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Spatio-temporal analysis of dynamics and future scenarios of anthropic pressure on biomes in Brazil

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ABSTRACT

Anthropogenic transformations, which have become intensified by land use and land cover changes and industrialization, have contributed to increased anthropogenic pressure on biodiversity. These disturbances contribute toward fragmentating habitats at different scales and putting species at risk, in addition to compromising the main biogeochemical cycles. To better understand the spatiotemporal dynamics of anthropogenic pressure on Brazilian biomes, this study sought to develop a composite index to identify and analyze the degree and distribution of anthropogenic-based pressure on biodiversity, and identify internally homogeneous and heterogeneous regions regarding the dynamics of this pressure in different scenarios. To that end, we carried out an analysis of the impact of select anthropogenic factors. Specifically, we analyzed future scenarios involving land use and land cover changes in line with the global structure Shared Socio-Economic Pathways (SSPs) and Representative Concentration Pathways (RCPs), according to the narratives SSP1/RCP 1.9, SSP2/ RCP 4.5 and SSP3/RCP 7.0. We used cluster and spatial analyses to determine the spatial dynamics of the index and, consequently, the regions most susceptible to anthropogenic pressure. The results demonstrate intensified pressure on biodiversity in areas that have already been subject to a considerable degree of disturbances, especially the Cerrado, Caatinga, and Atlantic Forest biomes. In all scenarios, the region with the highest average pressure index, i.e., Region 4, which has an average pressure index of 0.57, corresponds to 30% of Brazilian territory. This method made it possible to determine the level of pressure in each region and, subsequently, identify the regions that have been most affected by human actions in an effort to guide priority actions and local policies. However, it should be noted that this approach should be complemented with additional information, such as soil erosion, field recognition, and socioeconomic information.

1. Introduction

Over the last few decades, human induced transformations to the terrestrial biosphere, which have mainly been driven by intensified land use and increased industrialization over the 20th century, have become more pronounced and worrysome (Ellis et al., 2013, 2010; Lautenbach et al., 2011; Ostberg et al., 2015; Souza et al., 2020; Vitousek et al., 1997; Walther, 2010). These anthropogenic disturbance have led to biodiversity transformations on local, regional, and global scales (Arnan et al., 2018; de Chazal and Rounsevell, 2009; Ellis et al., 2013; Fahrig, 2003; Fischer and Lindenmayer, 2007; Newbold et al., 2015; Sala et al., 2000; Tittensor et al., 2014). Whether through farming, forestry, industrialization, and/or urbanization, these disruptions alter fundamental biogeochemical cycles and contribute toward either adding or removing genetically distinct species and populations to or from habitats in most terrestrial ecosystems, thus jeopardizing the sustainability of ecological processes and the supply of goods and ecosystem services (Arnan et al., 2018; Cardinale et al., 2012; Mitchell et al., 2015; Vitousek

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et al., 1997).

Climate change associated changes to land use and land cover can be considered the main drivers of changes to natural ecosystems and, consequently, to biodiversity (de Chazal and Rounsevell, 2009; Hansen et al., 2001; Ostberg et al., 2015; Sala et al., 2000; Srinivasan and Wilcove, 2021; Travis, 2003). For example, according to Hansen (Hansen et al., 2001), land use can modify the climatic impacts on species distribution and, thereby, alter dispersal routes and create barriers that facilitate the dispersal of exotic species to the detriment of native species. Furthermore, these changes can both impact biodiversity at the species and community levels, and biomes, and can lead to dramatic changes in the type of biome, such as the replacement of forests by shrubs or pastures (Hansen et al., 2001). In the short term, the main threats to biodiversity from human activities include the loss and fragmentation od habitats (Clark and Covey, 2012; IPBES, 2019; Jacobson et al., 2019; Laurance et al., 2002; Newbold et al., 2015; Ribeiro-Neto et al., 2016; Tittensor et al., 2014; WWF, 2020). According to global assessments, the number of species at risk of becoming extinct has been increasing and species population sizes have been declining (Newbold et al., 2015; Pimm et al., 2014; Tittensor et al., 2014).

This context risks aggravating further by 2050 considering projected population growth and the subsequent increased demand for food (FAO, 2017; Godfray et al., 2010; Molotoks et al., 2021; Tilman et al., 2011; UN, 2019), animal feed, fuel, and fiber, met by either intensifying existing land or expanding plantation areas (Foley et al., 2011; Johnson et al., 2014; Ostberg et al., 2015; Tilman et al., 2011). To date, it is not fully known whether environmental impacts from increased deforestation and intensified land use to meet consumption demands and potential compensation schemes (Godfray et al., 2010; Tilman et al., 2011) can generate even greater impacts on terrestrial ecosystems.

Assessing the impacts of land use change on ecosystems is essential (Cui et al., 2021; Mao et al., 2019). Previous studies have been heading in this direction, for example, by assessing spatial–temporal variability (Pang et al., 2017). For Chazal and Rounsevell (de Chazal and Rounsevell, 2009), quantifying and predicting the effects of this anthropogenic pressure are urgently needed to guide efforts to conserve and manage ecological resources. However, given the complexity of this issue, in addition to classical change vectors, future studies must address changes to land use and land cover and climate change in a dynamic way. Quantifying these disturbances on a macrogeographic scale is both monetarily and temporally costly. Thus, indices that integrate different factors are needed (Antongiovanni et al., 2020; Arnan et al., 2018; Martorell and Peters, 2005). This article presents a comparative analysis between six biomes, each with with unique characteristics, and has the following objectives: i) to develop an index to establish the level and distribution of anthropogenic pressure on biodiversity in Brazilian territories; ii) to analyze the dynamics of anthropogenic pressure on biodiversity based on future land use and land cover change scenarios; and iii) to identify internally homogeneous and heterogeneous regions with respect to the dynamics of this pressure in different scenarios.

2. Material and methods

2.1. Selection of factors and data sources

To establish a metric to compare and rank areas according to either greater or lesser anthropogenic pressure on their biomes, a composite index that is capable of identifying and mapping the distribution of this pressure was developed to use as a proxy for anthropogenic impacts on the diverse biomes in Brazil. This index integrates and synthesizes the different dimensions of a given aspect, thus providing a basis of comparison between the units of analysis. Thus, the index can be considered a simplified representation that seeks to summarize multidimensional aspects in a dimensionless index, based on a given conceptual model.

The criteria adopted to choose the factors used in this study included: **a)** the relevance of the variable to the study topic; **b)** the importance of the variable in the context of biodiversity conservation; **c)** clarity and objectivity; **d)** technical and academic recognition; **e)** technical measurement possibilities; **f)** availability and collection of data for the unit of analysis, and **g)** reliability of available data (Nardo et al., 2008; Nothacker et al., 2021; Schang et al., 2021). In this study, a decision was made to work with a smaller unit of analysis, as it is more accurately able to identify the heterogeneity of anthropogenic pressure, thus permitting a better spatial demonstration of the situation with respect to the pressure that the analyzed areas are submitted. Table 1 presents the factors that were used to compose the index.

2.2. Data treatment: Methods and analyses

The methodological sequence used to obtain and treat the above information is detailed below.

2.2.1. Unit of analysis: Cellular space

Cellular space corresponds to a generalized matrix structure where each cell is related to different attributes (Fig. 1). The use of cell space allowed us to homogenize the factors described above, regardless of their original format (vector, matrix data, etc.), and aggregate them in the same space–time base. Cellular spaces were created with the ***FillCell plugin*** (Aguiar et al., 2008), through operators (e.g. Percentage of each class, minimum distance, etc.) used according to the geometric representation and semantics of the data attribute inputs. The spatial resolution of the cellular spaced used is 10 km × 10 km and was generated from the Brazil landmass polygon.

2.2.2. Obtaining and manipulating factors

a) Percentage of land use and land cover: current and future.

To integrate the land use and land cover classes, the ***"coverage"*** function was used This made it possible to establish the percentage of each class present in a single unit of analysis. The relationship between this factor and the pressure on biomes was found to be inversely proportional when natural classes were considered (Forest vegetation and Grassland vegetation) and directly proportional when anthropic uses were compared (Agriculture, Pasture, Mosaic, and Forestry). This is mainly due to the excessive use of natural resources in these activities.

b) Distance to main rivers.

The distance to the main rivers was calculated using the ***"distance"*** function, which calculates the minimum Euclidean distance between the nearest river and the centroid of the cell. Given that occupations mostly occur near watercourses, an assumption was made that the closer the occupation to a watercourse, the greater the pressure on the surrounding natural landscape, thus establishing a direct relationship.

c) Percentage of protected areas.

Both protected areas and natural vegetation areas play a fundamental role in maintaining ecosystems. Thus, the ***"area"*** function calculates the percentage values of the cell areas that are occupied by any of the protected areas considered (strictly protected conservation units, indigenous lands, and military areas). In this case, cells with higher percentages coveraged by protected areas face lower anthropogenic pressure, thus characterizing an inversely proportional relationship.

d) Proportion of agricultural establishments.

The agrarian structure directly contributes toward land use and land cover change dynamics, i.e., it is an important agent of transformation to the landscape. To understand the role that the size of these agricultural establishments plays in land use and land cover dynamics, the establishments were stratified into three groups: i) agricultural establishments of less than 10 ha, which were considered to be related to family farming; ii) agricultural establishments of between 10 ha and 100 ha; and iii) agricultural establishments with 100 ha or more. It should be noted that these strata cannot be classified as small, medium, and large farms given that the value of the fiscal module varies by region of the country. Considering that farming is an anthropic factor, it was considered that the greater the percentage of area occupied by

Table 1
Spatial factors used to determine anthropogenic pressure on biomes.

Factors		Description	Source
Land use and land cover present	Forest vegetation	Areas occupied by forests, including Dense Forests (forest structures with continuous top cover), Open Forests (forest structures with different degrees of top cover discontinuity, according to their type, including vine, bamboo, palm, or sororoca), Seasonal Forests (forest structures that suffer leaf loss from the upper strata during the unfavorable season - dry and cold), and Mixed Rain Forests (forest structures that comprise the natural distribution area of Araucaria angustifolia, a striking element in the upper strata, which generally forms a continued cover). Moreover, this factor also includes Savannah Forests, Campinarana Forests, Campinarana Arborizada Forests, and Mangrove Forests. Finally, this factor also includes humid areas, corresponding to natural herbaceous vegetation types that are either permanently or periodically flooded with fresh or brackish water (estuaries, swamps, etc.), such as ponds, swamps, and humid fields, among others.	(IBGE, 2015)
	Grassland vegetation	Areas occupied by grassland vegetation that is subject to grazing and other low-intensity anthropic interferences.	(IBGE, 2015)
	Agriculture	Areas occupied by temporary and/or permanent crops, whether irrigated or not, with land used to produce food, fiber and agribusiness commodities. These areas include all cultivated lands, whether planted or at rest, including cultivated wetlands. These areas can be represented by heterogeneous agricultural zones or extensive plantation areas.	(IBGE, 2015)
	Planted pasture	These areas are predominantly occupied by cultivated herbaceous vegetation, and are used for cattle grazing. They are formed by perennial forage plantations, and are subject to high-intensity anthropic interferences, such as land clearing (unblocking and cutting), liming, and fertilizing.	(IBGE, 2015)
	Mosaic of occupation	Mosaic of small-scale agricultural activities and remnants of natural vegetation (e.g., subsistence agriculture).	(IBGE, 2015)
	Forestry	Forests planted and managed with exotic species (e.g., eucalyptus, pine, etc.).	(IBGE, 2015)
Land use and land cover future	Forest vegetation Grassland vegetation Agriculture Planted pasture Mosaic of occupation Forestry	Land use and land cover data projections for 2050 from land use and land cover change scenarios generated by the Land Use and Coverage Model of Brazil - LuccME Brasil, developed by the Impacts, Adaptation and Vulnerabilities Division (DIIAV) of the National Institute for Space Research (INPE).	(Bezerra et al., 2021a, 2021b)
Rivers		The hydrographic distribution in Brazil.	(BRASIL, 2014)
Protected areas		Protected areas include strict protection conservation units, indigenous lands, and military areas.	(BRASIL, 2020)
Agricultural establishments (AE)		Area of agricultural establishments, categorized into three sizes: AE with less than 10 ha, AE with 10 to less than 100 ha, and AE with 100 ha or more.	(IBGE, 2006)
Highways (present)		Federal and state highways in use in Brazil.	(DNIT, 2020)
Highways (future)		Federal and state highways in use in Brazil, including planned highways.	(DNIT, 2020)
Hydroelectric		Hydroelectric power plants in operation.	(ANEEL, 2020)

agricultural establishments, the greater the pressure.

e) Distance to highways and hydroelectric plants.

The analysis of these factors sought to develop a better understanding of how infrastructure, and infrastructural expansion, impact ecosystems. In this case, a shorter distance to infrastructure (e.g. highways) was considered to indicate greater pressure on the surrounding biomes.

Table 2 briefly describes the procedures used to obtain factors and their relationship with the proposed index.

2.3. Scenario assumptions

The land use and land cover scenarios for 2050 adopted in this study come from Bezerra et al. (Bezerra et al., 2021a, 2021b). The regionalized scenarios were built based on global scenarios derived from the Integrated Model to Assess the Global Environment (IMAGE) (van Vuuren et al., 2017), to enable demand projections for different land uses in Brazil. To that end, scenarios were developed based on two main scenarios: **a)** the extent of climate change, represented by representative concentration pathways – RCPs (van Vuuren et al., 2011); and **b)** possible future socioeconomic conditions, described by the Shared Socioeconomic Pathways – SSPs (O'Neill et al., 2017). Fig. 2 shows the integration/translation structure of different information and scales to generate these scenarios.

To examine the anthropogenic pressure from different types of land uses and land cover, three scenarios were considered: a) the sustainable development scenario (SSP1), combined with a rigorous climate policy (RCP 1.9), which considers actions in the socioeconomic, institutional, and environmental dimensions that aim to establish a more sustainable world; b) the middle of the road developments scenario (SSP2 and RCP 4.5), which combines assumptions from the two extremes scenarios, for example, that both forest code restoration (RLs and APPs) and conservation measures are applied and encouraged, yet infrastructure projects, such as road paving and road construction, are also consolidated; and c) the strong inequality scenario, which associates SSP3 with RCP 7.0 and, in addition to being pessimistic and undesirable, develops in a context in which natural resources are under great pressure and may become exhausted due to a reduction of currently protected areas, in addition to increasing inequality.

2.4. Calculation of the anthropogenic pressure index on biomes (APIB)

The Brazilian territory is composed of six terrestrial biomes: the Amazon, the Caatinga, the Cerrado, the Atlantic Forest, the Pampa, and

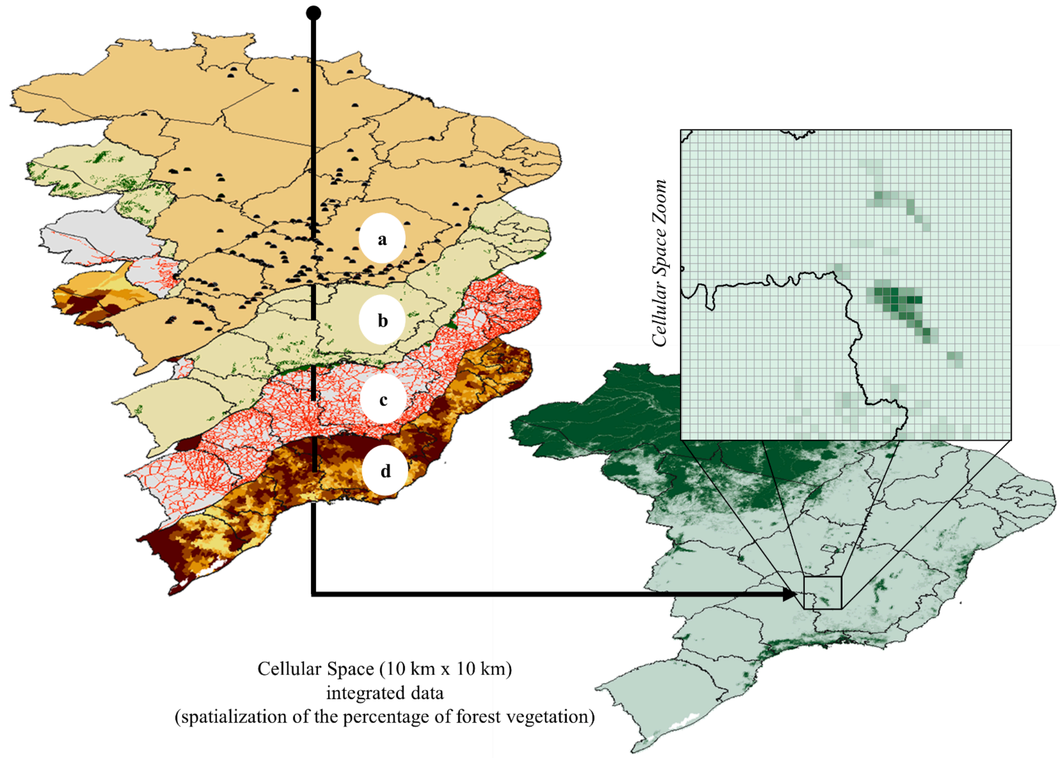

Fig. 1. Integration of factors into cell space. a) Hydroelectric power plants, b) Protected areas, c) Federal and state highways, and d) Large agricultural establishments (Bezerra et al., 2021a).

the Pantanal (MMA, 2020). Table 3 shows the main characteristics of each of these biome.

The main objective of calculating the Anthropogenic Pressure Index on Biomes (APIB) was to identify the regions that are most susceptible to anthropogenic pressures that are generic to the species. Thus, the APIB calculation was developed in two steps: a) first, the selected factors were normalized, and then b) the indicator was calculated.

The normalization of variables permits that they be compared and aggregated, and that a hierarchy be established as the variables assume values that range between 0 and 1 (Jha and Gundimeda, 2019; Lima et al., 2009; Moreira et al., 2021) to represent the best and worst scenarios, respectively, according to aspects related to biodiversity pressure. This was estimated using the below equation:.

$$IP_{ji} = \frac{I_{ji}\text{-}I_{jr}}{I_{jm}\text{-}I_{jr}} \tag{1}$$

Where $\mathbf{IP}_{ji}$ = the normalized value of the *j* factor in the i^{th} cell; $\mathbf{I}_{ji}$ = the value of the *j* factor in the i^{th} cell; $\mathbf{I}_{jr}$ = the value of *j* factor in the worst-situated cell; and $\mathbf{I}_{jm}$ = the value of *j* factor in the best positioned cell.

To calculate the Anthropogenic Pressure Index on Biomes (APIB), the arithmetic mean of the selected factors was used:.

$$APIB_i = \frac{1}{m}\sum_{j=1}^{n} IP_{ji} \tag{2}$$

Where $\mathbf{APIB_i}$ = Anthropogenic Pressure Index on Biomes in cell i^{th}; $\boldsymbol{i}$ = the analyzed cells = (1,…, m); and $\boldsymbol{j}$ = the analyzed factors = (1,…, n).

The percentage contribution of each factor to the Anthropogenic Pressure Index on Biomes was calculated according to equation (3):.

$$C_{ji} = \frac{1}{n}\left(\frac{APIB_{ji}}{APIB_i}\right).100 \tag{3}$$

Where **C*ji*** is the percentage contribution of factor j^{th} in the Anthropogenic Pressure Index on Biomes.

2.5. *Spatial analysis of the anthropogenic pressure index on biomes (APIB)*

2.5.1. *Clusters analysis*

The cluster analysis aimed to identify and segment the observations by dividing them into groups that wre internally homogeneous, yet heterogeneous among them, i.e., based on their similarities or differences. For the cluster analysis, the APIB values in each cell for the periods 2000, 2014, and 2050 were considered for each scenario. Clusters were determined using the k-means method (non-hierarchical grouping), given that this method is more suitable when working with a large set of observations (Fávero et al., 2009; Maroco, 2003). In the present study, 87,283 cells were considered. The number of clusters was determined by analysing the Anova one-way coefficient of determination (R^2) value, which was obtained by calculating the ratio of the sum of squares between the groups and the sum of all squares for each of the variables used in the analysis (Maroco, 2003).

2.5.2. *Analysis of the IPAB change spatial relationship*

To analyze the spatial dynamics of the APIB and test the hypothesis that the spatial dependence has been influencing the dynamics of change in the distribution of anthropogenic pressure on biodiversity over the years, and to verify whether this pressure distribution occurs randomly or follows some systematic spatial pattern, we carried out a spatial autocorrelation test. To do so, we used the spatial autocorrelation statistic through Moran's global spatial association index (I), which provides an overall mean of the spatial association, and the Local Spatial Association Index (LISA) (Anselin, 1995), the latter of which identifies similar groupings (clusters) and outliers.

The Moran's index (I) was calculated using equation (4) (Câmara et al., 2004):.

$$I^{(k)} = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}^{(k)}(z_i\text{-}\overline{z})(z_j\text{-}\overline{z})}{\sum_{i=1}^{n}(z_i\text{-}\overline{z})^2} \tag{4}$$

Table 2
Metrics used to prepare spatial factors that determine the level of anthropogenic pressure on biomes and their relationship.

Factor	Operation	Description of the operation	Relationship to the index	
Land use and land cover (forest vegetation, grassland vegetation, planted pasture, agriculture, mosaic of occupation, and forestry)	*coverage*	Total percentage occupied and/or overlapped by each cell usage class.	% Forest vegetation	↘
			% Grassland vegetation	↘
			% Agriculture	↗
			% Planted pasture	↗
			% Mosaic of occupation	↗
			% Forestry	↗
Rivers	*distance*	Minimum Euclidean distance from the river course closest to the cell's centroid.	Distance	↘
Protected areas (PA)	*area*	Percentage of the cell occupied and/or overlapped by protected areas. Only protected areas were selected.	% PA	↘
Agricultural establishments (AE)	*area*	Total percentage of the cell occupied and/or overlapped by each category of agricultural establishment.	% AE less than 10 ha	↗
			% 10 ha <=AE less than 100 ha	↗
			% AE>=100 ha	↗
Highways	*distance*	Minimum Euclidean distance to the road closest to the cell's centroid.	Distance	↘
Hydroelectric	*distance*	Minimum Euclidean distance from the nearest hydropower plant to the cell's centroid.	Distance	↘

* ↗= Directly proportional; e ↘= Inversely proportional.

Where **n** is the number of cells evaluated; zi represents the attribute value of area *i*; **zj** is the attribute value of area j; **z** is the mean of the attribute's value overall cells; **wijk** represents the elements of the k-order spatial proximity normalized matrix.

The Moran's index assumes values between –1 and 1. Values close to the extremes, whether they be negative of positive, represent the existence of autocorrelation. Values close to zero indicate the absence of spatial autocorrelation. In this analysis, the hypotheses tested were as follows:.

H0: I = 0 (There is no spatial dependence);.
H1: I > 0 (There is spatial dependence).

To calculate the Local Index of Spatial Association (LISA), equation (5) was used (Câmara et al., 2004):.

$$I_i = \frac{z_i \sum_{j=1}^{n} w_{ij} z_j}{\sum_{j=1}^{n} z_j^2} \quad (5)$$

Where **n** is the number of cells studied; **zi** represents the attribute value normalized in cell *i*; **zj** is the attribute value of cell *j*; **wij** represents the elements of the spatial proximity normalized matrix.

3. Results

In this section, we present the results of the Anthropogenic Pressure Index on Biomes (APIB) analysis. The calculated index was not intended to quantify the pressure, but rather to qualify the regions by ranking the severity of each problem according to the selected indicators To be able to identify the regions that are most affected by human pressure and, subsequently, guide priority actions and local policies.

Fig. 3 shows the spatiotemporal distribution of each scenario of the Anthropogenic Pressure Index on Biomes (APIB) for all of Brazil for the years 2000, 2014, and 2050. From the results it is possible to observe that in the year 2000 the highest APIB values were in the Atlantic Forest region. In the Sustainable development scenario, the pressure in this region decreases. However, in that same scenario in the Northeastern part of the Legal Amazon, the distribution patterns remain the same as in the year 2014. In the Middle of the road development and Strong inequality scenarios, the pressure observed in previous years tends to worsen, particularly in the Pantanal (Δ = 0.04), Caatinga (Δ = 0.04),

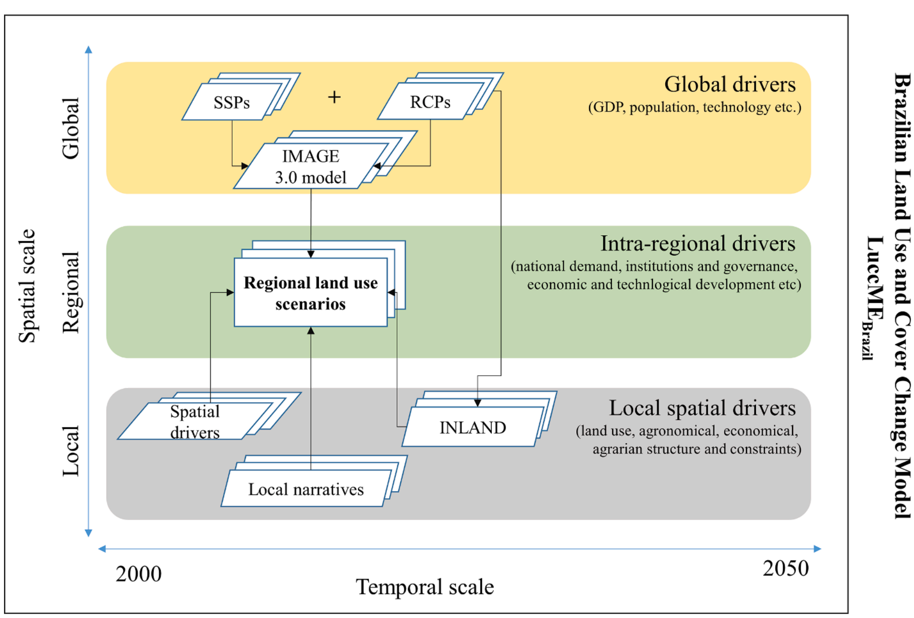

Fig. 2. Schematic representation of the development of regional land use and land cover scenarios, Shared Socio-Economic Pathways (SSPs) and Representative Concentration Pathways (RCPs) (Bezerra et al., 2021a).

Table 3
Main characteristics of Brazilian biomes (Based on Alvares et al., 2013; Dick et al., 2021; Ibge, 2019; MMA, 2020).

Biome	Total area (ha)	Climate	Predominant Vegetation	General Aspects
Amazon	419,694,300	Af and Am - tropical zone without a dry season	Humid tropical forest	The Amazon is estimated to contain around 20% of the world's freshwater, in addition to huge mineral reserves. The Amazon Region Biome is considered to contain the largest reserve of biological diversity in the world. According to some estimates, it houses at least half of all living species on the planet.
Caatinga	84,445,300	BSh - tropical and subtropical steppe climate	Steppe savanna (Caatinga)	Although it possesses a semi-arid climate, this area has a huge variety of landscapes, some relative biological richness, and some species that only live in this Biome. The Caatinga constitutes the oldest representation of the aridity of the last Glacial Period
Cerrado	203,644,800	Aw - two well-defined seasons with dry winters	Savanna	Hundreds of plant species from the Brazilian Cerrado have been used throughout the centuries by the native population for food, medicine, fodder, decorations, food for bees, construction materials, handicrafts, and for obtaining fibers, oils, tannins and other products. The fauna is rich. At the moment, the Cerrado Biome is the main region of agricultural and cattle raising expansion in the country. These activities have already led to in the elimination of native vegetation in this Biome and to the fragmentation of most of its natural habitats.
Atlantic Forest	111,018,200	Af - tropical rainforest climate	Dense ombrophilous forest, mixed ombrophilous, semideciduous seasonal, deciduous seasonal and open ombrophilous, in addition to associated ecosystems, such as restingas, mangroves and altitude fields.	Given that this biome is located in the region closest to the Brazilian coast, an area with a higher population density, it is the biomes that is most under threat in Brazil. Although its area is very reduced and fragmented, this biome is of utmost importance given that its reduced remaining green formations are home to unique biological diversity, which provides many environment benefits. The remaining forests are mainly located in areas that are difficultto access.
Pampa	17,649,600	Cfa -humid subtropical with hot summers	Grasslands with bush formations	Throughout the entire Pampa biome, human activities have turned the green covering rather uniform, mainly to be used as natural grazing land for the cattle or other agricultural activities, particularly rice plantations.
Pantanal	15,035,500	Aw -dry winters and rainy summers	Floodplains	The Pantanal is the largest continuous floodplain on the planet, which is its main characteristic and what makes it so different from the other biomes. This biome unites almost all fauna found in Brazil.

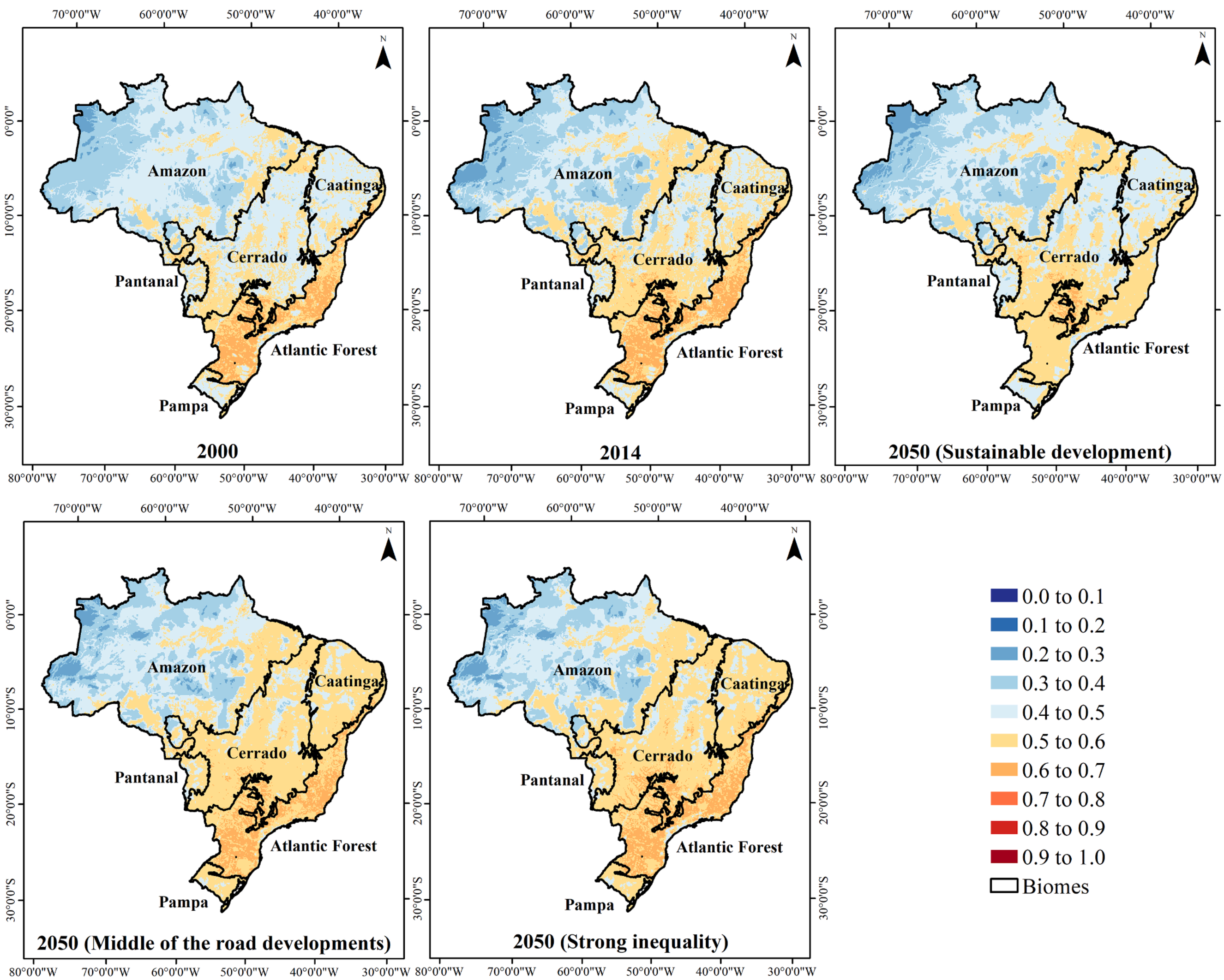

Fig. 3. Spatial-temporal distribution of the Anthropogenic Pressure Index on Biomes (APIB) for Brazil.

Pampa (Δ = 0.03), and Cerrado (Cerrado) biomes Δ = 0.03).

The percentage distribution of APIB values for Brazil is shown in Fig. 4. In the Sustainable development scenario, approximately 1% (54,345 km2) of Brazil's landmass is included in the range between 0.00 and 0.25, 61% (5,226,213 km2) between 0.25 and 0.50, and 38% (3,235,442 km2) between 0.50 and 0.75. In the other scenarios, about 45.3% (3,858,997 km2) of Brazil's landmass is concentrated in the range between 0.25 and 0.50, and 54.6% between 0.50 and 0.75 (4,648,124 km^2), with only 0.1% (8;879 km^2) included in the range between 0.00 and 0.25. In the Middle of the road developments and Strong inequality

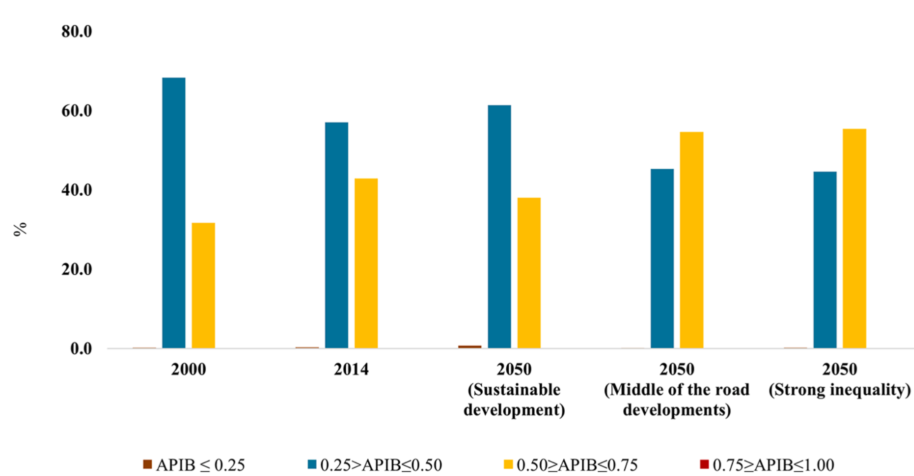

Fig. 4. Percentage distribution of the Anthropogenic Pressure Index on Biomes (APIB) values by year and scenario analyzed, including Sustainable development, Middle of road developments, and Strong inequality scenarios.

scenarios, an increase of approximately 44% (1,412,682 km^2) was observed in the areas with the highest pressure on biodiversity values (Fig. 5.).

According to the results presented above and spatially distributed below, the proportion of Brazil with high APIB values increases with the consolidation of the Strong inequality and Middle of the road development scenarios. This increase occurs in areas of Brazil that are already fragile when it comes to maintaining biodiversity. In the Sustainable development scenario, a reduction in the level of anthropogenic pressure on biodiversity was observed for a significant part of Brazil, especially in areas with biodiversity that has historically been under threat, such as the Atlantic Forest. However, there was a slight increase in APIB values in the Amazon compared to the current observed state. Considering changes related to the Middle of the road developments scenario, APIB value increases in the Amazon biome tend to occur in a smaller areas compared to the previous scenario, however, this increase is still relatively significant. Furthermore, in the Pampa, Pantanal, Cerrado, and Caatinga biomes, this increase occurs in greater proportions.

According to Fig. 6, it is possible to verify that both decreases and increases in APIB values indicate spatial autocorrelation (I = 0.59, on average), i.e., these changes tend to occur in a regionalized manner and are directly influenced by the behavior of neighbouring environments. This spatial dependence decreases in the Middle of the road developments and Strong inequality scenarios. However, the neighborhood effect can still be observed in larger parts of the Amazon biome and Atlantic Forest, thus indicating that in the latter biomes change takes place in a more concentrated matter, whereas in the other biomes changes are more widespread.

When comparing the biomes according to their APIB values, both within and between the years analyzed, including the scenario years, it is possible to observe different behavior according to the biome (Table 4). In the initial year of analysis (2000), the Pampa and Cerrado biomes did not show any significant differences ($p > 0.05$) in APIB values, 0.493 and 0.494, respectively. However, this was not the case in the 2014 to 2050 Sustainable development scenario. In the latter scenario, all biomes had significant differences ($p \leq 0.05$) among them. However, considering the year 2050 for the other scenarios, the Pampa and Cerrado biomes did not present significant differences ($p > 0.05$) in

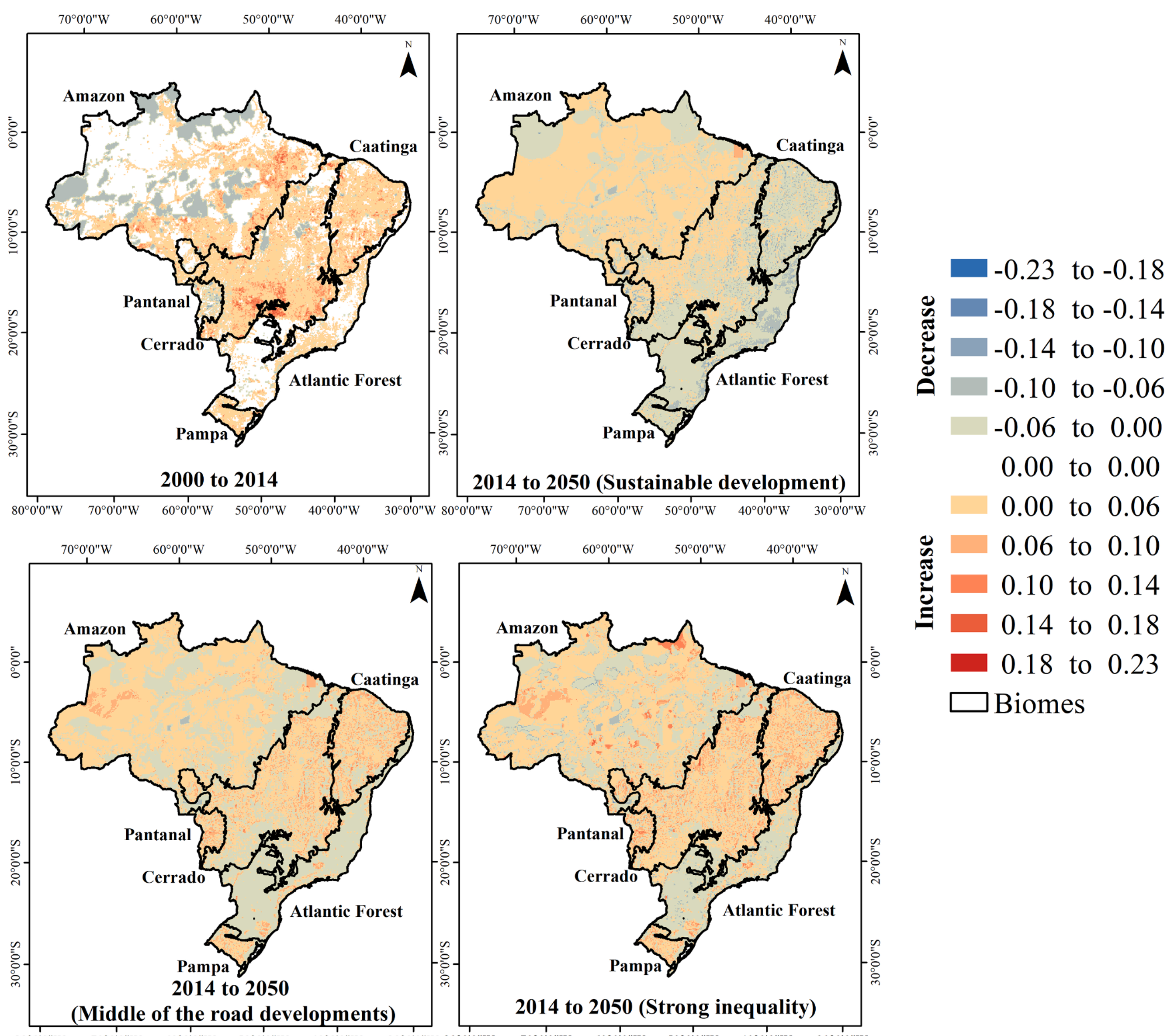

Fig. 5. Distribution of the spatiotemporal dynamics of the Anthropogenic Pressure Index on Biomes (APIB) change for the periods 2000 to 2014, 2014 to 2050 (Sustainable development), 2014 to 2050 (Middle of the road developments), and 2014 to 2050 (Strong inequality).

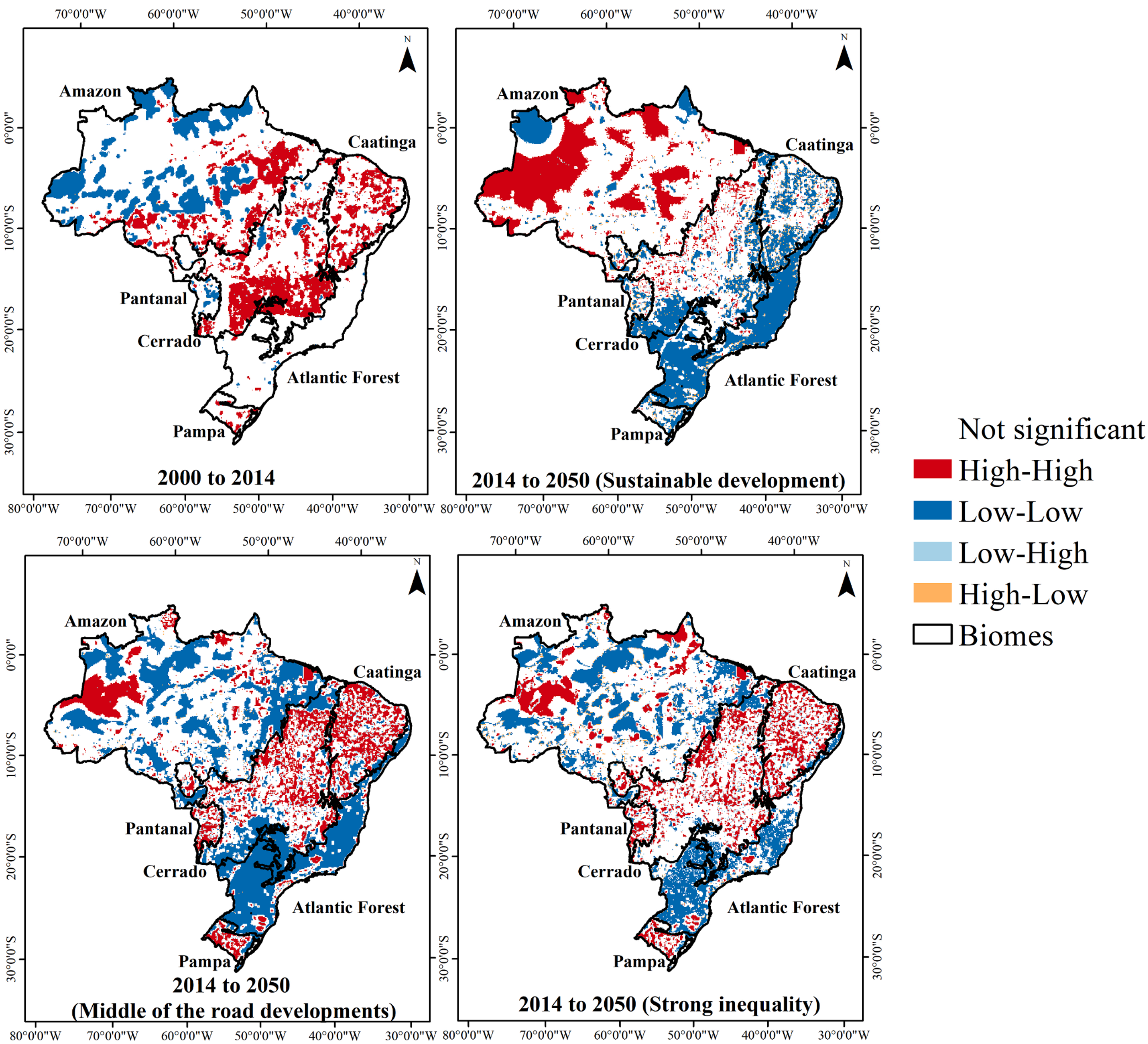

Fig. 6. Distribution of the local spatial association of change index from the Anthropogenic Pressure Index on Biomes (APIB) for the periods 2000 to 2014, 2014 to 2050 (Sustainable development), 2014 to 2050 (Middle of the road developments), and 2014 to 2050 (Strong inequality).

Table 4
Average Anthropogenic Pressure Index on Biomes (APIB) values, according to Brazilian biomes and development scenarios.

Biomes	2000		2014		2050 (Sustainable development)		2050 (Middle of the road development)		2050 (Strong inequality)	
Amazon	0.417	**aA**	0.415	**aA**	0.416	**aA**	0.429	**aB**	0.429	**aB**
Caatinga	0.473	**bA**	0.498	**cB**	0.475	**cA**	0.532	**cC**	0.536	**cC**
Cerrado	0.494	**dA**	0.519	**eC**	0.505	**eB**	0.542	**dD**	0.548	**dE**
Atlantic Forest	0.577	**eB**	0.580	**fBC**	0.547	**fA**	0.587	**eD**	0.584	**eCD**
Pampas	0.493	**dA**	0.507	**dB**	0.491	**dA**	0.538	**dC**	0.542	**cC**
Pantanal	0.487	**cB**	0.484	**bB**	0.468	**bA**	0.520	**bC**	0.522	**bC**

Means followed by equal letters on the same column are statistically equal ($P > 0.05$) according to the Tukey test.
Means followed by equal letters on the same line are statistically equal ($P > 0.05$) according to the Tukey test.

APIB values, 0.538 and 0.542, respectively in the Middle of the road development scenario. In the Strong inequality scenario, the Pampa presented a similar value ($p > 0.05$) to the average value of the Caatinga. A comparison of the three scenarios reveals that there is a significant difference ($p \leq 0.05$) in APIB values between the Sustainable development scenario and the other scenarios, regardless of the biome. Furthermore, the Cerrado biome was the only biome that presented a significant difference ($p \leq 0.05$) in APIB values irrespective of the year/scenario analyzed.

Table 5 shows the chosen percentage values of the contributions of each factor to compose the APIB. The factors Highways, Rivers, Grasslands and Protected Areas, Hydroelectric Plants and Agricultural

Table 5
Percentage contribution of factors in the Anthropogenic Pressure Index on Biomes (APIB) for the years 2000, 2014, and 2050, according to the scenarios developed.

Fatores	2000	2014	2050 (Sustainable development)	2050 (Middle of the road developments)	2050 (Strong inequality)
	%				
Forest vegetation	8.68	9.04	7.83	7.83	9.55
Grassland vegetation	13.04	13.94	14.40	14.40	14.56
Agriculture	1.03	1.61	0.53	0.53	1.35
Planted pasture	0.64	0.88	0.72	0.72	1.04
Mosaic of occupation	2.22	2.66	3.00	3.00	4.65
Forestry	0.09	0.14	0.04	0.04	0.11
Highways	15.07	14.91	15.55	15.55	14.13
Rivers	15.00	14.94	15.16	15.16	14.32
Agricultural establishments (less than10 ha)	1.41	1.45	1.14	1.14	1.08
Agricultural establishments (>=10 ha less than 100 ha)	3.51	3.52	4.72	4.72	4.44
Agricultural establishments (>=100 ha)	11.95	11.83	11.37	11.37	10.76
Protected areas	14.95	12.79	13.01	13.01	12.20
Hydroelectric	12.44	12.29	12.52	12.52	11.81

Establishments (> = 100 ha) were observed to contribute the most to the state of anthropogenic pressure on biodiversity, irrespective of the year and scenario.

Based on the cluster analysis, similar areas were identified with respect to anthropogenic pressure on biodiversity, considering the Sustainable development, Middle of the road developments, and Strong inequality scenarios, as described below (Fig. 7).

Region 1 covers approximately 17% of Brazil's landmass in the Sustainable development scenario, whereas in the Middle of the road development and Strong inequality scenarios this percentage falls to 16 %. This region is almost entirely covered by the Amazon biome and, on average, is characterized by higher percentages of forest vegetation (96%) and protected areas (58%), greater distances to highways (146 km), rivers (10 km) and hydroelectric plants (578 km), and higher percentages of small (less than 10 ha − 18%) and medium (areas either equal to or > 10 ha and less than 100 ha − 25%) agricultural establishments. Additionally, the Amazon biome has the lowest percentage of agricultural establishments that are either equal to or > 100 ha, approximately 56%. Thus, considering these characteristics, in both scenarios this region has the lowest pressure values on biodiversity (APIB = 0.34).

Similar to Region 1, Region 2 is mostly made up of the Amazon biome. This area corresponds to approximately 24% of Brazil's total landmass in the Sustainable development scenario, 22% in the Middle of the road developments scenario, and 23% in the Strong inequality scenario. The average percentages of forest and grassland vegetation are 73% and 16%, respectively. In thisregion the percentage of protected areas is significantly lower (12%) than in Region 1. Moreover, the distances to highways (76 km) and hydroelectric plants (365 km) in this region are shorter than in Region 1, whereas the distance to rivers is 9 km. In an analysis of the proportion of agricultural establishments, those with areas either equal to or > 100 ha (67%) stand out, followed by establishments of 10 to less than 100 ha (23%), and those with areas smaller than 10 ha (8%).The average distance from these establishments to highways and the hydroelectric power plant, as well as the low degree of protected areas and high proportion of large agricultural establishment contributed to an increase in APIB values (0.37) in this region.

Region 3, which is mostly covered by the Cerrado and Caatinga biomes, covers approximately 29% of Brazil's landmass in the Sustainable development scenario, 32% in the Middle of the road developments scenario, and 31% in the Strong inequality scenario. In this region, the percentage of grassland vegetation is greater than forest vegetation, 40% and 21%, respectively. As in Region 2, the percentage of protected areas is low (2%) and the distances to highways and hydroelectric plants are shorter, 16 and 222 km, respectively, and the distance to rivers is around 7 km. This region has the highest proportion of agricultural establishments that are either equal to or > 100 ha (77%), and, consequently, a low proportion of medium-sized agricultural establishments of 10 to 100 ha (18%) and small-sized agricultural establishments of less than 10 ha (3%). In this region the following classes of land use and coverage stand out: occupation mosaics (20%), agricultural areas (8%), and managed pastures (4%). In Regions 1 and 2 these factors were not significant. Together, these factors contribute to the second highest APIB values,i.e., an average of 0.44.

Region 4 is spatially distributed, and mostly covers the Atlantic Forest biome and, to a smaller degree, the northeast Amazon biome. It extends over 30% of Brazil's landmass in all scenarios. Both forests, and grasslands have low values (5% and 8%, respectively), as do protected areas (1%). By contrast, the proportionate values for mosaic of occupations (45%), agricultural areas (21%), managed pastures (15%), and forestry (2%) are the highest of all the regions observed. Additionally, the distances to highways (7 km), rivers (7 km), and hydroelectric plants (149 km) are the smallest among all the regions. Regarding the agrarian structure, like in regions 2 and 3, the peecentage of agricultural establishments > 100 ha (72%) stands out, followed by establishments with areas of 10 to 100 ha (24%), and establishments of less than 10 ha (3%). Compared to other regions, this region has the highest values of anthropogenic pressure on biodiversity, with an average of 0.57.

4. Discussion

The objective of this study was to propose a methodology to determine an index capable of considering anthropogenic factors, specifically changes to land use and land cover, to spatially and temporally identify anthropogenic pressure on biomes. Specifically, this study sought to develop a methodology that is capable of determining and spatializing the pressure of these anthropic factors on Brazilian biomes to contribute both to the debate surrounding the level of pressure in each region, and the dynamics of this pressure according to an analysis of future land use and land cover change scenarios associated with the shared Socio-Economic Pathways (SSPs) and Representative Concentration Pathway (RCPs). This approach is relevant in the context of efforts to understand and define biodiversity conservation and maintenance strategies and to meet sustainable objectives (SDGs), particularly those in the scope of SDG 15. The approach presented in this study seeks to contribute toward reducing the knowledge gap surrounding the contribution of land use and land cover change, and climate change to biodiversity disturbances, a need that has been highlighted in previousstudies (de Chazal and Rounsevell, 2009; Hansen et al., 2001; Ostberg et al., 2015; Sala et al., 2000; Travis, 2003). Although robust, this index could be improved by including other biome change driving factors, and including the concept of anthropogenic biomes (de Chazal and Rounsevell, 2009; Hansen et al., 2001; Ostberg et al., 2015; Sala et al., 2000; Travis, 2003).

The study of anthropogenic pressure from the perspective of

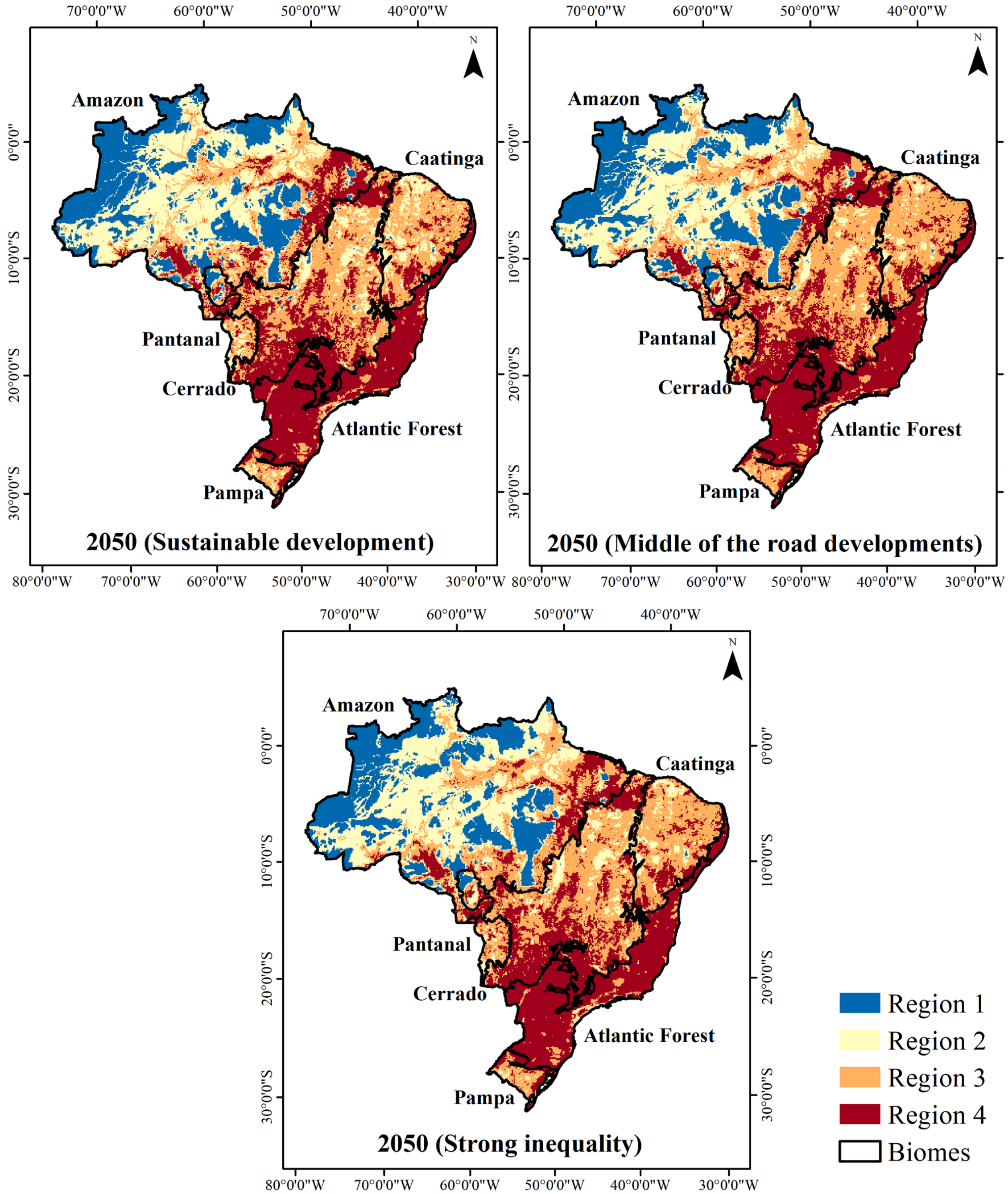

Fig. 7. Distribution of the cluster analysis, according to the spatial–temporal dynamics of the Anthropogenic Pressure Index on Biomes (APIB) for the scenarios.

scenarios corroborated with studies that highlighted the need to rethink the current development model (Ellis et al., 2013; Foley et al., 2011; Joly et al., 2019; Neumann et al., 2010; Popp et al., 2017; Tilman et al., 2011; van Vuuren et al., 2017). The scenarios presented in this study point toward an intensification of pressure on biodiversity in areas that already present a considerable degree of disturbances, particularly the Cerrado, Caatinga, and Atlantic Forest biomes, which, together, correspond to approximately 46% of Brazilian territory (Aide et al., 2013; de Area Leão Pereira et al., 2019; de Oliveira et al., 2012; de Rezende et al., 2015; Freitas et al., 2010; Morellato and Haddad, 2000; Rausch et al., 2019; Sobrinho et al., 2016; Souza et al., 2020; Tabarelli et al., 1999). In these regions, there is a larger number of species in threat of extinction (IBGE, 2020; ICMBio, 2018), and intensification of human activities could further aggravate this situation, according to the scenarios presented (Fig. 8).

The intensification of pressure on biodiversity is mostly related to the following factors: a) infrastructure, especially highways, either planned or existing; b) distance from the main rivers, here treated as population vectors, often without planning or basic infrastructure; c) the loss of natural vegetation, mainly grassland vegetation; d) the percentage of protected areas, whereas in the Strong inequality scenario this percentage tends to decrease, and e) land concentration. Furthermore, the results of this study point toward landscape fragmentation trends, which reinforces the risk of future habitat loss. Habitat fragmentation and loss negatively impact biodiversity conservation, given that biological diversity progressively erodes (Fahrig, 2003; Tabarelli et al., 1999; Terborgh and Winter, 1980; Tilman et al., 1994). These results corroborate the findings of Overbeck et al. (Overbeck et al., 2015), who underscored the importance of extending conservation and sustainable land use policies to non-forest ecosystems given that these Brazilian ecosystems

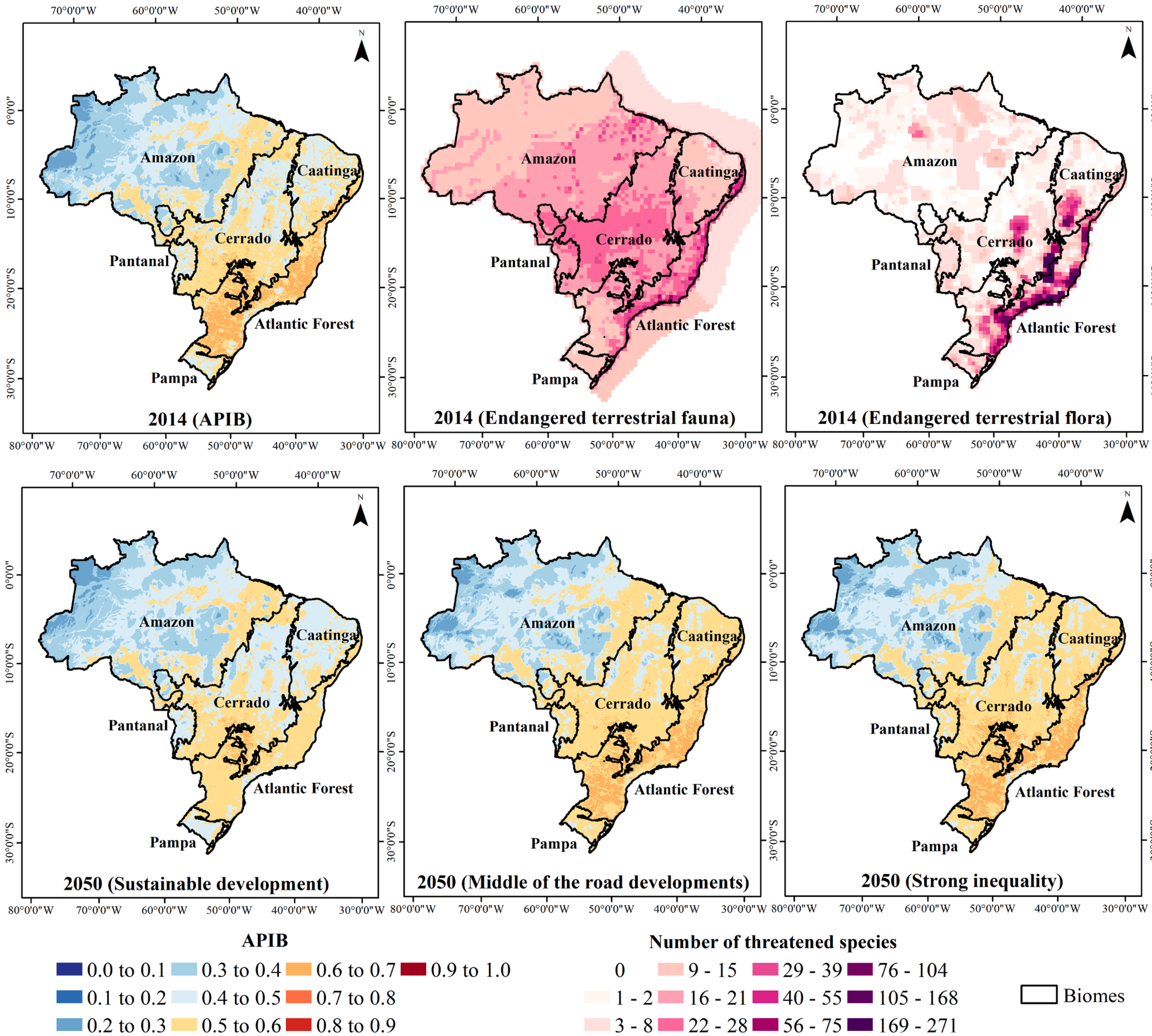

Fig. 8. Spatial-temporal distribution of the Anthropogenic Pressure Index on Biomes (APIB) for the Brazilian territory versus Spatial distribution of the number of threatened species (IBGE, 2020; ICMBio, 2018).

are considered to be the world's breadbasket and are home to a wealth of biodiversity and ecosystem services. In doing so, it would prevent the disruption of much of the natural communities present in these ecosystems.

5. Conclusions

We developed and tested a spatiotemporal approach that allowed us to identify and analyze the distribution of anthropogenic pressure on Brazilian biomes. The resulting index presented factors related to both the structure of Brazilian territory and changes to land use and land cover associated with SSPs and RCPs. Moreover, the scenarios presented made it possible to observe the dynamics of pressure throughout the analyzed period. Furthermore, the index made it possible to identify the specific spatiotemporal dynamics of anthropogenic pressure in distinct regions.

This research demonstrated the importance of using land use and land cover change scenarios to identify areas with greater potential for anthropogenic disturbances, i.e., disturbances that can degrade biodiversity. The association between the current scenarios and possible land use change paths is what differentiates this methodology from other studies that only aim to identify the areas that suffer from greater or lesser disturbances. The results of this study reveal that the dynamics of anthropogenic pressure on Brazilian biomes are not homogeneous, especially when with respect to the spatialization and location of APIB values. Furthermore, the multitemporal analysis also indicates that despite the efforts made in recent decades to protect biodiversity, there remains a potential risk that natural landscapes will become fragmented, especially in biomes that are currently considered to be highly anthropogenic, such as the Atlantic Forest and the Caatinga, among others.

The methodology proposed in this study proved to be useful, timely, and efficient to developing a potential indicator that is capable of identifying and monitoring anthropogenic pressure on Brazilian biomes and, therefore, contributing toward biodiversity recovery and maintenance actions, in line with international agreements. It should be noted that although this approach is useful, it should be complemented with additional information, such as soil erosion, field recognition, and socioeconomic information.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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