scenes, number of satellite images, and processed mosaics used for mangrove mapping in Collection 3.0 of MapBiomas Ecuador.

Country	Class	Scenes	Number of satellite images used for mosaic parameterization	Mosaics parameterized and processed for the 1985–2023 time series
Ecuador	Manglove	13	5459	36

Source: Prepared by Ecociencia, 2025

These mosaics significantly improve data integrity by identifying pixels that may be affected by the albedo caused by cloud presence (Chander et al., 2009). In summary, during processing, the mean pixel value from a set of temporal images is used, rejecting values that are too bright (in this case, clouds) or too dark (such as shadows) (Diniz et al., 2019).

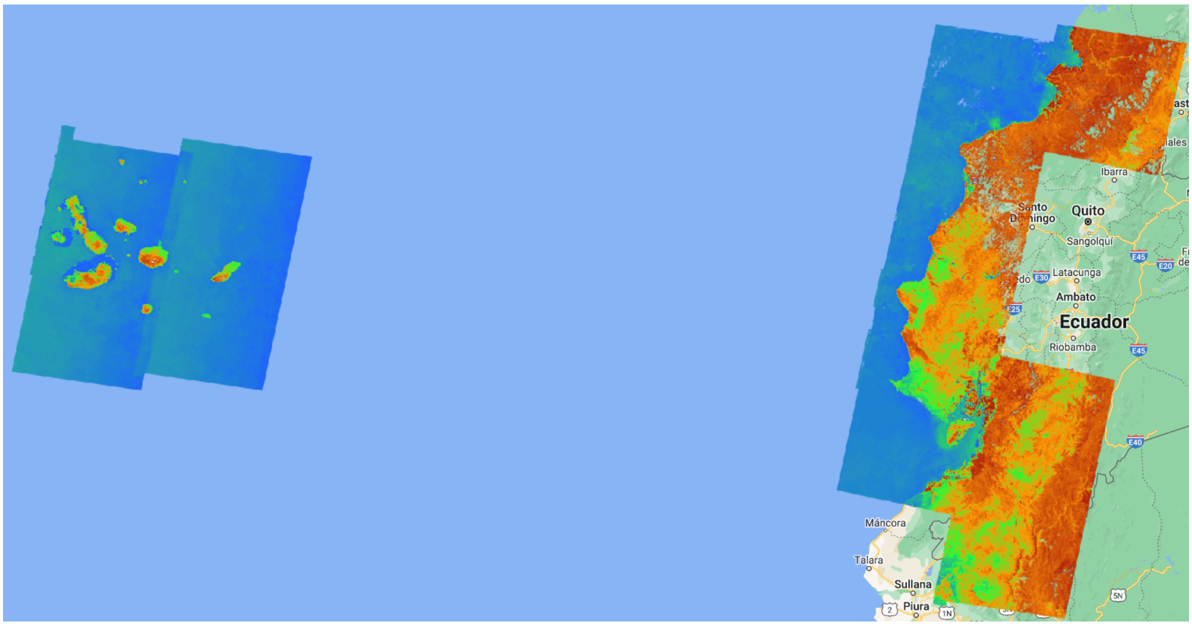

Figure 3. *Image of the MMRI (Modular Mangrove Recognition Index) generated from Landsat (Top of Atmosphere) data for the coastal and insular zones of Ecuador. Source: Ecociencia, 2025.*

Additionally, as complementary visual support to the parameterized mosaics used in the general map for stable sample collection, datasets with 151 bands each were employed (detailed in the General ATBD). These include, in addition to the satellite's own bands, derived spectral indices that use the following aggregation methods[1]:

[1] These aggregation methods were applied to the Landsat images selected by path/row and to all the spectral indices derived from them.

- **Median (_median):** The pixel value that separates the upper half of the pixel set from the lower half and includes all cloud-free pixels from the images available for each year.
- **Dry-season median (_dry):** The pixel value that separates the upper half of the pixel set from the lower half, using only the images corresponding to the annual 25th percentile of NDVI.
- **Wet-season median (_wet):** The pixel value that separates the upper half of the pixel set from the lower half, using only the images corresponding to the annual 75th percentile of NDVI.
- **Amplitude (_amp):** The difference between the two extremes of an annual pixel interval.
- **Standard deviation (_stdDev):** A measure of dispersion obtained as the square root of the variance of the annual pixels.
- **Minimum (_min):** The lowest pixel value within the dataset for a given year.
- **Maximum (_max):** The highest pixel value within the dataset for a given year.

The selection of scenes and construction of the final mosaics were carried out using the parameters mentioned below as reference, which were stored as metadata in each constructed asset:

- **ID:** Unique identifier of the region.
- **Year:** Year (1985 to 2024) corresponding to the mosaic.
- **Path Row:** Landsat scene identifier.
- **Start and end date:** Dates used to define the temporal range for selecting images from the collections available on Google Earth Engine.
- **Sensor:** Sensor identifier (L5: Landsat 5 TM, L7: Landsat 7 ETM+, L8: Landsat 8 OLI, LX: Combination of Landsat 5 and Landsat 7 scenes).
- **Cloud cover:** Maximum allowed percentage of cloud cover. Scenes exceeding this percentage were excluded from mosaic creation.
- **Blacklist:** List of scenes considered to be of poor quality, which were excluded from mosaic construction.

All generated mosaics are stored as an image collection in Google Earth Engine and are available at the following path: projects/mapbiomas-raisg/MOSAICOS/mangrove-5.

2.1. Mosaic Composition

The mosaic composition for the Mangrove cross-sectional classification was carried out using satellite images without atmospheric correction (TOA) from the Landsat 4, 5, 7, and 8 sensors, covering the surface associated with the area of interest (Pacific region and insular zone). These were generated annually over a 40-year time series from 1985 to 2024. The data processing and analysis were conducted using Google Earth Engine. Table 2 shows the image collections hosted on the aforementioned platform.

Table 2. Landsat data collections used for mangrove mapping in MapBiomas Ecuador Collection 3.0.

Sensor	Collection ID in GEE
Landsat 4 TM	LANDSAT/LT04/C02/T1_TOA
Landsat 5 TM	LANDSAT/LT05/C02/T1_TOA
Landsat 7 ETM+	LANDSAT/LE07/C02/T1_TOA
Landsat 8 OLI /TIRS	LANDSAT/LC08/C02/T1_TOA

Likewise, Figure 4 graphically describes the general methodology for mosaic production. First, the mosaics were composed according to the availability of Landsat image collections for each year from 1985 to 2024, hosted in the Google Earth Engine repositories. The image composition used the global millionth-scale grid, where an appropriate parameterization was developed to produce each mosaic based on criteria associated with temporality for each country (start and end dates), sensor, cloud cover, and exclusion scenes that interfere with the quality of the median image.

$$MMRI = \frac{|MNDWI| - |NDVI|}{|MNDWI| + |NDVI|}$$

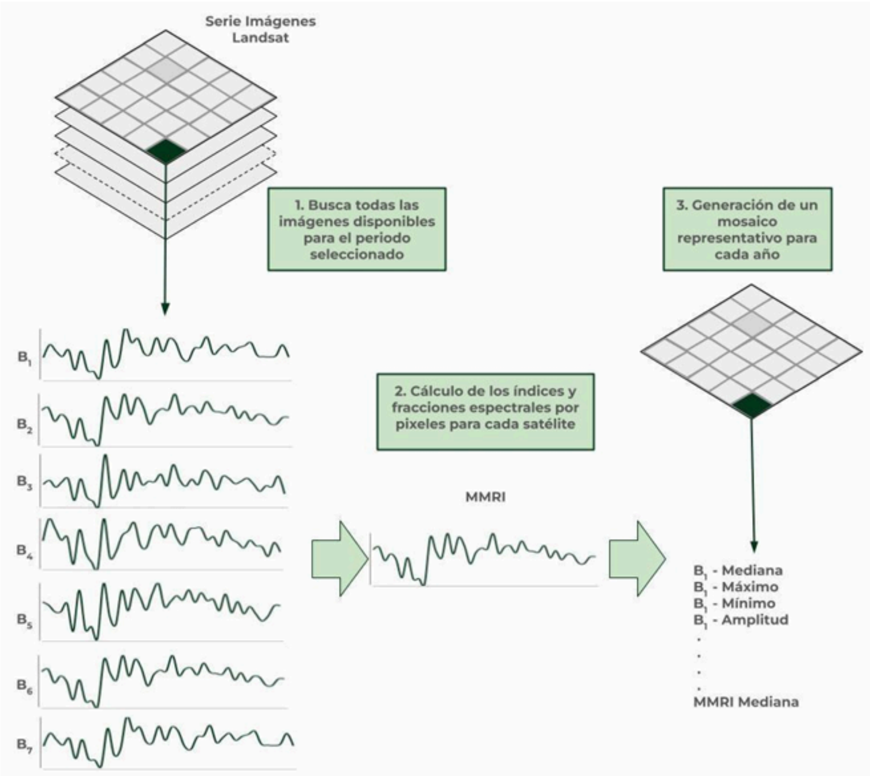

Figure 4. *Method for generating annual mosaics, Collection 3.0 MapBiomas Ecuador. Source: MapBiomas, 2023*

Based on the parameterization, the preprocessing included the application of the Cfmask and CloudScore algorithms. For Landsat 4, 5, and 7 (mosaics from 1985 to 2024), two bands were used: pixel_qa — pixel quality attributes generated from the CFMASK algorithm, and sr_atmos_opacity — atmospheric opacity (<0.1 = clear; 0.1–0.3 = average; >0.3 = hazy). In this process, if the cloud bit (5) and cloud confidence bit (7) are set to high, or if the cloud shadow bit (3) is set, the pixel is considered invalid and the edge pixels that do not appear in all bands are removed. For Landsat 8 (mosaics from 2013 to 2024), the pixel_qa band was used, considering bits 3 and 5 as clouds and shadows. After the removal process, the median of the cloud-free image collection was calculated to generate the annual mosaic.

2.2. Selection of classification variables

Based on the generated mosaics, preliminary classification tests were conducted to reduce the number of variables required to produce the final classification. Based on the results of these tests, topographic bands (elevation, slope, and slppost) derived from the SRTM DEM (Shuttle Radar Topography Mission – V03) were also included in the classification process. A total of 14 variables were used to implement the classification. The details of each are shown in Table 1 below.

Table 3. Variables for the classification of floodable cover types in Collection 3.0, MapBiomas Ecuador

Band	Description	Reducer
green	Green band value	Median
red	Red band value	Median
nir	Near-infrared (NIR) band value	Median
swir1	SWIR1 band value	Median
swir2	SWIR2 band value	Median
CAI	Cellulose Absorption Index	Median
GCVI	Green Chlorophyll Vegetation Index	Median
NDFI	Normalized Difference Fraction Index	Median
SAVI	Soil-Adjusted Vegetation Index	Median
NDVI	Normalized Difference Vegetation Index	Median
EVI	Enhanced Vegetation Index	Median
NDWI	Normalized Difference Water Index	Median
MNDWi	Modified Normalized Difference Water Index	Median
NDSI	Normalized Difference Soil Index	Median
MMRI	Modular Mangrove Recognition Index	Median
slope	Slope	
slppost	Stratified slope	
altitude	Altitude	

Source: Prepared by Ecociencia, 2025

3. Classification

Based on the selected mosaics, a supervised classification was carried out using the Random Forest algorithm available in Google Earth Engine (GEE). The processing was entirely developed on the GEE platform, and the results were stored as an image collection within the same platform. The coverage detection focused on identifying the mangrove class (ID 5 in the MapBiomas Ecuador Collection 3.0 legend). The classification process considered only two possible classes: the class of interest (mangrove) and the "Not observed" class (everything different from the class of interest).

3.1. Class definition

Mangroves (ID 5) are natural formations of dense, evergreen forests located in coastal areas, occupying a transitional zone between the continent and the ocean (García Murcia & Cortes Castillo, 2018; MapBiomas, 2023). They develop on sandy or silty-clay soils that may be permanently or occasionally flooded due to tidal influence. These ecosystems form belts along estuaries, bays, inlets, coastal lagoons, river mouths, and tidal channels, where they receive inputs from continental runoff and the influence of marine or brackish waters (Díaz Gaxiola, 2011).

MapBiomas Ecuador defines the "mangroves" class as: Areas with dense, evergreen forest cover dominated by mangrove species that occur in intertidal zones, river mouths, and estuaries, adapted to shallow brackish waters, with structural adaptations that allow growth on flat, muddy soils. The predominant mangrove genera include *Rhizophora spp.*, *Avicennia spp.*, *Conocarpus spp.*, and *Laguncularia spp.*

Due to climatic, edaphic, oceanographic, and fluvial conditions, the vegetation exhibits a set of particular morphological and physiological characteristics that allow it to thrive in unstable, anaerobic, and flood-prone environments, with soils that have low oxygen concentrations and high salinity levels. These adaptations include elongated and flexible roots for colonizing unstable substrates, anatomical structures known as lenticels and pneumatophores that enable gas exchange with the atmosphere, and reproductive strategies such as buoyant seeds capable of floating for extended periods (Villalba Malaver, 2006). In Ecuador, mangroves are located along the Pacific coast.

3.1.1 Mangrove in the Insular Zone

In the Insular Region, the Galápagos Islands are the only volcanic islands in the Pacific where mangroves occur naturally, covering about 35% of the coastline. Four mangrove species are distributed across the islands and islets: White Mangrove (Laguncularia racemosa), Black Mangrove (Avicennia germinans), Red Mangrove (Rhizophora mangle), and Buttonwood Mangrove (Conocarpus erecta). Depending on the species, they can be found from the intertidal zone to the linear part of the coast. Their height ranges from 3 to 30 meters, depending on the species (Moity & Grijalva, 2020).

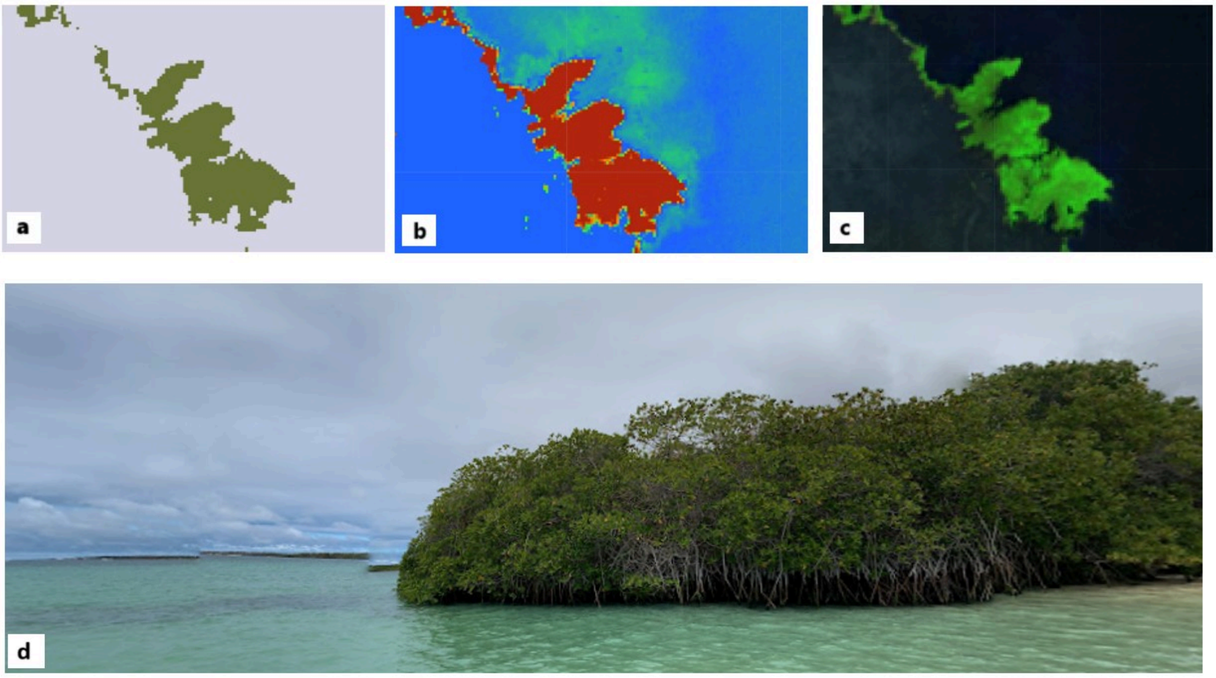

Figure 5. Reference images for the Mangrove class in the insular zone. (a) Land cover classification (Legend: Mangrove, Non-mangrove areas); (b) MMRI mosaic; (c) Landsat mosaic (RGB); (d) Google Street View image.

3.1.2 Pacific mangrove

The mangroves of the Ecuadorian Pacific are influenced by two main systems: (i) the Chocó mangroves and (ii) the Equatorial Pacific mangroves.

The Chocó mangroves are located in the northwest of Manabí Province, distributed from the Mataje River to the Cojimíes estuary, within the humid and very humid tropical forest life zones, with an average annual precipitation ranging from 1,500 to 4,000 mm (Cornejo & PMV, 2013). The high rainfall levels in the Chocó region produce abundant freshwater discharges rich in organic matter and nutrients that flow downstream through rivers to the estuarine areas, forming extensive mangrove forests with large tree species reaching up to 40 meters in height, distributed from Darién in Panama to northwestern Ecuador (Cuatrecasas, 1958a, 1958b; Little, 1969; Cintrón et al., 1981, 1985; Alvarez León, 1993; Cornejo, 1994). In Esmeraldas Province, some individuals of *Rhizophora spp.* reach giant sizes up to 50 meters tall and trunks over one meter in diameter, reported as the tallest mangroves in the Americas and the world (Little, 1969).

South of the Chocó mangroves lie the Equatorial Pacific mangroves, distributed from approximately 0º latitude near the Pedernales area in Manabí Province, extending discontinuously to the San Pedro de Vice mangroves in Piura, Peru. This portion of Ecuador is referred to as the Jama-Zapotillo mangrove region (Cornejo et al., 2013), located within dry forest, very dry tropical forest, and thorn scrub life zones, with an average annual rainfall below 600 mm (Cornejo, 2013).

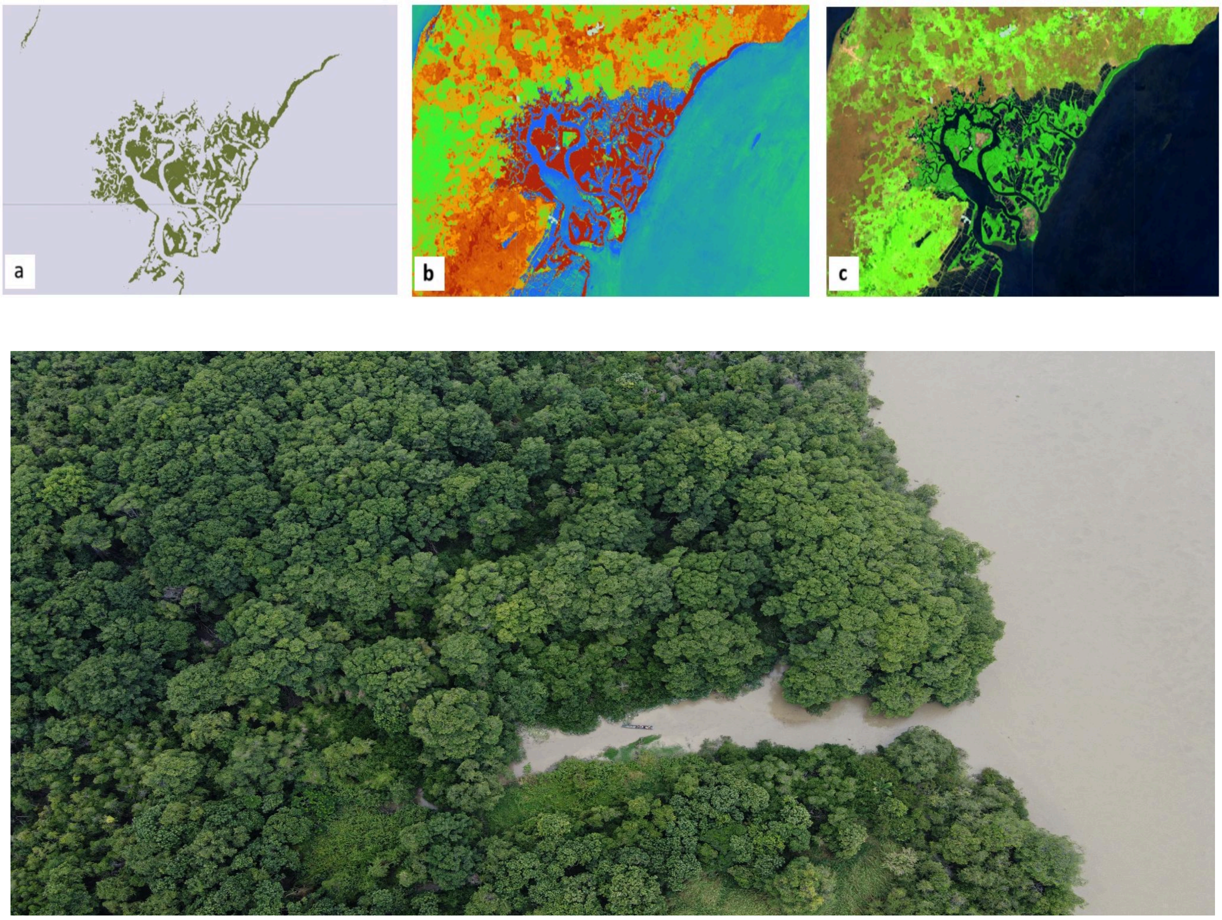

Figure 6. *Reference images for the Mangrove class on the Ecuadorian Pacific coast. (a) Land cover classification (Legend: Mangrove, Non-mangrove areas); (b) MMRI mosaic; (c) Landsat mosaic (RGB); (d) Landscape image (Ecociencia, 2025).*

3.2 Reference information

To generate the mangrove reference layer, geospatial information was collected from governmental, private, and international institutions, covering different time periods as applicable, and available in either vector or raster formats. Subsequently, all the gathered references (Table 4) were merged into a single vector file. A visual analysis was then conducted to add polygons in areas where mangroves could be found along the Pacific coast and in the Galápagos Archipelago. The resulting dataset (Figure 7) served to guide manual inspection and sample collection.

Table 4. Reference layers for the mangrove class

Reference	Global	Ecuador
Global Mangrove Watch (GMW) años 1996,2007-2010, 2015-2020	yes	yes
Global Tropical and Subtropical Wetlands Map (SWAMP)	yes	yes
ESA World Cover	yes	yes
Manglee (Servir Amazonía/Ecociencia, 2022)	no	yes
Land Cover and Use Map and Agricultural Production Systems of Continental Ecuador (MAG)	no	yes
Land Cover and Land Use Map and Agricultural Production Systems of Continental Ecuador (MAG)	no	yes
Vegetation Cover Map of Continental Ecuador 1982	no	yes
Vegetation Cover Map of Continental Ecuador 1990	no	yes
Ecosystems Map of Continental Ecuador (MAATE) 2013	no	yes
Charles Darwin Foundation (FCD)	no	yes
Mangroves (Ecociencia)	no	yes

3.3 Training samples

Once the national mangrove reference layer was generated, stable samples of the mangrove class (ID 5) and non-mangrove areas or land covers unrelated to mangroves (ID 27) were visually and manually selected. This process ensured that, throughout the temporal series from 1985 to 2024, the pixels remained stable according to each mosaic and their corresponding class (Figure 7b).

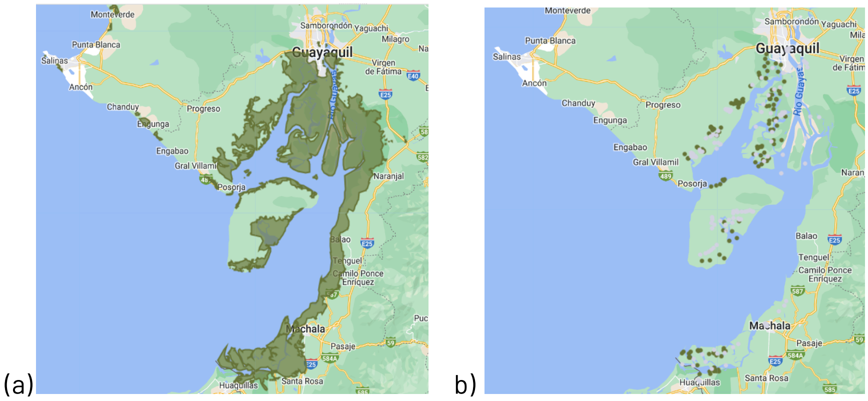

Figure 7. *(a) Mangrove map with reference layers; (b) Manual training samples of mangrove (dark green) and non-mangrove (gray). Source: Ecociencia, 2025.*

4.Post-classification

It is common to find certain inconsistencies in the mapping results, such as noise, salt-and-pepper effects, data gaps, and temporal inconsistencies. Therefore, a series of post-classification filters were applied: gap-fill, temporal, frequency, and spatial filters.

4.1 Gap Fill Filter – Filling information gaps

The gap fill filter corrects missing data caused by sensor issues or persistent cloud cover by replacing pixels without information with the classification from the nearest year. If data from the previous year are unavailable, the next year is used, leaving gaps only where no information exists across the entire time series.

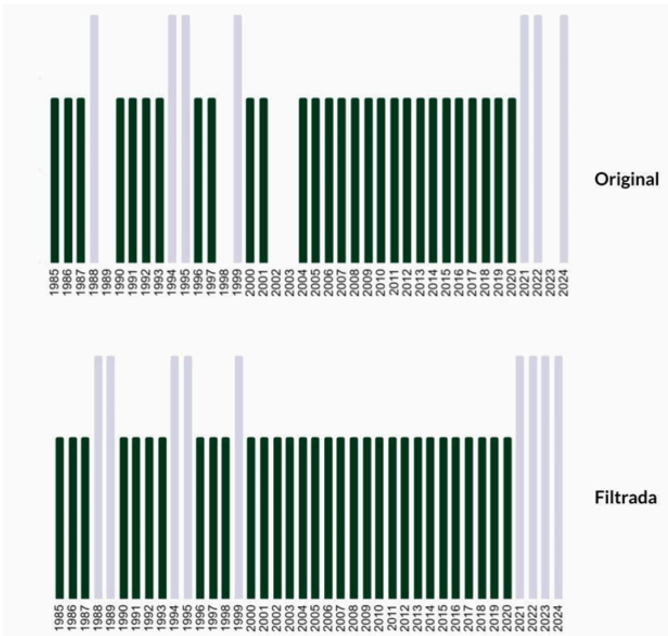

Figure 8. *Example of the gap-fill filter mechanism. Source: MapBiomas, 2025.*

4.2 Temporal filter

The temporal filter applies sequential classifications within a one-directional moving window of 3, 4, or 5 years across the entire time series. Its main purpose is to detect and correct abrupt, temporally inconsistent transitions that are not coherent with the expected behavior of the mapped cover. The filter operates under three rules:

- The first-year rule (FR) is applied only to the first year of the time series (1985) when an abrupt change occurs relative to the subsequent years.
- The last-year rule (LR) is applied only to the final year (2023) when there is an abrupt change compared to previous years.
- The general rule (GR) is applied to all intermediate years (1986–2021), replacing inconsistent pixels within the sequence with the value from the consistent years at the edges. In 3-year sequences, there is only one central year, while in 4- or 5-year sequences, there are two or three possible central positions (Figure 9).

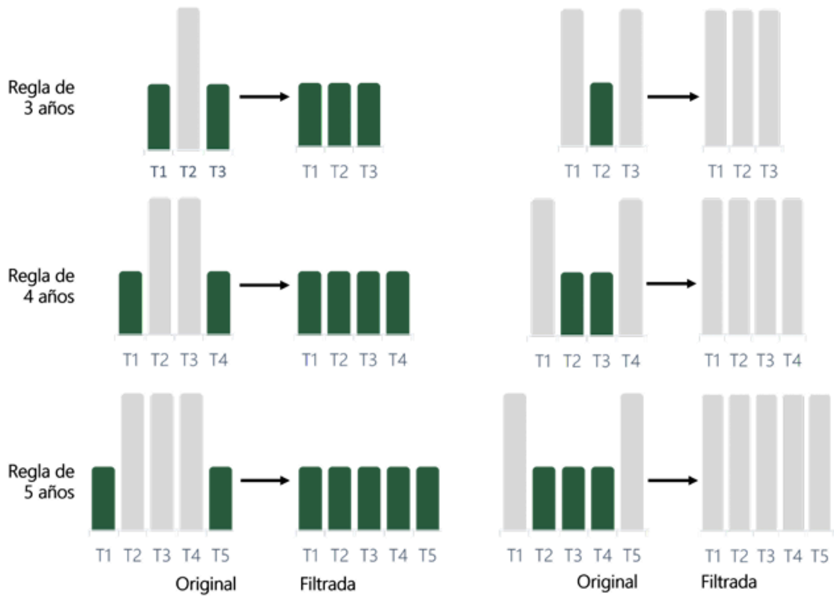

Figure 9. *Example of the temporal filter mechanism. Where: CO = Original classification, CF = Classification after filtering. Source: MapBiomas, 2025.*

4.3 Frequency filter

Finally, the fourth filter applied in the post-classification sequence was the frequency filter. As shown in Figure 10, this filter considers the percentage of occurrence of each class throughout the time series to refine the classification results, ensuring that each pixel is assigned the value of the most frequent land cover class from 1985 to 2024.

This filter was applied differently for class 5 (Mangrove) and class 27 (Not observed), the latter representing all non-mangrove classes included in the classification mask. First, it helped complete mangrove cover classifications in areas where underestimations occurred due to mosaic defects or classification errors that were not corrected by the temporal filter.

Secondly, it helped remove remaining noise, a particularly common issue in the Ecuadorian Pacific region due to high rainfall and persistent cloud cover in the mosaics. Figure 10 illustrates the effect of this filter.

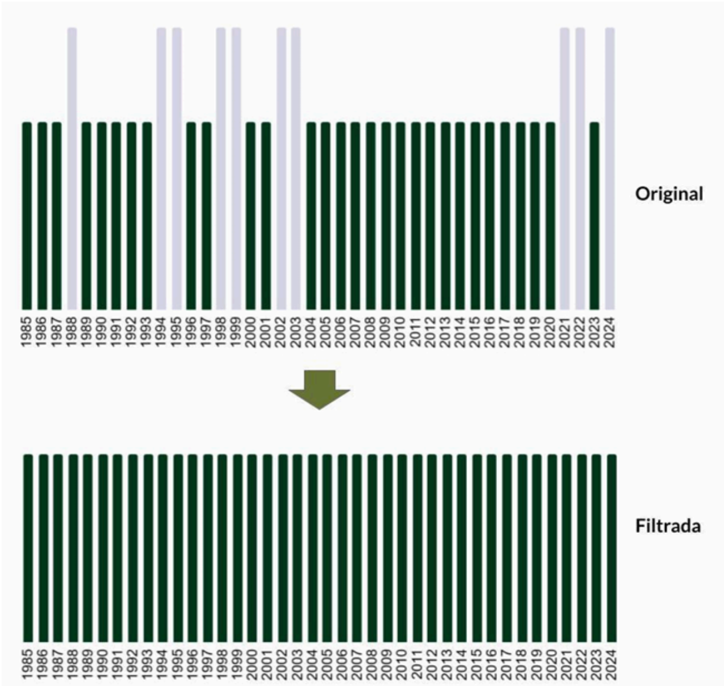

__Figure 10.__ Effect of the spatial filter application.

4.3 Spatial filter

The spatial filter is based on Google Earth Engine's "connectedPixelCount" function, which reduces the "salt and pepper" effect or isolated pixels, thus homogenizing the classification. It assigns isolated pixels the value of the dominant surrounding class if they do not meet a minimum area criterion (0.5 hectares, equivalent to 5 pixels) and connectivity with neighboring pixels of the same class. Consequently, isolated pixels that fail to meet this condition are reclassified into the predominant adjacent class, removing noise and unifying the mosaic coverages. Figure 11 shows an input image (CO) with an isolated pixel, which after applying the filter (CF) is replaced by the surrounding dominant class.

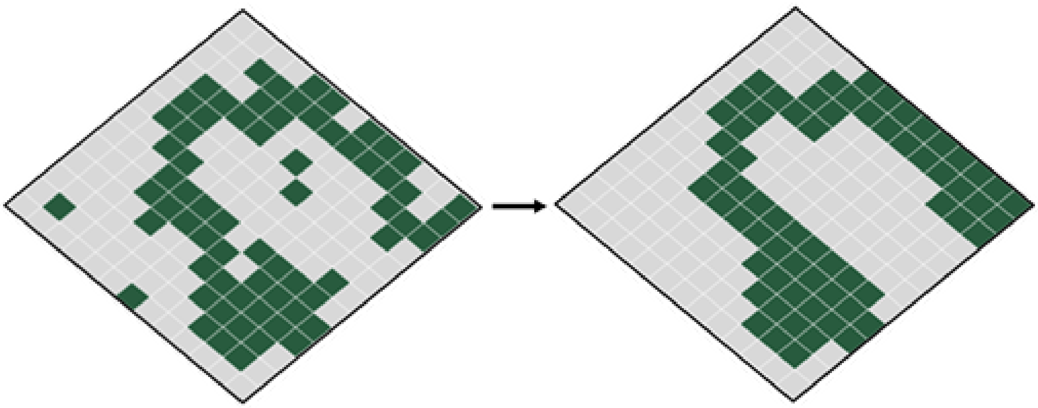

__Figure 11.__ Effect of the spatial filter application. Where: CO: Original classification, CF: Filtered classification.

4.5 Integration with other MapBiomas Ecuador classes

After applying the sequence of post-classification filters, the resulting mangrove images (Figure 12) are integrated into the general maps of each biome. This integration follows a set of specific hierarchical rules that assign a precedence order to each class. As a result, annual land cover and land use maps for the entire territory of Ecuador are obtained (Figure 13).

Figura 12. Clasificación multitemporal, Guayaquil. Elaboración: Ecociencia, 2024.

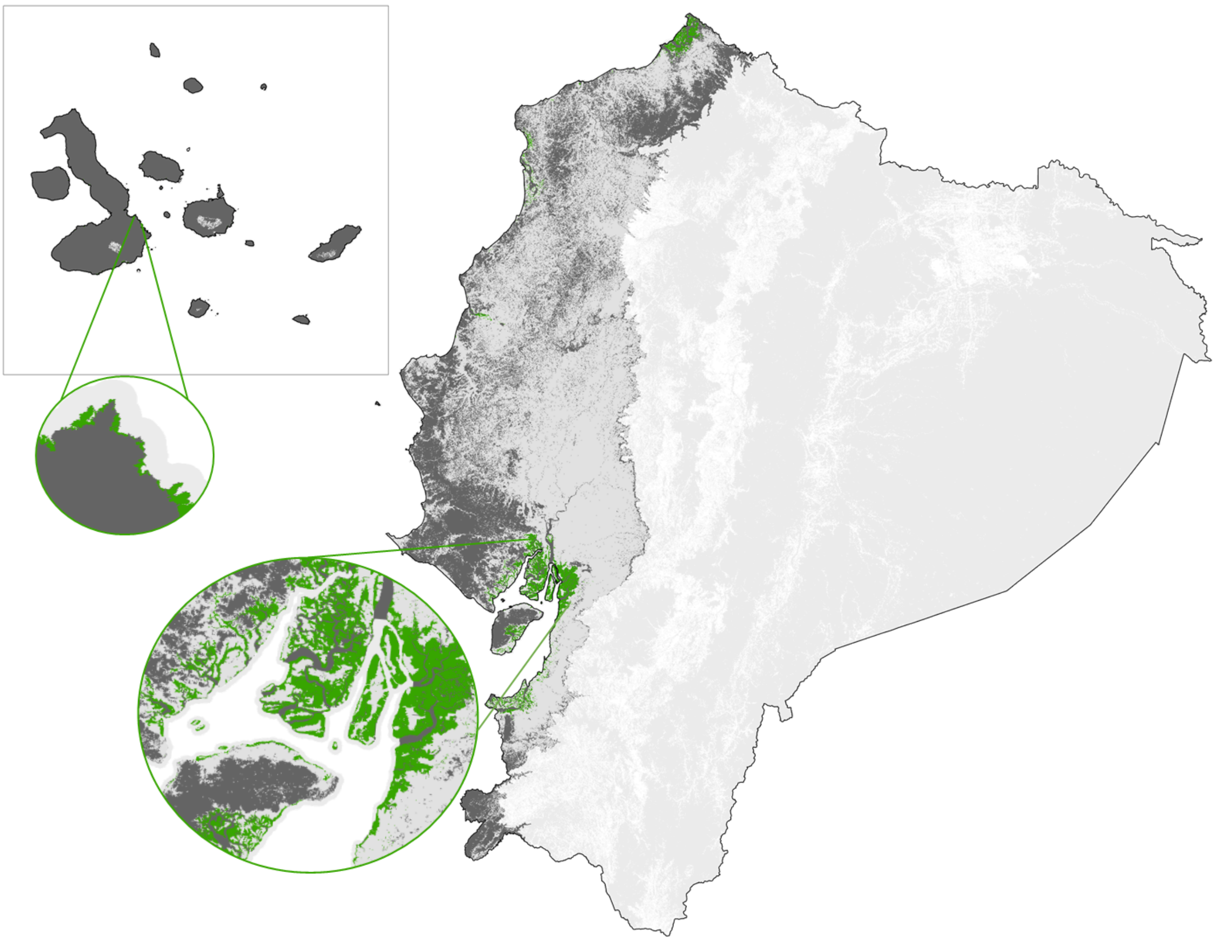

Figure 13. *Mangrove map for the year 2023. Source: Ecociencia, 2025.*

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