Algorithm Theoretical Basis Document (ATBD)

MapBiomas Degradation

Module BETA

Version 1

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Table of Contents

1. Introduction

1.1. Overview

Since 2015, the MapBiomas network has been producing annual land use and land cover maps for Brazil. This extensive data collection, which uses data from the Landsat satellites with a spatial resolution of 30 meters, provides a comprehensive understanding of the country's land use patterns (Souza et al., 2020). Every year, MapBiomas releases a new collection of these annual maps, with new classes, improvements, and updated with the last year. The latest data collection (Collection 8) covers 1985 to 2022 (ATBD Collection 8), offering detailed information on land use changes over time. In this context, the network produces detailed information on the quantitative history of native vegetation and various anthropogenic uses, such as pastures, agriculture, and urban areas.

In addition to the land cover data, MapBiomas has expanded to other products, such as mapping fire scars, water surfaces, soil organic carbon, and deforestation alerts. This document describes the methods applied to the beta version of the degradation module in the MapBiomas Brazil platform (https://plataforma.brasil.mapbiomas.org). This module allows the analysis of native vegetation degradation in all the Brazilian biomes from 1986 to 2021. The degradation drivers considered in this first version of the module include the size and isolation of native vegetation fragments, their edge areas, the fire frequency and time since the last fire, and the secondary vegetation age. The degradation drivers were calculated using the annual maps of land-use/land cover (LULC) provided by MapBiomas Collection 8 and annual maps of fire scars of MapBiomas Fire Collection 2.

1.2. Context

Despite the quantitative history, the current database does not provide information on the quality of native vegetation remnants, which can be directly and significantly affected by disturbances. These disturbances may cause degradation and the consequent compromising of an ecosystem's functions, properties, and services, including, but not limited to, deleterious changes in carbon storage and uptake capacity, biological productivity, species diversity, forest structure, and climate regulation (Gatti et al. 2021; Lapolla et al., 2023). This direct impact on native vegetation underscores the urgency in managing and maintaining natural resources to improve the resilience of human populations in the face of climate change and the biodiversity crisis.

1.3. Scope and definition

Degradation is a significant threat to both natural and anthropized areas. In the first stage of our project, the institutions that are part of the MapBiomas network have taken a stand for environmental conservation by prioritizing the mapping of vectors of degradation on the native vegetation (Figure 1), which currently covers 2/3 of the Brazilian territory.

Detailed information and definitions about each native vegetation class for each biome can be found in Table 1 (see section 2.1).

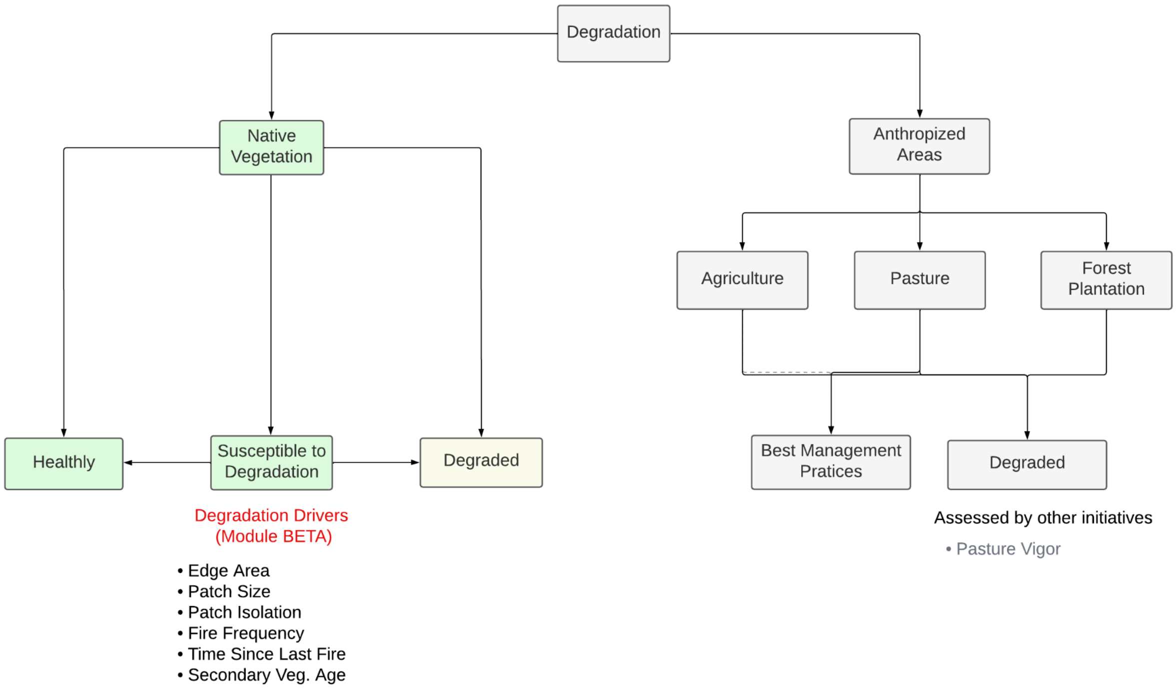

Figure 1: Conceptual model of degradation in Brazil. The green boxes represent the processes addressed in the BETA Collection, identifying healthy vegetation and areas susceptible to degradation using the vectors named in the red dotted box. The yellow box represents the next step in the project, in which we will identify degraded areas by incorporating other metrics (gray text). The gray boxes represent the degradation processes related to anthropized areas, which were not evaluated in the scope of this work.

1.4. How we are organized

MapBiomas is a multi-institutional initiative of the Climate Observatory (a network of NGOs working on climate change in Brazil - http://www.observatoriodoclima.eco.br/en/). The co-creators of MapBiomas involve NGOs, universities, and technology companies. For the MapBiomas Degradation, IPAM conducted technological and operational development. The geospatial tech companies Ecostage and Geodatin are responsible for the backend and dashboard/website/frontend development of MapBiomas Degradation. Expert teams in each biome carried out biome evaluation and analysis:

- **Amazon** – Amazon Institute of People and the Environment (IMAZON)
- **Atlantic Forest** – SOS Atlantic Forest Foundation and ArcPlan
- **Caatinga** – Geodatin and State University of Feira de Santana (UEFS)
- **Cerrado** – Amazon Environmental Research Institute (IPAM)

• **Pampa** – GeoKarten and Federal University of Rio Grande do Sul (UFRGS)
• **Pantanal** – SOS Pantanal Institute and ArcPlan.

2. Methodological description

This document outlines the theoretical concepts and methods employed to create yearly maps of areas of native vegetation susceptible to degradation in Brazil from 1985 to 2022, for each degradation vector of the MapBiomas Degradation Collection BETA. All the products were based on the MapBiomas Collection 8 (see Land Cover and Land Use ATBD) and MapBiomas Fire Collection 2 (see MapBiomas Fire ATBD). All the codes used to build the database are accessible in the GitHub repository (https://github.com/mapbiomas-brazil/degradation).

2.1 Definition of native vegetation for each biome

The MapBiomas project uses a unified legend; however, it is important to note that each biome contains its own distinct characteristics. As a result, the same classification may represent different ecosystems. For a comprehensive understanding, Table 1 provides a detailed description of each native vegetation class considered at this stage of the project, and its meaning for each Brazilian biome.

Table 1. Detailed description of the native vegetation classes for each biome

Forest Formation	Amazon	Dense Ombrophilous Forest, Evergreen Seasonal Forest, Open Ombrophilous Forest, Semideciduous Seasonal Forest, Deciduous Seasonal Forests, Wooded Savanna. Bamboo forest (Acre).
	Caatinga	Vegetation types with a continuous canopy - Seasonal Forested Savanna, Semi-Deciduous and Deciduous Seasonal Forest.
	Cerrado	Vegetation types with a predominance of tree species, with continuous canopy formation (‘Floresta Ripária’, ‘Mata de Galeria’, ‘Mata Seca’, and ‘Cerradão’) (Ribeiro & Walter, 2008), as well as semideciduous seasonal forests.
	Atlantic Forest	Dense, Open, and Mixed Ombrophilous Forest, semi-deciduous Seasonal Forest, Deciduous Seasonal Forest, and Pioneer Tree Formation.
	Pampa	Woody vegetation with tree or tree and shrub species, with a predominantly continuous canopy. It includes the following forest types: ombrophilous, deciduous, semi-deciduous, and part of the pioneer formations.
	Pantanal	Tall trees and shrubs in the lower stratum: Seasonal Deciduous and Semideciduous Forest, Forested Savanna, Forested Seasonal Savanna, and Pioneer Formations with fluvial and/or lacustrine influence.
Savanna Formation	Amazon	Open vegetation with a rare shrub and/or tree layer, herbaceous layer always present.
	Caatinga	Vegetation types with a predominance of semi-continuous canopy species - Wooded Seasonal Savanna, Wooded Savanna
	Cerrado	Savanna formations with defined woody and shrub-herbaceous stratum (‘Cerrado Sentido Restrito’, ‘Cerrado denso’, ‘Cerrado típico’, ‘Cerrado ralo’ and ‘Cerrado rupestre’)
	Atlantic Forest	Savannas, Forested and Wooded Seasonal Savannas

	Pantanal	Small tree species, sparsely distributed and arranged in the middle of continuous shrubby and herbaceous vegetation. The herbaceous vegetation is mixed with shrubs.
Mangrove	All biomes	Dense, evergreen forest formations are often flooded by the tide and associated with the coastal mangrove ecosystem.
Flooded Forest	Amazon	Alluvial Open Ombrophilous Forest, established along watercourses, occupies the periodically or permanently flooded plains, which in the Amazon constitute the 'Mata de Várzea' or 'Igapó', respectively.
Wooded Sandbank Vegetation	All biomes	Forest formations that grow on sandy soils or dunes in the coastal zone.
Wetland	Amazon	Floodplain or grassland vegetation that is influenced by rivers and/or lakes.
	Cerrado	Vegetation with a predominance of herbaceous stratum subject to seasonal flooding (e.g. 'Campo Úmido') or under fluvial/lacustrine influence (e.g. 'Brejo'). In some regions, the herbaceous matrix is associated with tree species of savanna formation (e.g. 'Parque de Cerrado') or palm trees ('Vereda', 'Palmeiral').
	Atlantic Forest	Vegetation influenced by rivers and/or lakes.
	Pampa	Swampy areas, regionally known as 'banhados' or 'marismas' (saline influence). Typically hygrophilous vegetation, with emergent, submerged or floating aquatic plants. They occupy plains and depressions of the land with waterlogged soil and also the shallow margins of lakes or water reservoirs.
	Pantanal	Herbaceous vegetation with a predominance of grasses subject to permanent or temporary flooding (at least once a year) according to natural flood pulses. The woody element may be present on the grassland matrix, forming a mosaic with shrub or tree plants (e.g. 'cambarazal', 'paratudal', and 'carandazal'). Swampy areas generally occur on the banks of temporary or permanent ponds occupied by emergent, submerged, or floating aquatic plants (e.g. 'brejos' and 'baceiros').
Grassland	Amazon	Savanna, 'Savana Parque' (Marajó), Seasonal Savanna (Roraima), Woody-Grassy Savanna, 'Campinarana' for regions outside the Amazon/Cerrado Ecotone. For regions within the Amazon/Cerrado Ecotone, the herbaceous stratum predominates.
	Atlantic Forest	'Savana Parque' and Woody-Grassy Savanna. Includes Steppe, Shrubby and Herbaceous Pioneers.
	Caatinga	Vegetation types with a predominance of herbaceous species ('Savana Parque', Woody-Grassy Savanna) and Flooded areas with a network of interconnected ponds, located along watercourses and in lowlands that accumulate water, composed predominantly of herbaceous to shrubby vegetation.
	Cerrado	Grassland formations with the predominance of a herbaceous stratum ('campo sujo', 'campo limpo', and 'campo rupestre') and some areas of savanna formations such as the 'cerrado rupestre'.
	Pampa	Vegetation with a predominance of herbaceous-grassy stratum, with the presence of herbaceous dicotyledons and shrubs. Occur on deep to shallow soils, including rocky ('campos rupestres') and sandy soils ('campos arenosos' or 'psamófilos'). They range from well-drained soils (mesic grasslands) to soils with a higher moisture content ('campos úmidos').
	Pantanal	Vegetation with the predominance of herbaceous-grassy stratum, with the presence of isolated shrubs and woody plants. The botanical composition is influenced by edaphic and topographic gradients and by pastoral management.
Herbaceous Sandbank Vegetation	All biomes	Herbaceous vegetation with fluvial and marine influence.

2.2 Edge Area

2.2.1 Description

The edge area corresponds to the the peripheral area of a patch of native vegetation affected by phenomena from the neighborhood where part of the original native vegetation has been removed and some anthropogenic use is taking place (such as planted pasture, agriculture, or urban areas). This condition generates negative effects from the outside to the inside of the native vegetation patch, which may include changes in the microclimate, such as greater exposure to winds and solar radiation, changes in nutrient cycling, an increase in the invasion by exotic species, and which together result in the loss of habitat quality and the impoverishment of biological and functional diversity (Silva-Junior et al., 2020; Dodonov et al., 2013; Banks-Leite et al., 2010; Broadbent et al., 2008). Because the distance and effects of edge area reported in the scientific literature vary depending on the species and the ecosystem type considered, eight layers were generated with different distance thresholds measured inside each native vegetation patch from the edge in contact with an anthropogenic class (30 m, 60m, 90m, 120m, 150m, 300m, 600m, and 1000m). This practical approach allows the user to apply the information they consider most appropriate for the group of organisms or ecosystems they are interested in when assessing or considering the potential negative effects of this ecological phenomenon.

2.2.2 Method

First, we utilized annual land use and land cover data from Collection 8, then we standardized the native vegetation classes to a single class for each year to avoid edge area between different vegetation types. For example, areas of Savanna Formation do not produce edge areas over areas of Forest Formation. Furthermore, we considered that Rocky Outcrop (ID 29), Hypersaline Tidal Flat (32), and Water (33) classes should also not generate edge areas over native vegetation classes. We thentreated all anthropic use classes as a single class and employed the *ee.Kernel.euclidean()* function in Google Earth Engine to calculate the distance of edge areas over native vegetation. This was achieved by considering buffers of 30, 60, 90, 120, 150, 300, 600, and 1000 meters. It is important to note that we did not differentiate or weigh the edge area based on its source (e.g., Pasture, Agriculture, or Urban). All the buffers were considered equal, regardless of the source class.

2.3 Patch Size

2.3.1 Description

Ecological literature indicates that many native plant and animal species have minimum habitat area requirements in order to maintain viable persistent populations. As remnants of native vegetation become smaller in area, there tends to be a decrease in the resources available to maintain a population of individuals, and local extinction of species may occur. Additionally, smaller fragments are less likely to be recolonized by migrant individuals dispersing from neighboring patches, further contributing to population declines (Lawrence et al., 2018; Magioli et al., 2015). At last, the smaller the fragment, the greater the proportion occupied by the edge area, which also contributes to a decrease in habitat quality.

The sum of these effects results in biologically impoverished patches of habitat. These patches often exhibit reduced biodiversity and ecological function as their area decreases.. Moreover, larger patches are generally more effective at providing ecosystem services, such as carbon sequestration, water regulation, and air purification, which are crucial for the health of the surrounding landscapes and human communities (Brancalion et al., 2019).

In the context of edge effects, an ecosystem's species and functions are differently impacted based on the minimum size of a native vegetation patch. Larger patches are typically more resilient and capable of sustaining diverse biological communities and ecological processes (Laurance et al., 2011). However, scientific evidence still shows few well-documented cases of these effects for Brazilian biomes. For this reason, maps were generated with small patches with different maximum sizes: 3 hectares (ha), 5 ha, 10 ha, 25 ha, 50 ha, and 75 ha. This allows users to select the most appropriate threshold according to the specific ecological and conservation context of interest.

2.3.2 Method

We utilized land use and land cover maps from Collection 8 and applied a systematic approach to consolidate native vegetation classes into a single class each year. This method ensures that spatially connected native vegetation types are treated as a single patch. In the case of Pantanal, the water class was also considered as “pseudo” native vegetation in the algorithm. Subsequently, by using the *.connectedPixelCount()* function in Google Earth Engine, we computed the area of each native vegetation patch in hectares. The patches were then categorized based on their area: patches equal to or less than 3 hectares (ha), 5 ha, 10 ha, 25 ha, 50 ha, and 75 ha. All patches larger than 75 ha were excluded from this data layer.

2.4 Patch Isolation

2.4.1 Description

Ecological literature reports that the permanence of species in fragmented habitats can be better understood within the concept of metapopulation. In this case, the species' population is considered on a landscape scale, occupying a set of isolated habitat patches and their distance from source areas (large fragments). The presence of the species in a given habitat patch results from a balance between local extinctions and recolonization from neighboring habitat patches. As a result, the more isolated a habitat patch is from the other surrounding patches , the greater the risk of local extinctions of the species due to the lower probability of migrants arriving (Almeida et al., 2019; Hatfield et al., 2018; Martensen et al., 2008).

Isolation is not the only factor to consider. The size of the patch (target fragment) is also important. Smaller patches have fewer resources and are less likely to be reached by dispersing individuals. The size of the larger neighboring patches (source fragments) is a key consideration, as they are typically the main sources of immigrants. Large patches, with their more favorable habitat conditions, play a crucial role in maintaining species diversity by providing better conditions for species reproduction and by making migrants able to disperse to other neighboring patches (Fahrig, 2003).

Species have different dispersal capabilities; therefore, distance influences genetic connectivity between isolated populations in small fragments and larger areas. Gene flow is essential for maintaining genetic diversity in populations, and connected landscapes allow for the exchange of genetic diversity. This connectivity helps prevent inbreeding and increases the adaptive potential of populations (Frankham, 2005). Thus, the worst-case scenario for biodiversity conservation is when the target fragment is smaller and more isolated from neighboring large fragments.

2.4.2 Method

We defined three variables to be used in the analysis, each one with three factors:

1) Size of Target Patch: Area equal to or less than 25 hectares (ha), 50 ha, or 100 ha. The higher the value, the greater the number of fragments considered isolated.
2) Distance to Source Patch: Distance equal to or more than 5 kilometers (km), 10 km, or 20 km. Distance here represents a threshold of isolation tolerance. Therefore, lower values indicate less tolerance, resulting in a greater number of isolated fragments in the landscape.
3) Size of Source Patch: Area equal to or greater than 100 ha, 500 ha, or 1000 ha. The higher the value, the smaller the number of source fragments in the landscape, resulting in a greater number of isolated fragments.

To process this information in Google Earth Engine, we followed the steps:

1. **Resampling Data**: We resampled the data from Collection 8 with a spatial resolution of 30m to 100m.
2. **Exporting Native Vegetation Data**: We exported native vegetation data grouped into two categories: “forest” (including Forest Formation, Savanna Formation, Mangrove, Flooded Forest, and Wooded Sandbank Vegetation) and “Non-Forest” (including Wetland, Grassland, and Herbaceous Sandbank Vegetation). Exclusively for the Pantanal, the water class was also considered a ‘pseudo’ native vegetation as Non-Forest.

3. **Creating Connected Natural Areas Mask**: We exported a mask of connected natural areas with up to 1024 pixels, which allowed us to separate forest and non-forest areas into categories of more than 100 hectares (100 pixels), 500 hectares (500 pixels), and 1,000 hectares (1,000 pixels), representing the “source patch” maps.
4. **Generating Distance Map**: Using the *ee.Kernel.euclidean()* distance function in the Google Earth Engine, we generated a distance map from source patches, classifying distances into categories of equal to or greater than 5km, 10km, and 20km.
5. **Removing Large Fragments**: We used the same databases as a mask to remove all fragments over 100 hectares. This generated a database of natural areas with an area equal to or less than 100 hectares.
6. **Reclassifying Target Fragments**: The remaining natural areas were reclassified to generate the layer of target fragments: natural areas with an area equal to or less than 25 hectares, 50 ha, and 100 ha.

2.5 Fire

2.5.1 Description

Fires in native vegetation may or may not represent a degradation factor. This is because some vegetation types, such as grasslands and savannas, have an evolutionary history of coexistence and adaptation to fire triggered by natural factors (Bowman et al., 2009). On the other hand, forest formations generally have no adaptation to fire, so any burning event can be considered a degradation factor.

The frequency of fires is a critical factor in determining their impact. In ecosystems like grasslands and savannas, fire regimes (which include frequency and time since the last fire) play a significant role in maintaining ecological balance (Bond & Keeley, 2005). These ecosystems are adapted to specific fire regimes, and deviation from these natural patterns due to anthropogenic causes can lead to degradation. When fire frequency increases beyond natural levels, it can exceed the recovery capacity of these fire-adapted ecosystems, leading to significant ecological consequences (Archibald et al., 2013).

In contrast, forest ecosystems, which typically do not have an evolutionary history of frequent fire exposure, are more susceptible to degradation from fire events. Fire in these areas often results in loss of biodiversity, soil degradation, and changes in vegetation structure, contributing to long-term ecological damage (Cochrane, 2003).

2.5.2 Fire Frequency Method

The burned area frequency maps represent how many times the same pixel was mapped as burned over a period from 1985 to 2022. Fire frequency data is aggregated into a single map with 38 classes: Class 1 represents pixels that burned once, Class 2 represents pixels that burned twice, and so on.

To create these maps, we retrieved yearly burned areas from MapBiomas Fire Collection 2. We computed the fire frequency by binarizing yearly burned areas for each year (1= burned, 0= unburned) and summing the fire occurrences across years. This data also includes the land use and cover classes from MapBiomas Collection 8 for the last year. For more details, see the MapBiomas Fire ATBD.

2.5.3 Time Since The Last Fire Method

The Time Since Last Fire represents the age (in years) since each pixel last burned based on the MapBiomas Fire Collection 2.

To construct this dataset, we followed these steps:

1. **Generate Fire Age**: For each pixel, we calculated the fire age by starting a count from the year after the first observed fire event. From the year following the fire, we added 1 to each subsequent year without a fire event.
2. **Determine Last Fire Year**: When a new fire event was observed, the number of years since the last fire was recorded. The count then reset in the following year, starting again from 1.
3. **Mask Unburned Pixels**: All pixels with no observed fire events are masked in the map.

The resulting map shows the number of years since each pixel last experienced a fire, providing valuable information on fire history and intervals between fire events across the landscape.

2.6 Secondary Vegetation Age

2.6.1 Description

The removal of primary vegetation by an anthropogenic and natural processes, followed by abandonment, gives rise to a process of passive succession. The impact of secondary vegetation on the climate, soil, and hydrology differs from that of primary or anthropic areas. Over time, the structure and functionality of patches of secondary vegetation in the recovery process tend to improve due to an increase in the diversity of plant species present and the structural complexity of the vegetation (Chazdon, 2014). As a result, these recovering areas are more resistant and resilient to the effects of different degradation processes.

In this context, patches of secondary vegetation can be considered susceptible to degradation, particularly those that are relatively young. Consequently, the age of secondary vegetation is an important indicator of its ecological stability and resistance to further disturbances (Arroyo-Rodríguez et al., 2017).

This layer of information was generated from the results obtained by the Deforestation and Secondary Vegetation MapBiomas dataset. By processing data from the annual land use and cover maps, this dataset identifies areas containing secondary vegetation each year, allowing the calculation of the age of each existing patch of secondary vegetation for the most recent year.

2.7.2 Method

Using the MapBiomas Deforestation and Secondary Vegetation dataset (see Deforestation and Secondary Vegetation ATBD), we map the regrowth of native vegetation by year and compute the age (in years) of regrowth for each pixel.

The process is as follows:

1. **Initial Mapping**: Identify areas of deforestation and secondary vegetation for each year using the MapBiomas dataset.
2. **Regrowth Calculation**: For each year following deforestation, increment the regrowth age of each pixel by +1. This is done annually, starting from the year of deforestation.
3. **Age Computation**: The age of regrowth for each pixel is determined by summing the years of regrowth. For example, if a pixel was deforested in 2010 and identified as secondary vegetation in subsequent years, by 2022, the pixel would have 12 years of regrowth.

This method allows for the calculation of the precise age of secondary vegetation regrowth for each pixel, providing valuable information on the recovery and resilience of ecosystems over time.

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