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Mapping Caatinga Vegetation using Optical Earth Observation Data – Opportunities and Challenges

Mapeamento da Vegetação da Caatinga a partir de Dados Ópticos de Observação da Terra – Oportunidades e Desafios

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Abstract: The Caatinga biome represents around 10% of the Brazilian territory, and it has an estimated population of 28 million inhabitants. Its tree-shrub vegetation, adapted to semi-arid conditions, plays a fundamental role in maintaining the hydrological balance, feeding the energy matrix, and generating revenues for Brazil. Despite its importance, the Caatinga is one of the most neglected biomes by the scientific community. Therefore, this review article aims to present elements that contribute to updating the state-of-the-art on the use of optical Earth observation data in the conservation of Caatinga vegetation, based on the identification of mapping initiatives at different scales that consider the biome. To this end, this study carried out a systematic bibliographic review in which the main focus was the characterization of orbital sensors, image classification techniques, land-use and land-cover classes, validation strategies, and the time interval defined by each mapping initiative. This detailed overview allowed us to assess the degree of usability and reliability of the existing products. Therefore, this study looks to open up possibilities to fill current scientific gaps that need further investigation regarding the role of optical Earth observation data in mapping the vegetation of the Caatinga and subsidizing resources for new initiatives, restoration actions, and hence the

improvement of public policies favoring the conservation and sustainable use of the Caatinga's resources.
Keywords: Remote Sensing. Seasonally Dry Tropical Forests. Semiarid. Land-cover. Northeast Brazil.

Resumo: O bioma Caatinga representa cerca de 10% do território nacional e tem uma população estimada em 28 milhões de habitantes. Sua vegetação arbóreo-arbustiva, adaptada às condições de semiaridez, exerce um papel fundamental na manutenção do balanço hidrológico, na alimentação da matriz energética e na geração de receitas para o país. No entanto, o bioma ainda é um dos que recebe menor atenção da comunidade científica. Diante disso, o presente artigo de revisão visa apresentar elementos que contribuam para a atualização do estado da arte sobre o uso de dados ópticos de observação da Terra na conservação da vegetação da Caatinga, a partir da identificação das iniciativas de mapeamento em diferentes escalas que contemplam o bioma. Para tal, esse estudo fez uma revisão bibliográfica sistemática cujo enfoque principal foi a caracterização dos sensores orbitais imageadores, técnicas de classificação de imagem, legendas de uso e cobertura, estratégias de validação, e o intervalo temporal compreendido por cada iniciativa. Esse detalhamento permitiu avaliar o grau de usabilidade e confiabilidade dos produtos existentes. Assim, esse estudo espera abrir possibilidades para preencher lacunas científicas existentes e que carecem de investigação no que diz respeito ao papel dos dados ópticos de observação da Terra no mapeamento da vegetação da Caatinga e no subsídio de recursos para novas iniciativas, ações de restauração e, consequentemente, aprimoramento de políticas públicas em prol da conservação e uso sustentável dos recursos do bioma.
Palavras-chave: Sensoriamento Remoto. Florestas Tropicais Sazonalmente Secas. Semiárido. Cobertura da terra. Nordeste do Brasil.

1 INTRODUCTION

The Caatinga is the only exclusively Brazilian biome, and is considered one of the largest (MORO et al., 2016) and most populated (RIBEIRO et al., 2016) semi-arid regions in the world, with an estimated 28 million inhabitants. It is rich in biodiversity and is home to several endemic species (SOBRINHO et al., 2016), but is one of the most undervalued and scientifically understudied biomes in Brazil (VELLOSO et al., 2002; SANTOS et al., 2011). This neglect likely stems from most other studies focusing on mapping only dense and humid forests. Meanwhile, deforestation and burnings threaten the Caatinga and make the biome one of the most sensitive to climate change, reaching critical levels of vulnerability.

This scenario results in damage to human health, greater water scarcity, small- and large- scale economic impacts, and increased desertification. Yet, the Caatinga's tree-shrub vegetation adapted to semi-arid conditions plays a fundamental role in maintaining the hydrologic balance and preserving existing water resources. In addition, the main sources that sustain the economy of the Northeast region of Brazil are derived from Caatinga vegetation, either through the firewood that feeds the energy matrix or through the non-timber forest resources used to manufacture revenue generating-products for the country (PAREYN, 2010).

A survey carried out on all databases hosted on the Web of Science platform in June 2020 indicated that the Caatinga is 73% less studied than the Amazon, 68% less studied than the Cerrado, and 65% less studied than the Atlantic Forest. Moreover, most institutional mapping programs on a biome scale are focused on the Amazon, the Atlantic Forest, and, more recently on the Cerrado, with little technical-scientific investment put towards the Caatinga. This underlines the importance of increasing scientific efforts to fill existing gaps for producing more accurate and up-to-date information on the conservation status of Caatinga vegetation in the scope of Remote Sensing.

Within this context, this study aims to enrich these discussions by identifying the mapping initiatives already carried out in the biome, characterizing the classification techniques employed and describing the orbital imaging sensors used. The time interval, land use and land cover legends, and validation strategies employed by these initiatives were also analyzed, and the accuracy levels were examined. To accomplish this, a systematic bibliographic review was performed, in which national and international journals were assessed; the studies were not filtered according to pre-defined time intervals. Compiling this information allows for updating of the state-of-the-art regarding the mapping of Caatinga vegetation in the scope of Earth observation optical data.

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2 CAATINGA: AN EXCLUSIVELY BRAZILIAN BIOME

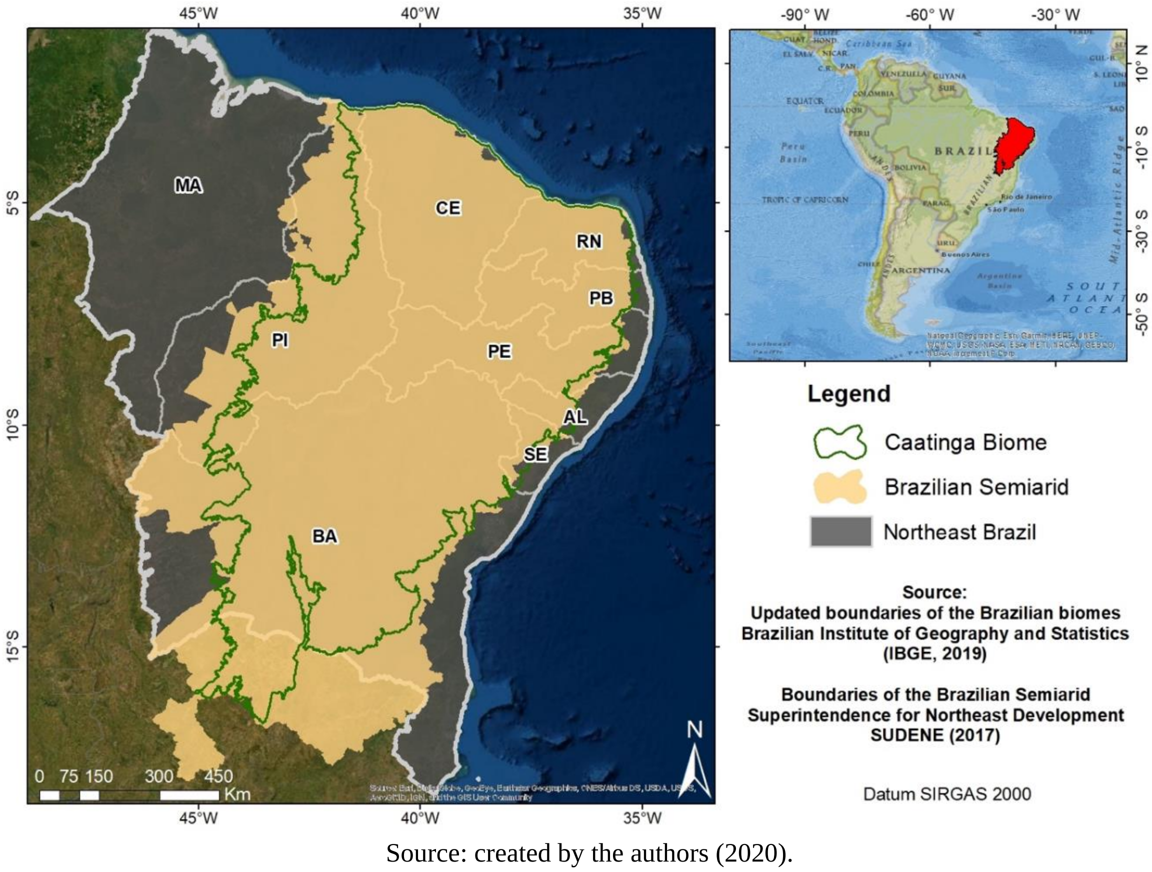
The word caatinga comes from *Tupi-Guarani* and means "white forest", due to the dry and whitish aspect of the landscape when the leaves fall during the dry season (ALBUQUERQUE; BANDEIRA, 1995). In a broader context, the Caatinga is part of another global biome, referred to as seasonally dry tropical forests (ALBUQUERQUE et al., 2012; BRITO; PRESLEY; SANTOS, 2012), and is the largest and most continuous area of this group in South America (SANTOS et al., 2012).

In Brazil, the term Semiarid is often used to refer to Caatinga. However, it should be clarified that, in the Brazilian context, Semiarid refers to a region delimited by the Superintendence for Northeast Development (SUDENE – *Superintendência de Desenvolvimento do Nordeste*), which occupies approximately 12% of the national territory, equivalent to 1,128,697 km^2, encompassing 1,262 Brazilian municipalities (BRASIL, 2017a). For a municipality in the area in which SUDENE operates to be considered suitable for inclusion in the Semiarid region, it must meet at least one of the following three technical-scientific criteria (BRASIL, 2017b, p.1):

> I - average annual rainfall equal to or less than 800mm;
> II - Thornthwaite's aridity index equal to or less than 0.50;
> III – a daily percentage of water deficit equal to or greater than 60%, considering all days of the year.

Most of the Semiarid region is located in Northeast Brazil (NEB), extending also to Minas Gerais, where it occupies approximately 18% of the state's total area. In addition, another Brazilian biome occurs in the Semiarid region: the Cerrado. Therefore, it is important to highlight that *Semiarid* is a political delimitation, defined based on climatological parameters, while Caatinga is a biome, defined by its prevailing vegetation type. Figure 1 shows the location map and the boundaries of both Caatinga and Semiarid, as well as the states that both encompass. It should be noted that the new boundaries of the biome defined by the Brazilian Institute of Geography and Statistics (IBGE, 2019) were considered for creating this map.

Figure 1 – Map delimiting the boundaries of the Northeast region of Brazil, the Brazilian Semiarid and the Caatinga biome, as well as the states that each one encompasses.



Source: created by the authors (2020).

The total area of Caatinga is 862,818 km^2 (IBGE, 2019), which corresponds to approximately 10% of Brazil's territory. Caatinga is surrounded by the Atlantic Forest and Cerrado biomes, and represents 54% of the NEB, comprising 100% of the state of Ceará (CE) and part of the states of Alagoas (AL), Bahia (BA), Maranhão (MA), Paraíba (PB), Pernambuco (PE), Piauí (PI), Rio Grande do Norte (RN) and Sergipe (SE). In addition, the biome is also found in part of the state of Minas Gerais (MG), in the Southeast region of Brazil.

Climatologically, the semi-arid climate is predominant in Caatinga (ALVARES et al., 2013) and the rainfall rates are low, ranging from 250 to 900 mm per year (ALVES; ARAÚJO; NASCIMENTO, 2009). There is also a large space-time variability in rainfall (MARENGO; TORRES; ALVES, 2017), which results in long periods of drought, lasting from six to eleven months depending on the location (MORO et al., 2016).

Being located between the Equator and the Tropic of Capricorn, the Caatinga is exposed to high levels of solar radiation all year round (MORO et al., 2016). For this reason, the average temperature varies between 25ºC and 30ºC and there is not much difference between the winter and summer months. In rainy periods, the rain that falls is not stored by the rocky soil, which explains the high evapotranspiration rates (GANEM, 2017). The relative humidity, on the other hand, is low, with values close to 50%.

2.1 Dynamics of Land Use and Occupation

A considerable portion of the Caatinga's native vegetation has been heavily altered by human-induced processes (LEAL et al., 2003). Historically, the degradation of the biome may be explained by the process of occupation of Northeast Brazil, which began on the coast and advanced inland with increased extraction of natural resources and agricultural production for exportation purposes (ALVES; ARAÚJO; NASCIMENTO, 2009). From the 17th century on, cattle raising began on farms and the first towns started to emerge.

A characteristic feature of anthropism in Caatinga is the fragmentation of the landscape by agricultural activities - about 75% of farms have less than 10 hectares (REDO; AIDE; CLARK, 2013). This pattern is not easily detected by sensors with low to moderate spatial resolution, which justifies the use of high-resolution sensors (LAMBIN; GEIST; LEPERS, 2003; STROPPIANA et al., 2012). Although fragmented, agricultural activities have shown a decline in recent decades, as pointed out by Redo, Aide, and Clark (2013). According to the authors, this decline was mainly influenced by the loss of the economic competitiveness of crops (such as cotton), long drought periods, rural exodus movements, and the high cost of labor in the countryside.

Currently, livestock is Caatinga's main economic activity. For example, the biome's planted pasture area was equivalent to approximately 210,000 km^2 in 2018, equal to more than 25% of its total area (MAPBIOMAS, 2020). This is because the native vegetation enables dry matter consumption capable of meeting animal needs (ALVES; ARAÚJO; NASCIMENTO, 2009). Giulietti et al. (2004) pointed out that a considerable portion of the Caatinga is designated as native pastures in all states it encompasses, except in the northern portion of Minas Gerais. The authors also added that these pastures are more diverse than planted pastures, in addition to maintaining biodiversity and serving as an alternative to consolidated use.

Albuquerque (1999) stated that degradation in the Caatinga is not always directly anthropic, with climate also having to be taken into account. Climate plays a fundamental role in the land-use dynamics and the evolution of the biome's landscape (MALDONADO; SANTOS; CARVALHO, 2002). Specifically, in Caatinga, some studies point to desertification as one of the main threats imposed by land use and land cover changes (WAN et al., 2004; VIEIRA et al., 2015; TOMASELLA et al., 2018).

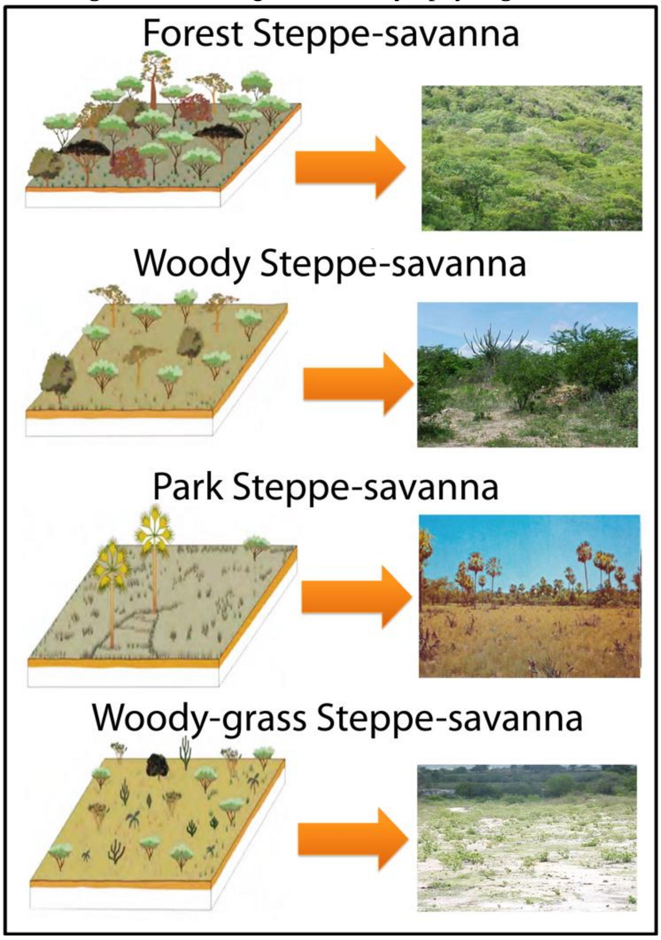
2.2 Characteristics of Caatinga Vegetation

Over the last decades, some classifications have been proposed for the different types of vegetation that exist in the Caatinga (ANDRADE-LIMA 1981; VELOSO; GÓES FILHO, 1982; EITEN, 1983; CHAVES et al., 2008; CAVALCANTI, 2018). The biome has plant species adapted to the typical water deficit of the region's semi-arid climate, which is evidenced by the predominance of shrubs and small trees, whose main characteristic is the deciduousness in the dry season (FERNANDES; QUEIROZ, 2018). Moreover, to better adapt to the most extreme climatic conditions, the plants generally have thin, small, and thorny leaves. However, this does not exempt Caatinga from having plant species that can be highly vulnerable to rapid climate change (ALBUQUERQUE et al., 2012).

Some plants store water, like cacti, and others have roots practically on the soil surface to absorb maximum rainfall. Since water availability limits plants' development and life cycle, the biome vegetation's phenological behavior is strongly influenced by the rainfall regime, even if it is short-lasting (LIMA; RODAL, 2010; ERASMI et al., 2014). Leaves appear rapidly and plants complete their reproductive cycles in a short period.

The vegetation structure of the Caatinga is quite heterogeneous (RODAL; BARBOSA; THOMAS, 2008), with sections of arboreal vegetation forming a continuous canopy, with low and sparse trees, and a denser shrub stratum (xerophytes). The patterns of vegetation distribution throughout the biome were also taken into consideration by Velloso et al. (2002) when defining eight ecoregions for the Caatinga. Within the biome, there are three different typical plant strata (ALVES; ARAÚJO; NASCIMENTO, 2009): arboreal (8 to 12 meters), shrubby (2 to 5 meters), and grassy (below 2 meters). Figure 2 presents the most commonly encountered phytophysiognomies of the Caatinga, based on the definition of the Technical Manual of the Brazilian Vegetation (IBGE, 2012).

Figure 2 – Caatinga's Main Phytophysiognomies.



Source: Adapted from IBGE (2012) and MapBiomas (2020) – Caatinga team.

In the Caatinga, the predominant type of vegetation is steppe-savanna. According to the Technical Manual of Brazilian Vegetation (IBGE, 2012), the forest steppe-savanna is formed by an upper stratum that can be heavily or slightly densified, and a lower woody-grass stratum, usually discontinuous and not highly expressive in terms of physiognomy. The woody steppe-savanna is made up of an upper, sparse shrubby-woody stratum, and a lower woody-grass stratum of high phytophysiognomic importance (IBGE, 2012). The park steppe-savanna is characterized by shrubs and small trees, usually of the same species, and a pronounced spatial distribution. Finally, the woody-grass steppe-savanna is distinguished by an extensive grassy ground.

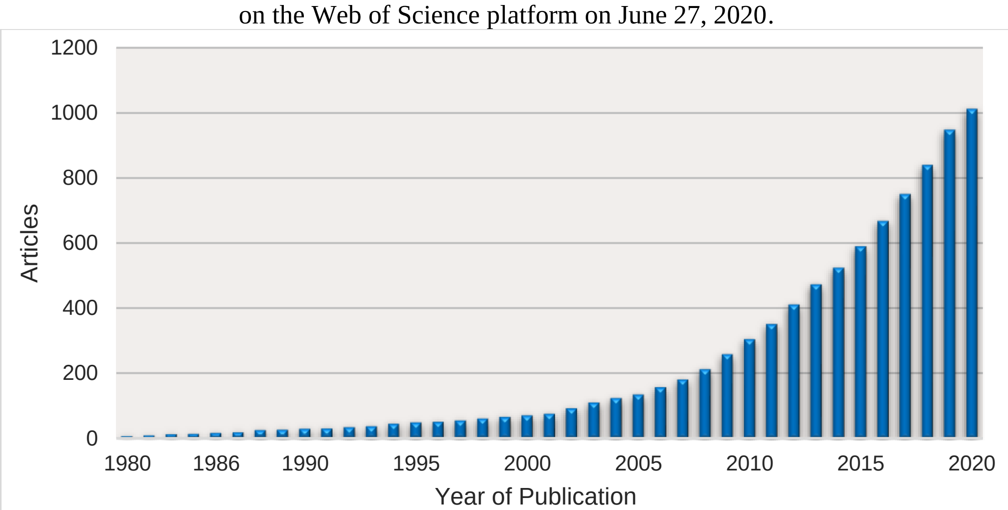
2.3 Bibliographic Analysis: Caatinga Vegetation in the Literature

A search performed on June 27, 2020, in all Web of Science (WoS) databases and using no pre-defined time interval returned 3,414 articles for the word "Caatinga". A second search using the expression "drylands AND Brazil" returned 61 articles. This expression was also used to encompass articles from the international literature that refer to the biome without using its name. Despite WoS limiting the number of exports to 500 per file, the entire database was extracted in order to analyze the co-occurrence of important words in the titles and abstracts of each article. This was done using VOSviewer (VAN ECK; WALTMAN, 2010), a software program for constructing and visualizing bibliometric networks.

For the co-occurrence analysis, a binary counting method was used, meaning that the number of times a given term occurred in the same article was disregarded. More than 14,000 terms were identified, and therefore a minimum of 50 occurrences per term was defined. Among the major occurrences, there are specific nomenclatures from ecology, trivial terms (i.e., "study", "region"), and the word "vegetation", returning 496 records. Because it is a term that is related to the core theme of this article, the word was used to refine the first search in WoS, which resulted in 1,011 articles that address Caatinga vegetation.

The publication rate of this set of articles varied little until the end of the 90s. The first article was published in 1960 and the publication of the second one took place after a 10-year gap, in the 1970s, a decade in which only five articles were published. In the 1980s, the average publication rate was 2 articles per year, a number that doubled in the 1990s. At the beginning of the 21st century, a more expressive publication rate can be noted, but it was in mid-2010 that it rose sharply, as shown by Figure 3.

Figure 3 - Number of articles returned (cumulative value) after searching for the expression "Caatinga AND vegetation" on the Web of Science platform on June 27, 2020.



Source: created by the authors (2020).

A significant portion of the published articles (91.8%) is associated with Brazilian institutions. The remaining works represent a smaller portion of the contributions (less than 10%) but are no less important, originating from institutions in countries such as the United States, Germany, England, Argentina, Australia, Mexico, and the Netherlands. At the national level, most articles are led by institutions located in states within the Caatinga boundaries, with Pernambuco leading the number of publications, followed by Paraíba, Ceará, Bahia, and Rio Grande do Norte.

In the database identified for Caatinga vegetation, some articles that used Earth observation data are worth mentioning for their recent biome-level approach. Redo, Aide, and Clark (2013) mapped land cover changes in Caatinga and other dryland ecosystems using Moderate Resolution Imaging Spectroradiometer (MODIS) sensor data from 2001 to 2009. Beuchle et al. (2015) relied on association functions defined by a collection of spectral signatures (RAŠI et al., 2011; RAŠI et al., 2013) to perform object-oriented classification in Landsat series images (TM, ETM+) for three periods: 1990, 2000 and 2010. Another set of articles found in the literature that used Earth Observation data in the Caatinga are related to the use of multi-temporal vegetation index data for studying the variability of phenology concerning precipitation and extreme drought periods (BARBOSA; HUETE; BAETHGEN, 2006; BARBOSA; KUMAR, 2016; BARBOSA et al., 2019).

Shimabukuro et al. (2020) developed a method to discriminate seven land use and land cover classes across all Brazilian biomes for 2015, based on the Linear Spectral Mixing Model (LSMM) applied to data from the Vegetation sensor onboard the Project for On-Board Autonomy (PROBA-V) satellite. In addition to the biome-level approach, studies at the state level or in small areas within the biome can also be found. In Bahia, Dutra (2019) classified the vegetation using intra-annual images and the Random Forest technique, also applying LSMM in MODIS images between 2000 and 2017 as an alternative for monitoring land use and land cover in the state.

More recently, Cunha et al. (2020) investigated spatiotemporal patterns of vegetation removal in a Caatinga area located in the state of Paraíba. The authors used Landsat (TM, ETM+, and OLI) data over 31 years (1985-2015) and compared the Enhanced Vegetation Index (EVI), the Normalized Difference Vegetation Index (NDVI), and surface albedo values, with the latter showing the best accuracy. In an area of Pernambuco, Santos et al. (2020) classified land use and land cover using the maximum likelihood technique in Landsat data from 2007 and 2017. Finally, Silveira et al. (2018) combined for the first time the classification of Caatinga's phytophysiognomies with physicochemical soil attributes using both Sentinel-2 and LiDAR data.

3 CAATINGA VEGETATION MAPPING INITIATIVES

In the last century, cartographic data on Caatinga vegetation had only been produced on a biome scale by the RADAMBRASIL project. However, this initiative did not use optical but rather radar data from 1975 to 1985 (IBGE, 2018). Due to the accelerated process of development of the Brazilian countryside in the last decades of the 20th century, RADAMBRASIL's vegetation maps no longer reflected reality (MMA, 2020). To fill this gap, in the 21st century, the Brazilian Ministry of the Environment (MMA) launched public notices to select sub-projects for mapping the vegetation cover of Brazilian biomes through the Project for the Conservation and Sustainable Use of Brazilian Biological Diversity (PROBIO). Thus, the mapping of Caatinga was carried out from September of 2004 to September of 2006, using 2002 as a reference year, and the official data were released in 2007 (MMA, 2006).

Subsequently, the Secretary of Biodiversity and Forests of the Ministry of the Environment promoted the Program for Monitoring the Deforestation of Brazilian Biomes by Satellite (PMDBBS). In March of 2011, was launched, aimed at mapping the Caatinga using all available mapping data up to 2002, and later for the period between 2002 and 2008 (MMA/IBAMA, 2011). In the following years, PMDBBS released updates of the 2009, 2010, and 2011 mapping data. It should be emphasized that the PMDBBS mapping data refer to accumulated deforestation, that is, they include deforestation prior to the mapped period. For Caatinga, this mapping showed an overall accuracy of 74%.

Shortly after the release of the first PMDBBS data, Vieira et al. (2013) developed a map of the spatial distribution of the main NEB vegetation types for later use in meteorological and climatic models. This initiative was named ProVeg-NEB and was developed within the context of the Vegetation Project (ProVeg), whose initial mapping included only the Brazilian Legal Amazon region (SESTINI et al., 2002). The methodology of this mapping was based on two stages: the correspondence between the classes of the RADAMBRASIL project, the IBGE, and the Simplified Simple Biosphere (SSiB) model (XUE et al., 1991), and land use and land cover mapping. The final map, which used 2000 as a reference year, was built from a mosaic of images from the 1999, 2000, and 2001 Landsat series. Two years later, Vieira et al. (2015) updated this map for the year 2010, which was used together with the map from 2000 to identify areas susceptible to desertification. In this update, PROBIO mapping and Google Earth images were used as auxiliary data.

In 2015, the Brazilian Land Use and Land Cover Mapping project (MapBiomas) was launched, an initiative formed by a group of universities, NGOs, and private companies that came together to generate a historical series of over 30 years of land use and land cover mapping data for all Brazilian biomes (MAPBIOMAS, 2020). Starting in 2016, MapBiomas began to launch one main collection per year, each with more improved versions of the processing methodology and covering a longer time interval. The overall accuracy of the collection 4.1 for each year of the time series (1985 - 2018) is 80% for the level 1 legend and 75% for the level 3 legend. Currently, MapBiomas is the most accurate mapping initiative made for the

Caatinga at the biome level, and also has the longest time span mapped.

More recently, the project "Environmental Monitoring of Brazilian Biomes by Satellites: Atlantic Forest, Caatinga, Pampa and Pantanal", launched with funding from the Amazon Fund, executed by the Foundation for Science, Technology and Space Applications (FUNCATE) and under the technical coordination of the National Institute for Space Research (INPE), was designed to meet the Environmental Monitoring Program of Brazilian Biomes (PMABB). For Caatinga, the project is still in the implementation phase and will eventually build a historical series of biennial deforestation maps for the period 2000 to 2012 to support the construction of a proposal for the Forest Reference Emission Level (FREL) of the biome (FUNDO AMAZÔNIA, 2020). First, the deforestation map for the year 2000 (base map) will be built, and then increment maps will be produced for each biennium, compatible with the base map. Parallel to the construction of FREL, the mapping will be generated from a set of images from the Landsat-8 satellite or similar for monitoring deforestation from 2013 to 2020, covering the entire Caatinga extension.

At the state level, studies are concentrated in Pernambuco and Bahia, with the other states still lacking initiatives to map their portions of Caatinga. In Pernambuco, the mapping project developed by Accioly et al. (2017) covered the semi-arid region of the state, including a total area of 86,135 km^2. The authors used topographic charts on a 1:100,000 scale and the classification was evaluated qualitatively through field trips. In Bahia, in 2019, the Institute for the Environment and Water Resources (INEMA) launched a mapping project for the state's vegetation cover using supervised classification and manual editing through visual interpretation of RapidEye image mosaic (CONSÓRCIO GEOBAHIA, 2018). This mapping was validated by field expeditions and 1:50,000 scale charts were used as a reference. In the end, a continuous base of the biome was elaborated respecting the framing of the chart to the millionth (1:100,000).

From a global perspective, Global Land Cover 2000 (GLC2000) was created from a partnership of the European Commission's Joint Research Centre (JRC) with a network of collaborators from around the world to produce a harmonized land cover map for the year 2000, at a spatial resolution of 1 km (BARTHOLOMÉ; BELWARD, 2005). The project's global map originally has more than 40 classes, and the South America map has 24 classes. The Global Forest Change (GFC) project is a partnership between the University of Maryland, Google, the United States Geological Survey (USGS) and the National Aeronautics and Space Administration (NASA), and was created to identify areas worldwide where tree coverage was lost (HANSEN et al., 2013). The data were produced using over 600,000 Landsat satellite images. Another project, Copernicus Global Land Services (CGLS) is a European Commission initiative in partnership with other institutions that in 2019 launched a global map using 2015 as reference year and PROBA-V images. The final accuracy of the product was around 80% (BUCHHORN et al., 2020), considered high for a map of this coverage.

Table 1 presents a summary of the main initiatives for mapping Caatinga vegetation, taking into consideration the following aspects: coverage scale (biome, state), reference, period mapped, type of satellite data used (including the sensor), technique(s) employed to produce the mapping and number of classes adopted in the legend. It is important to note that initiatives that covered more than one biome did not always make use of the same methodology for all biomes, so the information in Table 1 applies exclusively to the Caatinga.

Table 1 - Summary of the main information from the vegetation mapping initiatives that encompass the Caatinga.

(to continue next page)

Coverage	Project/Reference	Period	Optical Data	Technique	Legend
Global	**GLC2000** Eva et al. (2002)	2000	SPOT-4	ISODATA Classification	24 classes
Global	**GFC** Hansen et al. (2013)	2000 - 2019	Landsat (TM, ETM+ and OLI)	Decision Tree based Algorithm	% forest cover, gain and loss
Global	**CGLS** Buchhorn et al. (2019)	2015	PROBA-V	Random Forest	23 classes
Nationwide	**ProVeg-NEB** Vieira et al. (2013)	2000 and 2010	Landsat (TM and ETM+)	Unsupervised Classification ISOSEG	7 classes

(Conclusion)

Coverage	Project/Reference	Period	Optical Data	Technique	Legend
Nationwide (per biome)	**MapBiomas/** MapBiomas (2020)	1985 - 2018	Landsat (TM, ETM+ and OLI)	Random Forest	27 classes
Biome	**PROBIO** MMA (2006)	2002	Landsat (ETM+)	Supervised Classification	29 classes
Biome	**PMDBBS** MMA/IBAMA (2011)	2002 - 2011	Landsat (TM) and CBERS-2B	Visual Interpretation	2 classes
Biome	**PMABB** Fundo Amazônia (2020)	2000 - 2020	Landsat and similar	Visual Interpretation	2 classes
Bahia State	**INEMA** Consórcio GeoBahia (2018)	Single (2012/2014 mosaic)	RapidEye	Object-oriented Classification and Visual Interpretation	15 classes
Pernambuco State	**EMBRAPA** Accioly et al. (2017)	Single (2013/2014/2015 mosaic)	Landsat (OLI)	Fusion and Visual Interpretation	12 classes

Source: created by the authors (2020).

Data in Table 1 show the small number of existing biome or national initiatives for the Caatinga. Until March of 2011 (PMDBBS launch date for Caatinga), only PROBIO mapping was available for the biome. The PROBIO mapping represented a great advance for the Caatinga, which until then lacked vegetation cover maps produced by optical Earth observation data. Although PMDBBS used the PROBIO data as a starting point to develop its activities, the exclusive focus was on monitoring deforestation in the biome, and, therefore, the project adopted a binary legend (deforested or non-deforested area).

It is also evident in Table 1 that Landsat was the main satellite used to generate maps of the Caatinga. This practically homogeneous pattern in the selection of the sensor system can be explained by the fact that Landsat data have the largest continuous coverage of the Earth's surface when compared to other Remote Sensing data (LOVELAND; DWYER, 2012). In addition to Landsat, PMDBBS also used the High Resolution Camera (HRC) sensor images from the China-Brazil Earth-Resources Satellite (CBERS-2B) series. The way the images were acquired also varied. PROBIO and PMDBBS acquired data from INPE, whereas MapBiomas used the Google Earth Engine platform catalog (GORELICK et al., 2017) to build mosaics and process data. ProVeg-NEB, in turn, acquired 162 images from a private company to compose the Northeast Brazil mosaic (reference year 2000).

Another aspect that merits discussion is the technique used by each initiative to generate its final product. PMDBBS has adopted the procedure of identifying polygons from deforested areas, with a 2-hectare minimum mapped area determination (MMA/IBAMA, 2011). The project's analyses were done by visual interpretation and manual digitalization of the deforestation features, identified in the areas of the remaining polygons. Continuing along the same line, some studies used different resources to favor the process of visual perception. This was the case of the data generated by Accioly et al. (2017), who used image fusion through Geographic Resources Analysis Support System (GRASS) software. Image fusion is a multispectral imaging enhancement technique that results in improved spatial resolution. The fusion type used by the authors was the Intensity-Hue-Saturation (IHS), where the panchromatic band is combined with the 3 indicated bands in an RGB composition, which in this case were the Landsat-8/OLI bands 6, 5, and 4, respectively.

ProVeg-NEB used the ISOSEG unsupervised classification technique. This method examines numerous unknown pixels and divides them into a determined number of classes from image value groupings. Some initiatives also used supervised classification techniques, such as PROBIO. This type of classification requires the selection of previous samples by a user, but the official PROBIO report does not specify the classifier that was used. MapBiomas has also followed a processing logic based on supervised classification algorithms in each collection. More specifically in Collection 2, the project has generated its classifications using decision trees whose parameters were defined empirically. This means that all the metrics used as tree nodes had their values tested in order to find out which ones would result in a more reliable representation of the classes in the mappings generated for each year.

However, testing this data empirically for the entire time series takes time and may generate greater imprecision. Given this, collection 2.3 incorporated Random Forest (BREIMAN, 2001), aiming to optimize time and improve the quality of mappings. Random Forest is a machine learning classification technique that is also based on decision trees, allowing the analyst to select the samples to represent the target class as realistically as possible. After incorporating Random Forest, MapBiomas had a considerable improvement in its mapping accuracy, which justified employing the algorithm in subsequent collections.

As far as the legend is concerned, it is common to observe different class distribution levels in vegetation mapping. Based on the Caatinga initiatives, a first legend level may be associated with the nature of the area, that is, whether it presents vegetation or not. A second level usually separates the native vegetation cover from the anthropogenic vegetation, as well as individualizing urban areas, exposed soil, and water bodies. Finally, a third level creates a greater number of subclasses for the first level classes, increasing the legend detail. Generally, the greater the level of detail of the legend, the greater the demand for a more robust methodology for data processing and interpretation.

Among the mappings that used first level legends is PMDBBS, which adopted only the anthropic and natural classes to map deforestation, without identifying the land use type. The anthropic class is associated with deforested areas, while the natural class is associated with remaining vegetation. PROBIO used some criteria to identify vegetation remnants, such as the existence of anthropic traces as well as the vegetation structure. To map natural vegetation remnants, the legend was based on the same definition as the IBGE (2012). Among the characteristic Caatinga vegetation formations, there are the following classes: forest, woody, park or woody-grass steppe-savanna, and formation with fluvial and/or lacustrine arboreal, shrubby or grassy influence. The MapBiomas legend is the same for all biomes, not including Caatinga-specific classes. The classes of the project are: 1. Forest (includes forest and savanna formations, mangroves, and planted forest); 2. Natural Non-forest Formations (includes non-forest wetlands, grassland formations, outcrops, and apicum); and 3. Farming (includes pastures and agriculture). ProVeg-NEB, in turn, used seven classes in the 2000 map, expanding the legend to 19 classes in the 2010 map.

In relation to accuracy assessment strategies, the PMDBBS has adopted the global accuracy index. In summary, a stratified random sampling was made whose number of samples was calculated by a binomial function. The sample points were interpreted by the web platform developed by Adami et al. (2012) for thematic accuracy assessment within the Virtual Laboratory of Remote Sensing Time-Series (FREITAS et al., 2011). Finally, overall accuracy and commission and omission errors were calculated after the points were validated through independent interpretation.

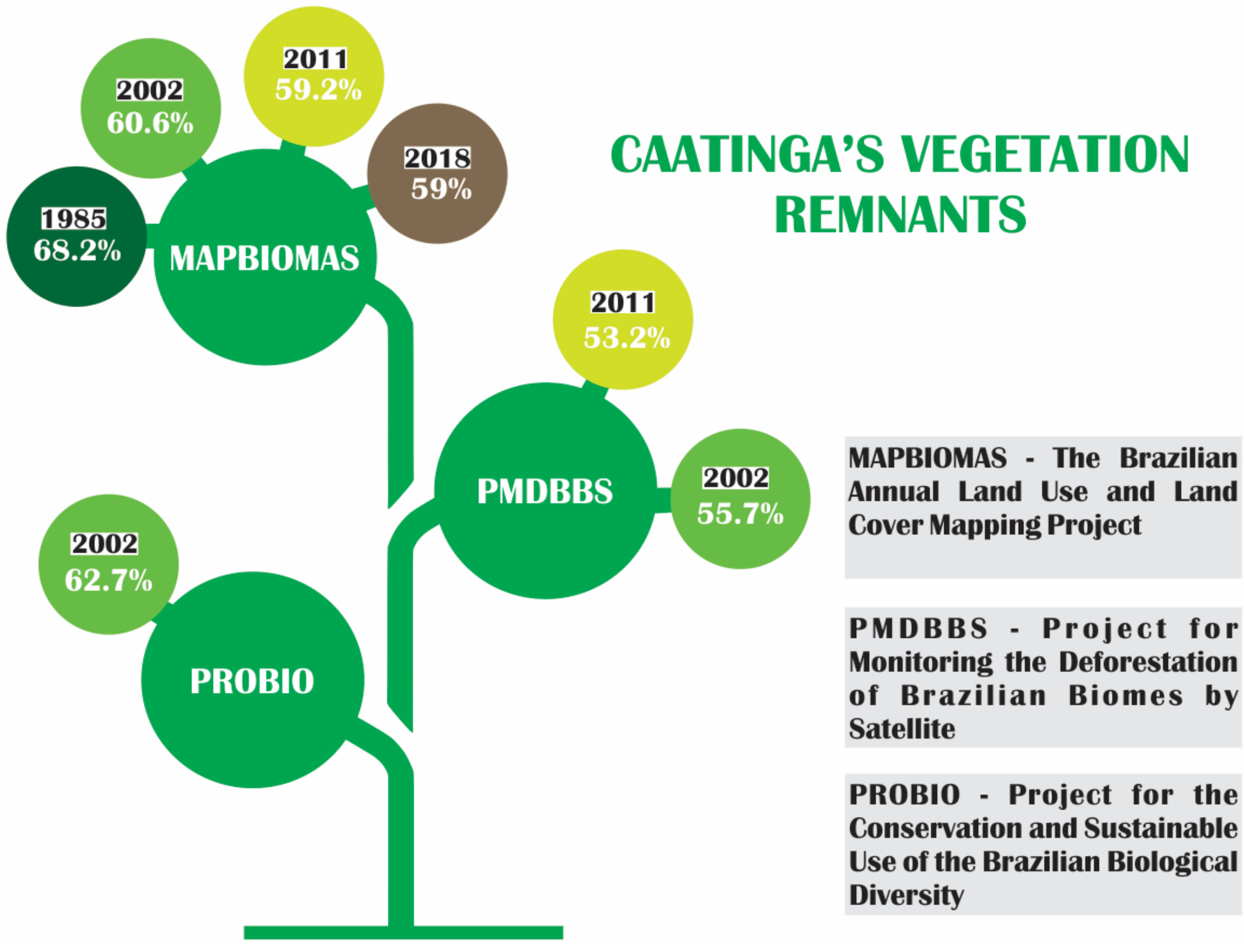
MapBiomas compared its results with existing reference maps and assessed accuracy using statistical methods and independent point sampling. For Caatinga, 9,738 points were validated for each year based on visual interpretation of Landsat pixel samples, inspected by three independent interpreters. The validation took place on the Temporal Visual Inspection (TVI) web platform, developed by the Image Processing and Geoprocessing Laboratory of the Federal University of Goiás (LAPIG/UFG), which provides access to MODIS data and time series precipitation data, as well as Google Earth images. The calculation of accuracy was based on error matrix and global, producer and user accuracy as defined by Stehman (2009), Stehman (2014), and Olofsson et al. (2014).

Most current studies that expand their analysis to very distant decades do not have reference data (field or images) to validate their products. For Caatinga, these data are even more lacking. Thus, Beuchle et al. (2015) assessed the quality of the maps they produced for the biome based on consistency assessment. This methodology assumes that measurements on a small subset performed by an independent interpreter using the same method should produce similar or more accurate results (MONK; MARCO; CERVIGÓN, 2002).

4 CAATINGA'S VEGETATION STATUS

Figure 4 shows a comparison of the percentage values of vegetation mapped by PROBIO, PMDBBS, and MapBiomas, the three initiatives that are currently the most used as a reference to discuss data or validate products from other studies. For PROBIO, 2002 is shown in the figure because it was the only reference year that the project mapped. In the case of PMDBBS, the values of the first and last year of data generated by the project (2002 and 2011) were included. For MapBiomas, in addition to the first and last year mapped as of the writing date of this article (1985 and 2018), the years 2002 and 2011 were also included for comparison with PROBIO and PMDBBS. It is important to clarify that the informed percentages consider both natural and planted vegetation.

Figure 4 - Percentages of Caatinga's vegetation remnants produced by the three main institutional initiatives that mapped the biome's vegetation.

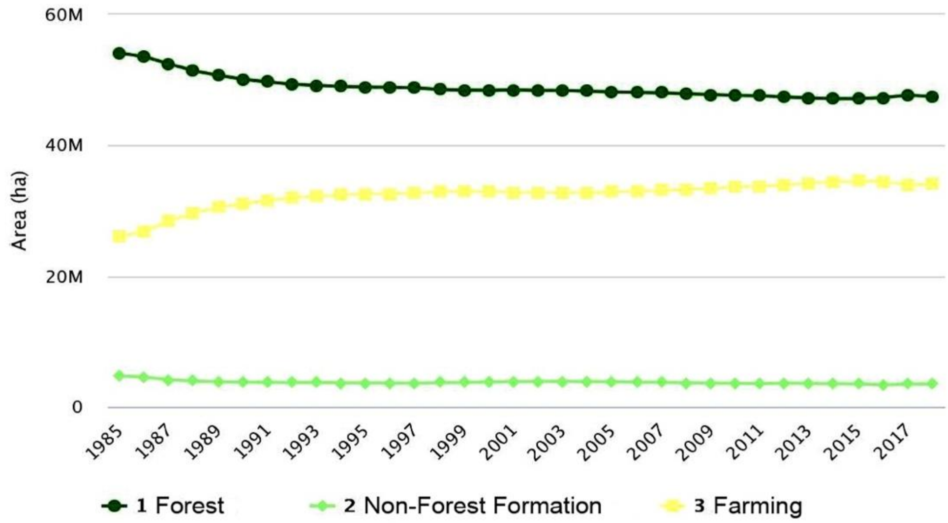


Source: created by the authors (2020).

For 2002, the percent of remnant vegetation from PMDBBS is lower than the values of MapBiomas and PROBIO by 4.9% and 7%, respectively. A similar pattern is observed for 2011, with a difference of 6% between the values of PMDBBS and MapBiomas. Comparing the percentages of the three initiatives in 2002, a greater convergence between PROBIO and MapBiomas data is noticed, with a difference of 2.1%. The PROBIO data indicate a vegetation coverage area of 518,635 km^2, which excludes the Caatinga portion of the north of the state of Minas Gerais (MMA, 2006). From this total, the native forest vegetation is equivalent to 24.39%, and the non-forest vegetation, to 38.38%. In addition, the four subclasses of steppe-savanna make up 35.9% of the remaining vegetation for the year 2002. Data from PMDBBS for the same year indicate a Caatinga vegetation coverage area equivalent to 460,327.6 km^2.

MapBiomas' forest class corresponded to 56.1% of the biome in 2002, while the non-forest formation was estimated at 4.5%. The first class includes the forest, woody, park steppe-savanna categories, while woody-grass steppe-savanna is encompassed by the non-forest formation class. Figure 5 displays MapBiomas data from 1985 through 2018 for the two vegetation classes of the project's first level legend, including farming data. As seen in the graph, the 33-year time series shows a loss of approximately 79,000 km^2 of vegetation cover (natural or not) and a corresponding increase in the farming class, with more significant changes being observed in the late 1980s and early 1990s.

Figure 5 - Temporal evolution of MapBiomas data for Caatinga's vegetation and farming classes.



Source: Adapted from MapBiomas (2020).

5 OPPORTUNITIES AND CHALLENGES FOR MAPPING CAATINGA VEGETATION

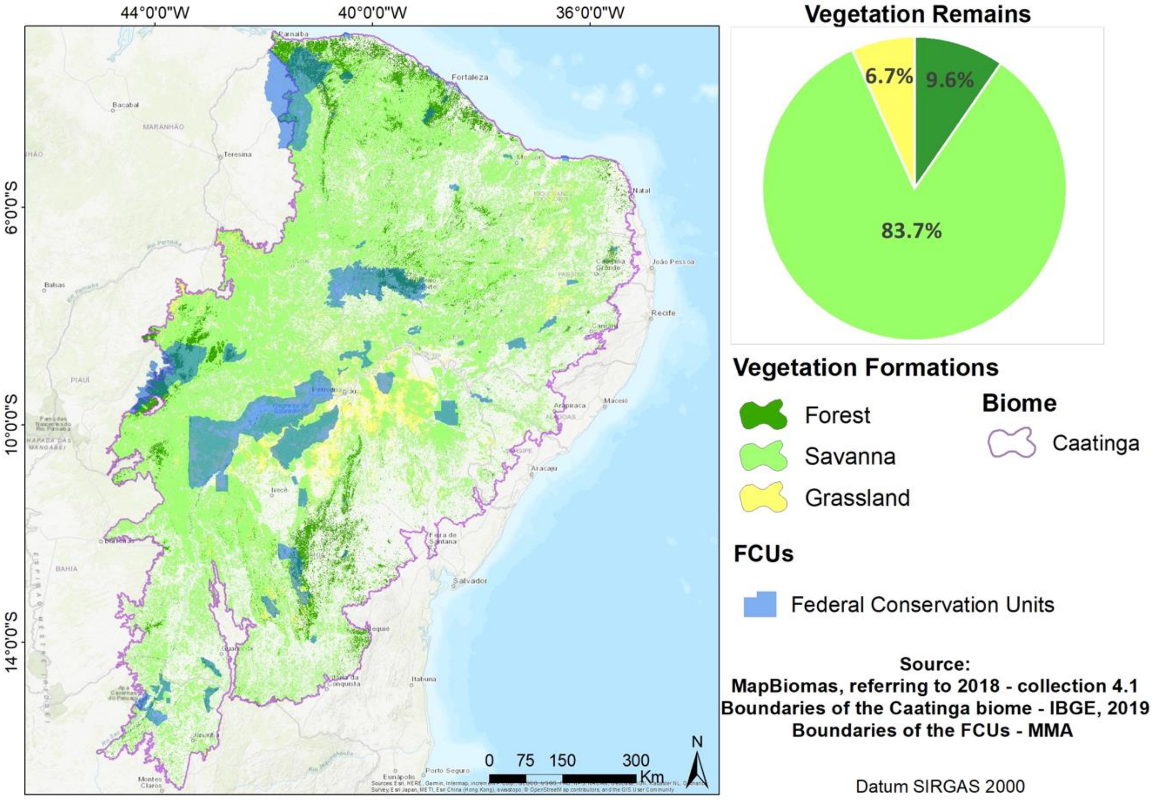
The conservation of the Caatinga biome's natural resources is an urgent matter, especially considering the influence that degradation and loss of natural habitats have on the intensification of droughts and the aggravation of climate change. There is also an intrinsic relationship between drought events and food security in the biome. The severe and recurrent droughts in the Caatinga threaten crop development and, consequently, create serious social problems (MARENGO, 2009). In addition, the occurrence of droughts represents one of the costliest environmental disasters. According to Cunha et al. (2015), the 2012/2013 drought event led to losses of the magnitude of $1.6 billion in agriculture. For this and other reasons, quantifying drought is essential to minimize economic and socio-environmental impacts.

In this context, optical Earth observation data become a valuable tool in achieving this goal. According to Wan et al. (2004), MODIS data play an important role in monitoring drought due to their high temporal resolution and easy data access. Taking advantage of MODIS, Tomasella et al. (2018) developed a mapping methodology to monitor bare soil, one of the indicators of land degradation, based on the study of NDVI behavior over 17 years. In turn, Vieira et al. (2015) identified different levels of susceptibility to desertification in NEB based on the influence of 11 factors (e.g., geology, land use and land cover change, population density), which were simulated for the years 2000 and 2010. This study, which is part of the Early Warning System for Droughts and Desertification (SAP) project developed at INPE, indicated that 94% of NEB varies from moderate to high susceptibility to desertification. This study also found that the number of areas susceptible to desertification increased by 4.6% (83.4 km^2) over the 10 years and that most of these areas are in the Caatinga.

Regarding institutional initiatives and their role in mitigating the effects of droughts, projects such as MapBiomas help to combat desertification in Caatinga by continuously monitoring land use and land cover changes, which enables enforcement and prevents more damaging environmental disasters. One promising output of the project in this sense was the creation of a system for monitoring degraded areas and intervention areas in NEB, MapBiomas Áridas (2020). This MMA initiative, funded by the Global Environmental Facility (GEF) and the United Nations Development Programme (UNDP), aims to generate diagnoses to define governmental goals that corroborate with the strategy of land degradation neutrality.

On the monitoring of vegetation remnants, the absence of regulatory legislation, economic instruments, public policies, and opportunities for Caatinga biodiversity conservation had already been described by Leal et al. (2005) as obstacles to implementing conservation strategies 15 years ago. In addition, the role of vegetation as an indicator of the conservation status of biota is important to define the presence or absence of species habitats, the maintenance of environmental services, or even the provision of essential resources to ensure the survival of the population. Leal et al. (2003) also warned about the difficulty of finding native vegetation remnants larger than 100 km^2 in Caatinga. Additionally, out of 62.7% of the vegetation mapped by PROBIO for 2002, 40.5% corresponds to the most conserved remnants. However, the creation and implementation of Conservation Units (CUs) in Caatinga remains an ongoing challenge. The map in Figure 6 shows the percentages of vegetation remnants mapped by MapBiomas, as well as the federal CUs of Caatinga considering IBGE (2019) limits.

Figure 6 - Map of the 2018 Caatinga's vegetation remnants and location of the biome's Conservation Units.



Source: created by the authors (2020).

The biome has about 5% of its area occupied by 27 federal CUs (ICMBio, 2019), most of which are located in Ceará and Bahia, respectively. Of the remaining, Pernambuco, Piauí, and Rio Grande do Norte each have three federal CUs in their Caatinga portions, whereas Paraíba has none. Out of the 5%, a little more than 1% corresponds to CUs of integral protection, and there are still only 12 Private Natural Heritage Reserves (RPPN) at the federal level in the biome. The map also reveals that there are few CUs created in the Caatinga forest and grassland formations, which represent, respectively, 9.6% and 6.7% of the remaining vegetation, according to the 2018 MapBiomas data.

The establishment of CUs is an alternative to contain habitat fragmentation. Leal et al. (2005) pointed out aspects that also contributed to the implementation of a large-scale conservation agenda in the Caatinga, such as population density in various parts of the biome and the modification of remaining habitats, coupled with a long history of poverty and drought. Reforestation initiatives are rare in Caatinga and recovering its native vegetation is still a great challenge, mainly because vegetation cover can take several decades to reestablish naturally (PEREIRA et al., 2003).

To assess deforestation, regeneration, or reforestation processes in semi-arid areas, optical Earth observation data are limited by the high space-time variability of vegetation. According to Mayes, Mustard, and Melillo (2015), this limitation is due to the complex regional ecology of vegetation combined with factors such as land-use practices and disturbance regimes. Tomasella et al. (2018) also stated that the wide variety of trees, shrubs, and pastureland irregularly distributed in the biome, coupled with their high level of fragmentation, diversifies spectral responses in these landscapes.

From the spectral point of view, bands that comprise red and near-infrared ranges are sensitive to the intensity of green vegetation (CURRAN, 1989). That is why most of the vegetation indexes were developed based on red and near-infrared reflectance – EVI and NDVI, among others. However, vegetation indices developed for multispectral data are difficult to relate to the non-photosynthetic fraction of vegetation and the task is even more challenging when there is an attempt to differentiate it from exposed soil.

In literature, some studies have sought alternatives to fill this gap. Nagler, Daughtry, and Goward (2000) created the Cellulose Absorption Index (CAI) and successfully differentiated soils from the non-photosynthetic vegetation fraction. Asner and Heidebrecht (2002) also demonstrated that the shortwave infrared (SWIR) range was very effective in achieving this goal. However, these studies were conducted on high spectral resolution images, which are unfeasible for large-scale applications due to their high acquisition cost and unavailability in certain areas.

Phenological behavior in semi-arid environments should also be highlighted in this discussion. In this regard, recent studies have explored new alternatives in Landsat images. Silveira et al. (2019) have developed an object-based change detection method to mitigate the effects of phenology on deforestation and fires in seasonally dry tropical forests. Miranda et al. (2020) developed and evaluated models based on the Plant Area Index (PAI) and Leaf Area Index (LAI) from field measurements. According to Albuquerque, Lima, and Araújo (2012), phenological data need to be collected for the various types of Caatinga vegetation given the high degree of anthropogenic disturbance, reduced water availability, and greater sensitivity of the biome to climate change. Therefore, evaluating methods to reschedule phenological data will promote advances in the real influence of phenology on the responses of seasonally dry tropical forests to environmental variables.

A very promising approach developed over the last decade for phenological studies is the near-surface Remote Sensing, which is based on the repetition of high-frequency digital photography - the so-called Phenocams (RICHARDSON et al., 2009; SONNENTAG et al., 2012). This method consists of the installation of digital cameras close to the Earth's surface in order to monitor changes in vegetation at the ecosystem scale (ALBERTON et al., 2019). Alberton et al. (2017) provided further details on this approach and highlighted some advantages of this methodology - data can be recorded daily or hourly, with a considerable decrease in time spent on fieldwork. In Brazil, the first and only study developed in the Caatinga using this approach was carried out by Alberton et al. (2019), where the authors compared phenological variations with the Cerrado and observed that in the Caatinga, the effects of rainfall are greater on vegetation, reinforcing what was already pointed out in section 2.2.

Especially in the last decade, sensors have been put into orbit and opened opportunities for new studies. They not only have unique characteristics but also present associated advantages and disadvantages. For example, PROBA-V, launched in 2013 as a continuation of SPOT, produces data every two days with a spatial resolution of 300 meters, and every 5 days at nadir with a resolution of 100 meters (STERCKX et al., 2014). Its images are available in surface reflectance and have been used to map areas on a national and global level. Offering a better spatial resolution (10 and 20 meters), the MultiSpectral Instrument (MSI) sensor images of Sentinel-2A and Sentinel 2B satellites together provide images at a time interval of approximately 4 days (DRUSCH et al., 2012).

In the scope of image processing, Google Earth Engine (GEE) should be highlighted for its ability to process data in the cloud, being one of the great advantages of the MapBiomas methodology. The advent of GEE significantly reduced processing time and optimized image preparation and analysis routines. Currently, the platform has been used for studies in different fields of knowledge. Recent applications that can be reproduced in the Caatinga include phenology monitoring (QI et al., 2020), seasonal indicators for extreme drought events (LAI et al., 2020), and land cover change detection (SIDHU; PEBESMA; CAMERA, 2018).

To collect data for mapping validation, the Geo-Wiki platform has a high potential. The Copernicus Global Land Cover Services (C-GLOPS) project has been very successful in using this platform to calculate the accuracy of its global mappings. In addition to the graphical interface, Geo-Wiki provides high-resolution images that can be combined with spectral index information calculated in Sentinel-2 and PROBA-V images to assist interpreters in decision making. Another positive aspect of the platform is the connectivity with Google Earth.

Finally, an innovative national project that will allow scientists and users to produce information on land cover changes in the Brazilian biomes is the Brazil Data Cube, a platform for analysis and visualization of large volumes of geospatial data that is in development as of January 2019 by INPE (2019). The main objective of this project is to create multidimensional data cubes ready for analysis using machine learning and time series analysis of medium spatial resolution Earth observation satellites, such as Landsat (period from 1974 to 1984) and CBERS. These data will be of extreme importance for Caatinga because they will produce information that precedes 1985, the oldest period mapped until then (by MapBiomas) using optical Earth observation data.

With regard to the development of future research for mapping the biome vegetation and its direct implications for the economy and society, several relevant questions merit further investigation. In the scope of optical data, some future challenges for Caatinga vegetation mapping include the development and evaluation of new methods for detection, classification, and filtering of clouds and their respective shadows. Therefore, how can researchers investigate which uncertainties in mapping the biome vegetation are associated with the presence of cumulus clouds and their respective shadows? The presence of cumulus clouds is very common along the entire northern coastal strip of Caatinga. Then, the regional and morphological location of clouds and shadows may not allow or add errors to the vegetation mapping, especially when the objective is to study their intra-annual and spatial variability in terms of phenology (DUTRA et al., 2020).

From a phenological perspective, what strategy should be adopted for the maintenance and expansion of field observation networks to better represent the space-time heterogeneity of Caatinga vegetation? How can these data help in the development of algorithms and methodologies adjusted specifically for semiarid regions, or even, in the assessment of new products and sensors? How can remote sensing optical data assist decision-makers in trying to mitigate the impacts of drought on vegetation in semi-arid environments and, consequently, on the population that depends directly or indirectly on these ecosystems? An alternative would be the development of sensors capable of detecting and monitoring diurnal variations in water use, moisture stress, and photosynthesis in these ecosystems, which is not detectable by the low temporal resolution sensors available today.

Regarding the numerical models of time and climate, it is necessary to parameterize the processes related to the Earth's surface that are strongly correlated with the type of vegetation, land use, and land cover. Among these parameters, surface albedo, evapotranspiration, and aerodynamic surface roughness stand out. In this context, detailed inter- and intra-annual mapping of Caatinga vegetation may bring new perspectives and opportunities for research aimed at understanding the impacts of climate change on semiarid ecosystems and the degree of resilience of local vegetation. In addition, weather and climate research can also be related to the estimates and uncertainties of wind and solar resources. Therefore, how can researchers relate the various aspects of vegetation with renewable energy and weather and climate simulations?

NEB is recognized as the region with the greatest potential for renewable energy generation in Brazil, mainly from solar and wind sources. In this context, detailed vegetation mapping is fundamental both for defining new Conservation Units, assessing environmental impacts of existing or planned projects, and assessing the wind and solar resources in areas of interest for the installation of new projects.

Another challenging question is: how can researchers develop methodologies that consider local geomorphological aspects for the characterization and quantification of this type of vegetation and its fragmentation throughout the biome? At the local mapping scale, geomorphological and topographic aspects, especially in regions of complex terrain such as mountains, scarps, and plateau borders, can make it difficult to map and identify vegetation due to the relief shadows and phenological characteristics of the vegetation.

Finally, how can researchers produce data that meet the demands of public policymakers for the sustainable management of the Caatinga in different government spheres? Certainly, this is one of the greatest challenges, since it requires incentives in technological, computational, and analytical development, in addition to expanding the participation of managers in the planning and production phases of this data.

6 CONCLUSIONS

The mapping of Caatinga vegetation using optical Earth observation data began as a very late and delayed process. Considering that more than 70% of the initiatives that have mapped the biome to date have used one or more sensors from the Landsat series and that the series' first satellite was sent into orbit in the 1970s, it is undeniable that the biome has been neglected for decades. The launching of the first effective data on the Caatinga vegetation in 2002 (PROBIO) proves this since it occurred three decades after the launching of the first Landsat satellite.

Among all initiatives presented, MapBiomas stands out for benefiting from all the attributes of the Landsat system, including the more than 30 years of available data. In addition, it is the only ongoing initiative that covers the entire Brazilian territory and is also the only one to produce the largest dataset of land use and land cover for the Caatinga. This represents a great advancement for knowledge, as it stimulates the emergence of new initiatives and provides more consistent subsidies for the planning and execution of public policies.

One strategy to improve the diffusion of knowledge about Caatinga vegetation, for example, is to invest in mapping initiatives at the state level. Among the states within the boundaries of the biome, only Bahia and Pernambuco have reference mappings. Therefore, multiplying the incentives to produce reference maps in other states would not only make territorial management more effective at the local level but also to strengthen biome or national scale mapping, since there would be new alternatives to compare and validate these products.

The partnership with universities and research institutes of NEB and the expansion of the data-sharing networks between institutions also proves to be a mutually beneficial solution, especially because these institutions were responsible for a majority of studies on the Caatinga, as highlighted by the WoS statistics. This fact alone reinforces the importance of creating opportunities to fund local research groups, and undergraduate and graduate programs, especially given that this is a historically less privileged region.

Despite the studies and initiatives identified in this work, it must be stressed that much still needs to be investigated about Caatinga vegetation in the scope of optical Earth observation data. Mapping land use and land cover changes in the biome is critical to developing new methodologies to estimate carbon stocks and calculate the extent of landscape fragmentation. Furthermore, these mappings allow for the creation of new metrics to assess the impact of land cover change dynamics on climate change, desertification, and even human health. Thus, combining robust mapping techniques with validation strategies that increase the accuracy of these products can not only ensure food security for the population but also subsidize public policies in favor of a more sustainable management of the Caatinga.

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Authors' Contribution

The research was conceptualized by Khalil Ganem/Andeise Dutra and designed by Khalil Ganem. Figures 1 and 6 were prepared by Marceli Terra. The text was written by Khalil Ganem and had the collaboration of Andeise Dutra, Marceli Terra, Ramon Freitas, Rosana Grecchi, and Rita Vieira. The manuscript was revised and edited by Egidio Arai, Fabrício Brito, Claudia Sampaio, Valdete Duarte, and Yosio Shimabukuro.

Conflicts of Interest

The authors declare no conflicts of interest.

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