MAPBIOMAS VENEZUELA

Appendix

Vegetation Loss and Secondary Vegetation Modules

Collection 3 | Beta Version

Responsible Team

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1. General Description

This document describes the methods applied to generate the Beta collection of annual Vegetation Cover Change Trajectory maps, based on the annual land use and land cover maps from Collection 3 of MapBiomas Venezuela. The result of applying the trajectory model constitutes the data source that can be consulted by users of the MapBiomas Venezuela platform through two modules: Vegetation Loss and Secondary Vegetation.

2. Methodology

2.1 Input Data

The primary objective of this trajectory change model is to identify natural vegetation loss events following anthropogenic disturbance, as well as the establishment of anthropogenic covers. Likewise, it identifies vegetation cover recovery events and the establishment of secondary vegetation, along with re-intervention events in previously recovered areas. In this model, secondary vegetation is a class resulting from pixel behavior across the time series rather than a spectral class. For the trajectory analysis, the 25 land use and land cover (LULC) classes from the Collection 3 legend were grouped into annual Vegetation Cover maps consisting of three classes: **Natural Vegetation (Nv)**, **Anthropic (A)**, and **Other Cover** (Figure 1).

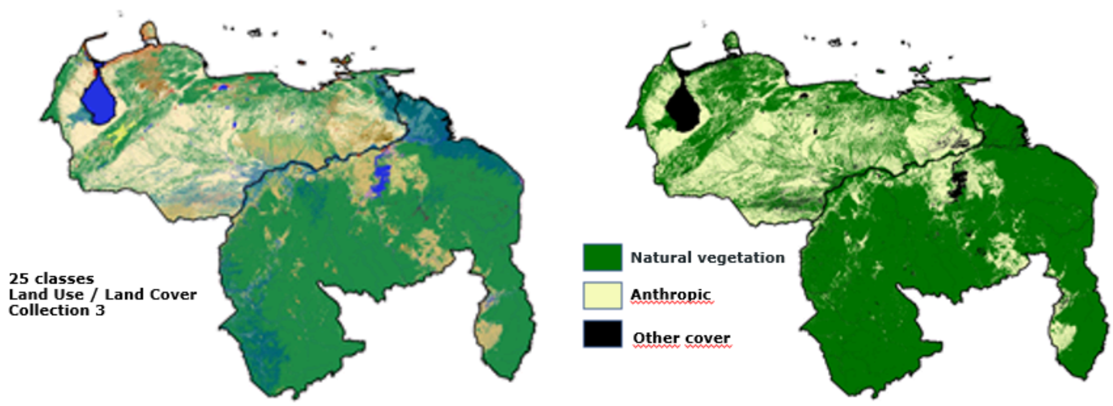

Figure 1. ***Comparison between the Land Use and Land Cover (LULC) map and the Vegetation Cover map for change trajectory analysis.***

The LULC time series (1985-2024) was used as the input source. LULC classes were reclassified into three categories to form the annual Vegetation Cover maps; the new legend is presented in Table 1.

Table 1. ***Legend of annual Vegetation Cover maps and source classes from annual LULC maps.***

Vegetation Cover Classes	Source LULC Classes	Vegetation Cover ID
Natural Vegetation (Nv)	Forest, Wooded savanna, Mangrove, Flooded forest, Flooded grassland/shrubland, Savanna/grassland, Shrubland, Xerophytic shrubland/grassland, Other non-forest natural formations, Andean herbaceous/shrubby vegetation, Flooded andean herbaceous/shrubby vegetation.	2
Anthropic (A)	Agriculture, Pasture, Cropland, Urban, Mining, Other non-vegetated anthropic areas, Aquaculture.	1
Other Cover	Forest plantation, Rocky outcrop, Hypersaline tidal flat, Beach or dune, River, lake or ocean, Glacier, Other non-vegetated natural areas	7

2.2 Vegetation Cover Change Trajectory Analysis

A methodology was developed for pixel-by-pixel vegetation cover change trajectory analysis using a set of iterative decision rules employing various moving temporal windows (3, 4, or 5 years), as well as rules applied to the penultimate year, the last year of the series, or the entire time series. To filter cartographic noise derived from mixed pixels (Xie et al., 2020) and ensure that transitions correspond to real ground events, the model integrates a persistence criterion that requires classification stability for a minimum period before and after each change. Records that do not meet this temporal consistency are automatically reverted to their previous state to avoid false trajectories.

The analysis generates new classes for the annual Vegetation Cover Change Trajectory maps. The decision rules identify the following change paths: Natural vegetation loss (NvL); establishment of Anthropogenic (A) covers; Vegetation cover recovery (R), marking the onset of secondary vegetation; Secondary vegetation (Sv) and re-interventions producing Secondary vegetation loss (SvL).

The general methodology is presented in Figure 2, which illustrates the sequence of land cover change trajectory analysis. This process begins with the source data, followed by its reclassification and the application of decision rules through both retrospective and chronological analyses. This sequence results in the generation of the collection of change trajectory maps, which subsequently serves as the data source that users can access via the two vegetation modules: Vegetation Loss and Secondary Vegetation.

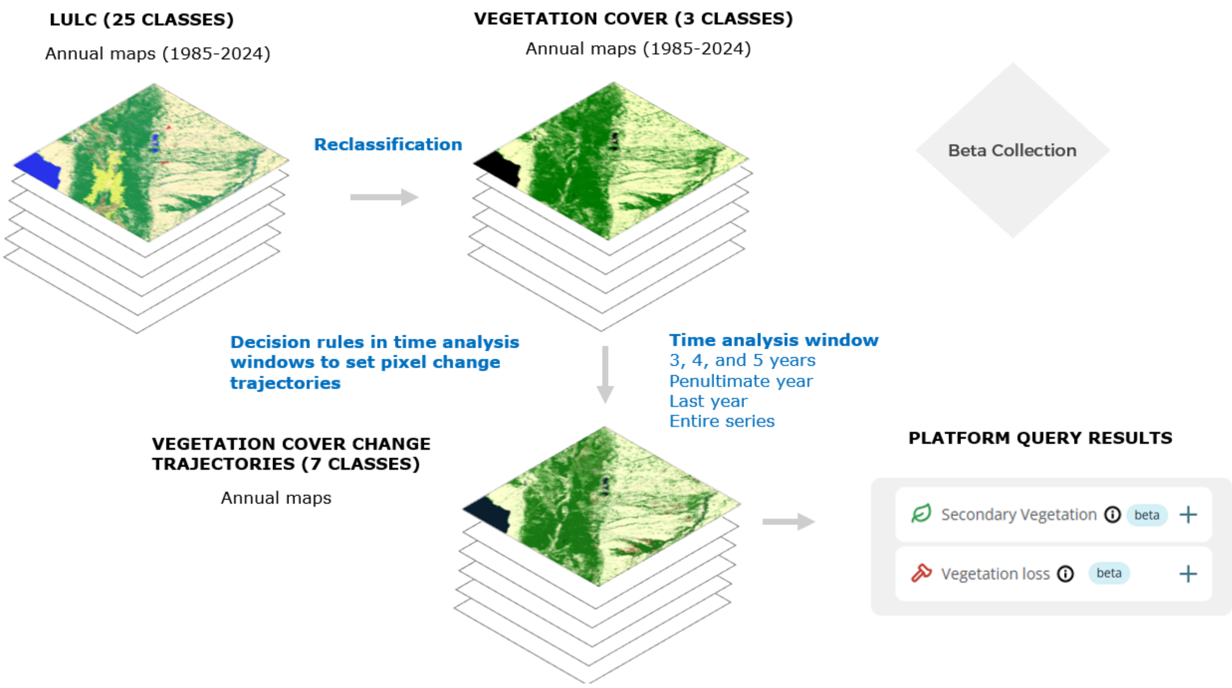

Figure 2. *Methodological summary of the Natural Vegetation Loss and Secondary Vegetation modules*

Furthermore, Figure 3 presents the pixel lifecycle and the possible change paths with the application of the model and the legend of the vegetation cover change trajectories maps: Natural vegetation loss (NvL) and establishment of anthropogenic vegetation (A), Vegetation cover recovery (R) and establishment of Secondary vegetation (Sv) and reintervention or Secondary vegetation loss (SvL). In this cycle, a pixel that has been intervened in any part of the time series, if it experiences recovery, will retain the memory of Secondary vegetation (Sv). Therefore, it would never return to the initial condition of Natural vegetation (Nv).

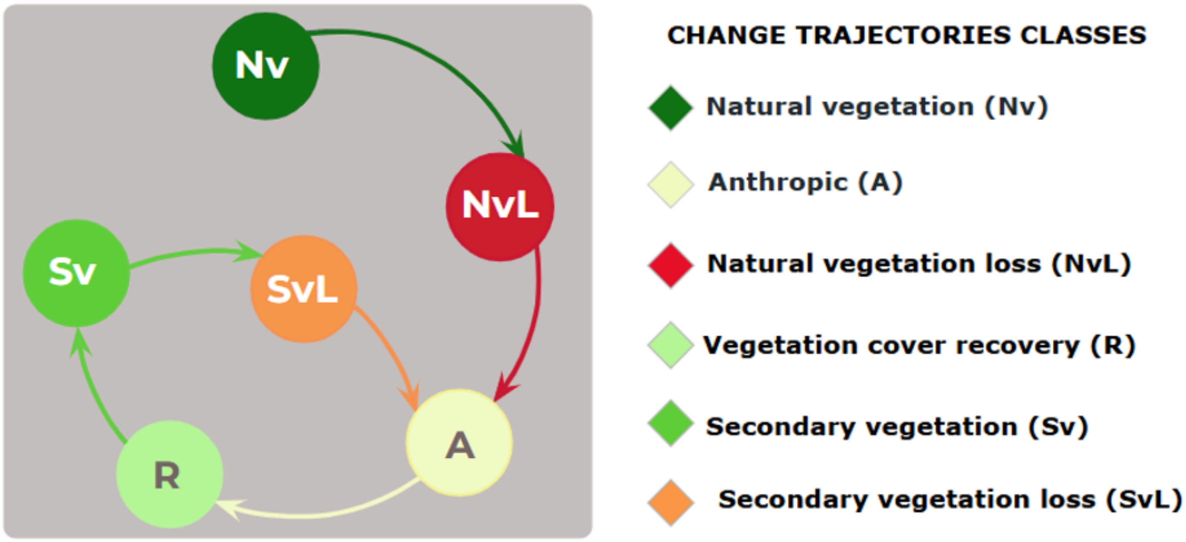

Figure 3. *Pixel life cycle and vegetation cover change trajectory legend.*

Based on the land cover maps and the application of rules for trajectory change analysis, the annual Land Cover Trajectory of Change maps are generated.The legend for the Change Trajectory maps, integrated by 7 classes, is presented in Table 2.

Table 2. Origin and description of classes for Vegetation cover change trajectory maps.

ID CHANGE TRAJECTORY	CLASS	SOURCE	DESCRIPTION
1	Anthropic (A)	At the beginning of the series, it corresponds to land covers of anthropic origin, such as: Agricultural use, Livestock use, Mosaic of agriculture and pastures, Urban use, Mining use, Other anthropic areas without vegetation, and Aquaculture. It may also be the result of change trajectories in the time series, corresponding to the second year of vegetation cover change following Natural vegetation loss (4) or Secondary vegetation loss (6).	Covers resulting from persistent human intervention

ID CHANGE TRAJECTORY	CLASS	SOURCE	DESCRIPTION
2	Natural vegetation (Nv)	Forest, Wooded savanna, Mangrove, Flooded forest, Flooded grassland/shrubland, Grassland, Shrubland, Xerophytic shrubland/grassland, Other non-forest natural formations, Andean herbaceous/shrubby vegetation and Flooded andean herbaceous/shrubby vegetation	Vegetation cover that has shown no signs of human intervention since the initial year (1985) in the analyzed historical series.
3	Secondary vegetation (Sv)	Result of disturbance of natural vegetation after anthropic intervention.	It begins in the second year of sustained vegetation cover recovery once its establishment is confirmed, after having undergone one year of Vegetation cover Recovery (R).
4	Natural vegetation loss (NvL)	Intermediate trajectory from Natural vegetation (2) to Anthropic (1).	The first year in which Natural vegetation is transformed by human uses. It constitutes the first year of change, marking the beginning of land covers of anthropic origin.
5	Vegetation cover recovery (R)	It is the intermediate trajectory between Anthropic (1) and Secondary vegetation (3)	It is the first year in which vegetation cover recovers after having been of anthropic origin. It marks the beginning of natural regeneration.
6	Secondary vegetation loss (SvL)	It is the intermediate trajectory between Secondary vegetation (3) and Anthropic (1).	It is the first year of vegetation cover re-intervention in areas previously classified as Secondary vegetation. New anthropic cycle. Successional trajectory intermediate between Secondary vegetation (3) and Anthropic (1)
7	Other cover*	Forest plantation, Beach or dune, Rocky outcrop, Hypersaline tidal flat, River, lake or ocean, Glacier, Other non-vegetated natural areas	Not part of vegetation dynamics analysis; includes non-vegetated natural areas, water bodies, and plantations

*The 'Other cover' (7) class is not shown on the query platform nor in the pixel life cycle diagram because these are areas (pixels) excluded from the vegetation cover trajectory analysis.

2.3 Data characteristics feeding the modules and change trajectory rules

The processing of geospatial data for the detection of changes in vegetation cover is based on a two-way analytical scheme, composed of 19 decision rules to determine and verify the trajectories of change.

2.3.1 Bidirectional Approach

It allows the classification to depend not exclusively on an isolated observation, but on the contextual consistency of the pixel in the time series.

- **Retroactive Phase (Backward):** Implements cleaning and stability filters over the pixel history, from the last year of the series back to the beginning. Its technical purpose is the mitigation of sensor artifacts, such as persistent clouds or projected shadows, through the validation of historical persistence. This phase ensures that current classifications are compatible with the evidence accumulated in previous years, establishing a clean database prior to the trajectory change analysis.
- **Chronological Phase (Forward):** Executes trajectory detection through the use of temporal windows or Kernels. It evaluates moving sequences to confirm whether a land cover change is a stable event or a transient fluctuation. This phase allows for the assignment of specific path identifiers based on the pixel's behavior in the reference year or time *t* and its immediate evolution toward the future. This approach enables a more precise distinction between real changes and temporal fluctuations or data noise.

The logic of the decision rules for the trajectory change analysis—including the functions and names found in the script (available for Google Earth Engine users on the MapBiomas Venezuela GitHub) for model application—the temporal windows used to ensure consistency in change confirmation, and the specific temporal element of the window being modified (time *t*, previous, and subsequent years) for each rule, are presented in Tables 3 to 5.

Table 3. ***Sequence of vegetation cover change trajectory rules (1-7) in the 40-year time series.***

RULE	FUNCTION (CODE)	INITIAL STATE	FINAL STATE	APPLICATION WINDOW TIME MODIFIED
1	**Temporal Filter (applyRules)** Cleans noise (1-year jumps) in natural classes. Retroactive (backward); first central year is 2023	[t-1, **t**, t+1]	[t-1, **t**, t+1]	2023 to 1986 3 years (t−1, **t** ,t+1)
2	**Stabilize Natural Vegetation (2) (rules) (R1)** Chronological (Iterates the series up to N-3)	[2, 2, **1**, 2]	[2, 2, **2**, 2]	1985 to 2021 4 years (t, t+1,**t+2**, t+3)
3	**Correct Anthropic error (1) (rules) (R2)** Chronological (Iterates the series up to N-3).	[2, **1**, 2, 2]	[2, **2**, 2, 2]	1985 to 2021 4 years (t, **t+1**,t+2, t+3)
4	**Detect Natural Vegetation Loss (4) (rules) (R3)** Chronological (Iterates the series up to N-3). The exact time of confirmed natural vegetation loss. The change to Anthropic (1) persists at least two years.	[2, 2, **1**, 1]	[2, 2, **4**, 1]	1985 to 2021 4 years (t, t+1,**t+2**, t+3)
5	**Detect Vegetation Recovery (5): onset of Secondary Vegetation (rulesSecVegK5).** Chronological (Iterates the series up to N-4)	[1, 1, **2**, **2**, **2**]	[1, 1, **5**, **3**, **3**]	1985 to 2020 5 years (t, t+1,**t+2**, **t+3**, **t+4**)
6	**Prevent return of Vegetation Recovery (5) to Natural Vegetation (2) (rulesSecVegK4) (R1)** Chronological (Iterates the series up to N-3).	[5, 3, 3, **2**]	[5, 3, 3, **3**]	1985 to 2021 4 years (t, t+1,t+2, **t+3**)
7	**Maintain Secondary Vegetation (3) by anthropic origin (rulesSecVegK4) (R2)** Chronological (Iterates the series up to N-3).	[3, **2**, **2**, **2**]	[3, **3**, **3**, **3**]	1985 to 2021 4 years (t, **t+1**,**t+2**, **t+3**)

Table 4. ***Sequence of vegetation cover change trajectory rules (8-13) in the 40-year time series.***

RULE	FUNCTION (CODE)	INITIAL STATE	FINAL STATE	APPLICATION WINDOW **TIME MODIFIED**
8	**Reclassify to Secondary Vegetation (3) and Secondary Vegetation Loss (6) if anthropic precedents exist (rulesSecVegK4) (R3)** Chronological (Iterates the series up to N-3).	[3, **2**, **2**, **4**]	[3, **3**, **3**, **6**]	1985 to 2021 4 years (t, **t+1**,**t+2**, **t+3**)
9	**Reclassify to Secondary Vegetation (3) and Secondary Vegetation Loss (6) if anthropic precedents exist (rulesSecVegK4) (R4)** Chronological (Iterates the series up to N-3).)	[3, 3, **2**, **4**]	[3, 3, **3**, **6**]	1985 to 2021 4 years (t, t+1,**t+2**, **t+3**)
10	**Stabilize Secondary Vegetation (3), modifies the last two years of the 4-year window (rulesSecVegK4) (R5)** Chronological (Iterates the series up to N-3).	[3, 3, **2**, **2**]	[3, 3, **3**, **3**]	1985 to 2021 4 years (t, t+1,**t+2**, **t+3**)
11	**Persistence of Secondary Vegetation (3), modifies the last year of the 4-year window (rulesSecVegK4) (R6)** Chronological (Iterates the series up to N-3).	[3, 3, 3, **2**]	[3, 3, 3, **3**]	1985 to 2021 4 years (t, t+1,t+2, **t+3**)
12	**Correct false Natural Vegetation (2) errors (rulesSecVegK4) (R7)** Chronological (Iterates the series up to N-3).	[1, **2**, **2**, **4**]	[1, **1**, **1**, **1**]	1985 to 2021 4 years (t, **t+1**,**t+2**, **t+3**)
13	**Confirm Secondary Vegetation (3) loss due to anthropic history (rulesDefSecVeg)** Chronological (Iterates the series up to N-3).	[3, **4**, 1]	[3, **6**, 1]	1985 to 2022 3 years (t, **t+1**,t+2)

Table 5. ***Sequence of vegetation cover change trajectory rules (14-19) in the 40-year time series.***

RULE	FUNCTION (CODE)	INITIAL STATE	FINAL STATE	APPLICATION WINDOW TIME MODIFIED
14	**Natural Vegetation Loss (4) at the end of the series (rulesEnd) (R1)** Chronological.	[2, 2, 2, **1**]	[2, 2, 2, **4**]	**2024** **(2021,2022,2023,2024)** 4 years at the end of the series
15	**Secondary Vegetation Loss (6) at the end of the series (rulesEnd) (R2)** Chronological.	[3, 3, 3, **1**]	[3, 3, 3, **6**]	**2024** **(2021,2022,2023,2024)** 4 years at the end of the series
16	**Transforms Natural Vegetation Loss (4) to Secondary Vegetation Loss (6) if there is previous use in the pixel (where Freq A).**	**Freq > 1 & 4**	**Changes 4 to 6 if it meets 2 years of intervention.**	**1985 to 2024** **Entire series**
17	**Transforms Natural Vegetation (2) to Secondary Vegetation (3) if there is previous use in the pixel (where Freq B).**	**Freq > 0 & 2**	**Changes 2 to 3 if it meets 1 year of intervention.**	**1985 to 2022** **Entire series**
18	**Nullifies false recovery via Anthropic (1) to Secondary Vegetation (3) trajectory in the penultimate year (where Final A).** **Retroactive.** Insufficient time to confirm recovery; maintained as anthropic.	[1, **3**]	[1, **1**]	**2023** (2022,**2023**) 2 years (t-1, **t**)
19	**Nullifies false loss via Secondary Vegetation (3) to Anthropic (1) transition in the penultimate year (where Final B).** **Retroactive.** Last year of the series; potential image error (clouds/shadows). Maintained as Secondary Vegetation.	[3, **1**]	[3, **3**]	**2024** (2023,**2024**)

2.3.2 Noise Stabilization (Rule 1)

It is a temporal filter that utilizes a 3-year window [t-1, t, t+1]. It is applied retrospectively (from 2023 back to 1986). Its function is to eliminate single-year "jumps" in natural classes. If a pixel changes only in the central year, it is corrected to match the adjacent years, ensuring stability before processing real changes.

2.3.3 Natural Vegetation Loss (Rules 2 to 4)

These rules identify the transition from Natural Vegetation toward Anthropic (A).

- Analysis Window: 4 consecutive years [t, t+1, t+2, t+3].
- Rules 2 and 3: Stabilize Natural Vegetation (2) by correcting errors where a pixel appears to be anthropic for a single year.
- Rule 4: Detects Natural Vegetation Loss (4). For the change to be confirmed, the Anthropic class (1) must persist for at least two consecutive years following the loss event.

2.3.4 Vegetation Recovery and Secondary Vegetation (Rules 5 to 13)

Unlike natural vegetation loss, secondary vegetation recovery is a gradual process that can span several years and depends on multiple ecological factors such as previous land use, availability of propagule sources, climate, and topography (Aide et al., 2000; Ferreira et al., 2015; Sobrinho et al., 2016; Uriarte et al., 2010). This phase is the core of persistence: once a pixel is intervened, the system "remembers" its origin.

- Rule 5 (Identification of Vegetation Recovery): Uses a 5-year window [t, t+1, t+2, t+3, t+4]. It identifies the start of Recovery (5). If an anthropic area shows persistent vegetation for at least 3 years, the pixel is immediately reclassified as Secondary Vegetation (3).
- Rules 6 to 13 (Persistence): Use 4-year windows. Their function is to prevent vegetation growing in interveded areas from being classified as vegetation cover again. These rules force the Secondary Vegetation (3) class, even if the annual classifier indicates natural vegetation, based on the usage history.

2.3.5 End-of-Series Rules (Rules 14 and 15)

Because future years are not available to confirm persistence at the closing of the series (2021-2024), specific criteria are applied:

- Rules 14 and 15: Confirm Natural Vegetation Loss (4) or Secondary Vegetation Loss (6) based on the previous 3-year stability.

2.3.6 Post-processing and Historical Frequency (Rules 17 to 19)

- Rules 16 and 17 (Historical Frequency): Analyze the entire 40-year series. If a pixel shows it has been Anthropic (1) in the past (Frequency > 0 or 1), any detected loss is labeled as Secondary Vegetation Loss (6) and not as Natural Vegetation Loss (4).
- Rules 18 and 19 (Final Adjustments): Act upon the years 2023 and 2024. They nullify false recoveries or losses occurring in the last year of the series, applying the "benefit of the doubt" to maintain the most probable state and avoid overestimating unconfirmed change trajectories.

3. Conclusions

The method for analyzing land cover change trajectories applied in the Vegetation Loss and Secondary Vegetation modules presents an analysis of land cover dynamics based on two contrasting classes: Natural Vegetation (Nv) and anthropogenic covers (A). The classes derived from the change trajectories over time are obtained through a set of rules applied across various temporal windows that ensure the consistency of detected changes.

The analysis is based on the premise that all vegetation cover mapped at the beginning of the time series (1985) is Natural Vegetation (Nv) until it undergoes a human disturbance that transforms it into Anthropic (A). This assumption is the starting point of the analysis, despite the fact that many areas of the country—especially north of the Orinoco River—had already intervened before 1985. This results in an underestimation of Secondary Vegetation throughout the time series, which is more significant in the early years of the series.

In this methodology, Secondary Vegetation does not correspond to a spectral category but rather to a historical category, the result of the change trajectory of a pixel that was initially Natural Vegetation, then transformed into Anthropic (A), and subsequently underwent other change routes toward Vegetation Cover Recovery (R) and later to Secondary Vegetation (Sv).

The combination of retrospective change rules and confirmation windows ensures that the vegetation loss reporting in Venezuela is consistent with the actual dynamics of the territory.

By evaluating the pixel's change trajectory in the time series using intervention memory criteria, the persistence of Secondary Vegetation is guaranteed once a pixel leaves its initial Natural Vegetation condition.

The applied model allows for the evaluation of actual vegetation losses resulting from an initial intervention (Natural Vegetation Loss) or from recurrent interventions (Secondary Vegetation Loss) throughout the time series.

The identification of Secondary Vegetation through this method cannot determine different successional stages or differences in developing vegetation covers;

therefore, it may represent contrasting ecological processes, such as the natural recovery of grasslands, shrublands, or forests, or even an increase in the cover of invasive species.

The quality of the maps resulting from these modules is directly linked to the precision of the input dataset (Collection 3 MapBiomas Venezuela). An independent validation protocol is currently being developed to evaluate the accuracy of the vegetation dynamics classes north and south of the Orinoco River throughout the time series of each new collection.

This approach recognizes inherent limitations, such as the impossibility of distinguishing between secondary vegetation and different growth forms of vegetation cover (such as forest, shrubland, and grassland), although it is robust in detecting temporal consistency.

These modules were designed to support conservation and restoration policies. Preliminary results suggest that the persistence and post-processing filters (Tables 3 to 5) significantly mitigate false positives, although challenges persist in regions with high inter-annual variability. The protocol under development will include stratified sampling and evaluation with high-resolution imagery to quantify omission/commission errors in the change classes.

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