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Abstract: In 2019, the official delimitation of the Brazilian biomes was updated to a considerably more detailed description compared to the previous definition that lasted 15 years. This work investigates the possible effects of such changes in different political-administrative scales, ranging from biomes to the municipality level. We define effect levels according to the changes between the biomes in each scale, indicating the areas more subject to the changes in the newest version of the Brazilian biomes. Depending on the scale of the study, the changes in the Brazilian biomes might have significant effects, mainly in the Pampa biome, in Piauí, São Paulo, Sergipe, and Bahia states, and at the municipality level.
Keywords: Biomes. States. Municipalities. MapBiomas. Policy implications.

Resumo: Em 2019, a delimitação oficial dos biomas brasileiros foi atualizada para uma descrição consideravelmente mais detalhada em comparação à definição anterior que durou 15 anos. Este trabalho investiga os possíveis efeitos de tais mudanças em diferentes escalas político-administrativas, desde os biomas até o nível municipal. São definidos níveis de efeito de acordo com as alterações dos biomas em cada escala, indicando as áreas mais sujeitas a alterações na versão mais recente dos biomas brasileiros. Dependendo da escala do estudo, as mudanças nos biomas brasileiros podem ter efeitos significativos, principalmente no bioma Pampa, nos estados do Piauí, São Paulo, Sergipe e Bahia, e na escala municipal.
Palavras Chave: Biomas. Estados. Municípios. MapBiomas. Implicações políticas.

1 INTRODUCTION[1]

A biome is an area of geographic space with dimensions up to exceeding one million square kilometers, represented by a uniform type of environment, identified and classified according to the macroclimate, phytophysiognomy, soil, and altitude, the main elements that characterize the diverse continental environments (WALTER, 1986; COUTINHO, 2006). Examples of biomes include tropical rainforests, savannas, tundras, deserts, and oceans. Despite the difficulties in defining biomes, they help describe ecosystems' function and role in the Earth system (MONCRIEFF; BOND; HIGGINS, 2016).

In Brazil, biomes are officially defined by the Brazilian Institute of Geography and Statistics (IBGE). The six biomes[2] are (ordered by size) Amazônia, Cerrado, Mata Atlântica, Caatinga, Pampa, and Pantanal. In 2004,

[1] This paper is an extended version of (ANDRADE et al., 2023), presented in XXIV Brazilian Symposium on GeoInformatics (GEOINFO 2023)

[2] In this work, we focus only on the terrestrial biomes.

IBGE and the Ministry of Environment (MMA) produced an official biome map with a scale of 1:5,000,000 (IBGE, 2004). It was the first official definition of Brazilian biomes, also called the *first approximation*. At the time of this publication, several points still needed to be better studied in the light of knowledge about more accurate information on the country's natural resources (IBGE, 2019).

In 2019, the official delimitation of the Brazilian biomes was updated to a considerably more detailed description compared to the previous definition that lasted 15 years (IBGE, 2019). It incorporates several conceptual and technological advances to the previous version of the biomes. The new version has a scale of 1:250,000, based on the latest vegetation map for Brazil, produced in the same scale.

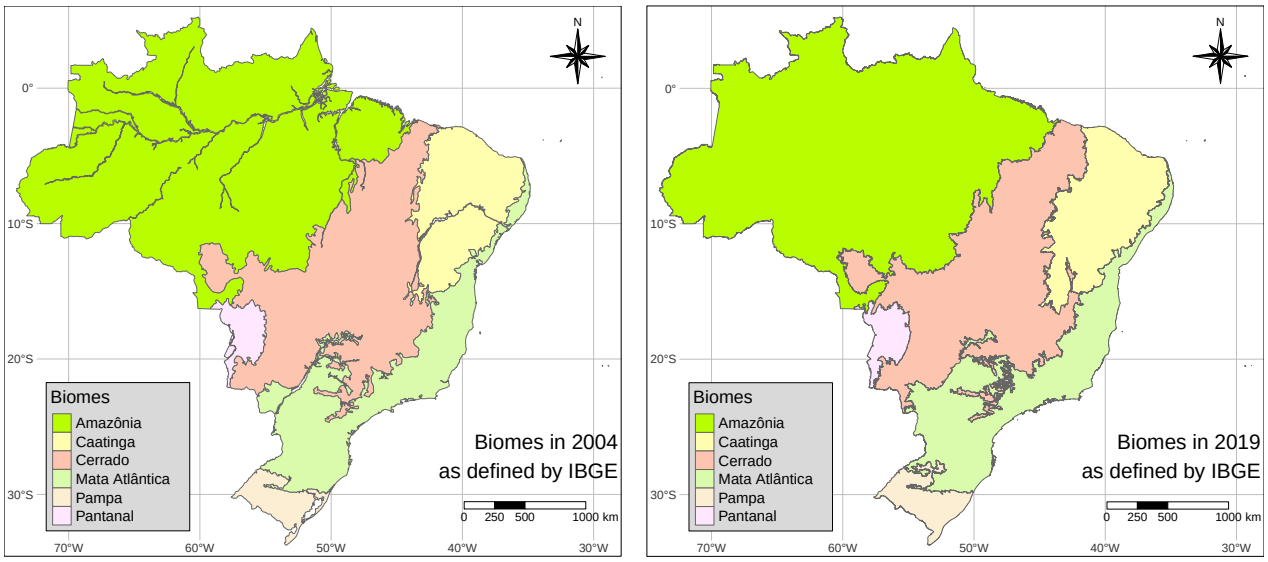
A Google Scholar search for the words "Brazilian biome IBGE" (without quotes) returned more than 16,000 papers published from 2004 until 2023. Several studies use the 2004 version of the Brazilian biomes (DE ARAÚJO; FERREIRA; ARANTES, 2012; MENEZES et al., 2012; RADA, 2013; SOTERRONI et al., 2019; SANO et al., 2019; RAJÃO et al., 2020; GUERRA et al., 2020; MENGUE et al., 2020; BEZERRA et al., 2022; ARCOVERDE et al., 2023). Articles that use the previous definition of the Brazilian biomes may potentially be affected by the changes implemented in 2019.

In this work, we investigate the possible effects of the changes in the definition of biomes in different political-administrative scales, ranging from biomes themselves to the municipality level. We define effect levels to indicate the areas more subject to the changes in the newest version of the Brazilian biomes. We also analyse possible legal effects of such changes according to the Brazilian Native Vegetation Protection Law, also known as the Forest Code.

2 METHODOLOGY

We use the biomes defined by IBGE for 2004 and 2019[3], shown in Figure 1[4]. Note how the data in 2004 has several holes related to hydrography. Additionally, in some locations, there are significant differences between the two versions of the biomes. Figure 2 shows details of a region between Amazônia and Cerrado. It is possible to see how the newest version is more detailed.

Figure 1 – Brazilian biomes in 2004 (left) and 2019 (right), as defined by IBGE.

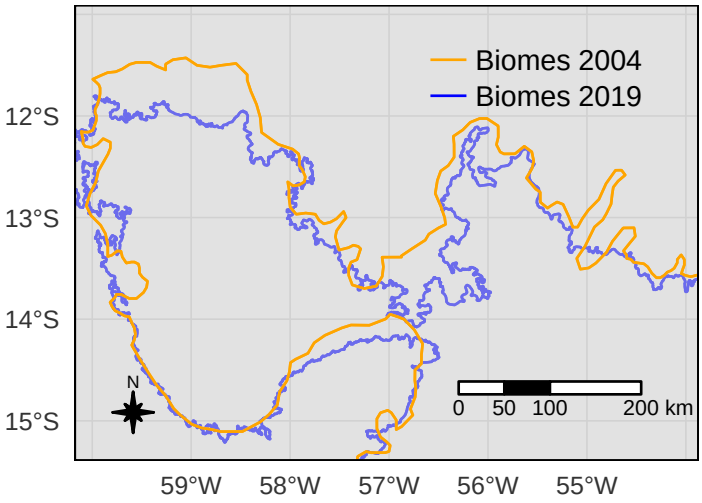


Source: The authors (2024).

[3] The data was obtained using R package geobr (PEREIRA et al., 2019), which is a copy of the original data available in IBGE's FTP at https://geoftp.ibge.gov.br/informacoes_ambientais/estudos_ambientais/biomas/vetores/. IBGE launched an updated version of the biomes maps after 2019. In this work, we use the version with such updates, but we refer to it as 2019 data. (ANDRADE et al., 2023) presents a comparison with the first version of the maps produced with the 2019 methodology.

[4] All the Figures in this article are vectorial; therefore, it is possible to zoom in to see minor details in the polygons.

Figure 2 – Detailing a region between Amazônia and Cerrado biomes.



Source: The authors (2024).

The biomes maps are not directly comparable, mainly because the 2004 version does not consider some rivers as part of the biomes. Additionally, they do not share precisely the same Brazilian limits. We use the official delimitation of Brazil from IBGE as our basis for producing maps of biomes with the same limits. This dataset has a scale of 1:250,000, the same used by the 2019 version of the biomes. Using this data allows a fair comparison of the areas of the biomes and assessing the changes in the state and municipality scales. The procedure to create comparable biome maps uses the following steps:

1. Remove the areas of the biomes outside the IBGE's delimitation for Brazil.
2. Compute the spatial difference between Brazil and the biomes, representing the areas within Brazil that are not mapped by the biomes data. The resulting polygons include the missing hydrography areas of 2004, for example. For 2004, there were 5,200 polygons, covering 15.23 million hectares (Mha), or 1.79% of Brazil. For 2019, there are 10,224 polygons covering 0.54 Mha, 0.06% of Brazil. As the 2019 data is more detailed, it has considerably more missing polygons but an almost insignificant missing area. These polygons will be added to the biomes maps to guarantee that the total area covered by the biomes is the area of Brazil, detailed in the next steps.
3. Apply a buffer of approximately 1 meter to such polygons (item 2) and then compute the overlap with the biomes. Polygons that overlap only one biome are added to the respective biome.
4. The remaining polygons overlap more than one biome. We first compute the intersection between these polygons and the biomes. Then, the biome with a greater intersection will contain the respective polygon.
5. Two polygons in 2004 cross biomes, as they represent the São Francisco and Tocantins rivers. They were split into three polygons each and allocated to the respective biome.

The procedure above generates updated and comparable maps for the biomes. We then investigate the following questions using these data:

1. How much area did each biome gain and lose from 2004 to 2019?
2. How much area of each state was affected by the changes in the biomes?
3. How many municipalities did each biome gain and lose from 2004 to 2019?
4. How much area of each municipality was affected by the changes in the biomes?

Finally, we investigate the native vegetation changes of each biome related to the newest definitions. We analyse the legal effects of such updates using the 2022 data of MapBiomas Collection 8 (SOUZA JR et al., 2020) by computing the natural vegetation in the areas that changed biome.

Based on the results of these questions, we analyze the changes across different scales. We consider that changes below 5% are not relevant, between 5% and 50% have considerable relevance, between 50% and 90% have high relevance, and above 90% have huge relevance.

3 RESULTS

Figure 3 shows the resulting maps of biomes for 2004 and 2019. We can see that the 2004 map fixes the hydrology issues. The 2019 map is very similar to the original one, but there are some differences, such as the area of Lagoa dos Patos in the southernmost part of the country (compare the right map with the respective map in Figure 1).

3.1 Biomes

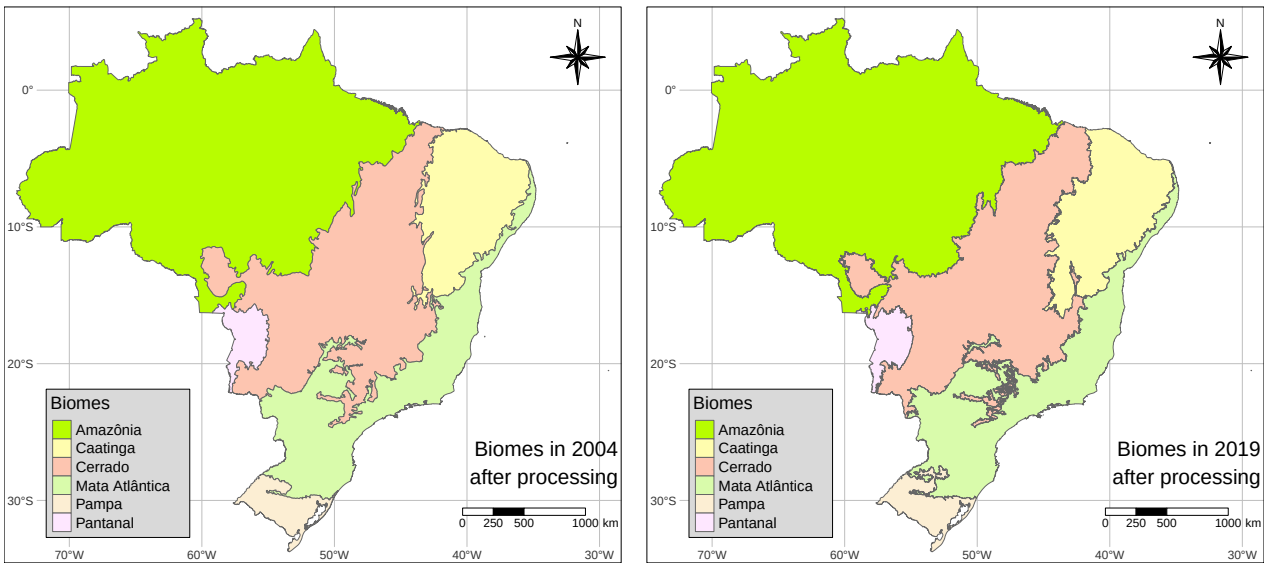
Table 1 shows the extent of each Brazilian biome in 2004 and 2019. In the final balance between gained and lost areas, most of the biomes experience minor relative changes in size, except for Pampa, which had an increase of nearly 10%. The Mata Atlântica and Cerrado biomes reduced their areas while the other biomes gained. Pantanal was the only one that kept its total area. In general terms, most of the area lost by Mata Atlântica moved to Pampa, while most of the area lost by Cerrado moved to Amazônia and Caatinga.

Table 1 – Area of the Brazilian biomes (in Mha). The Difference and Delta columns are for 2019 compared to 2004.

Biome	**Area 2004 (Mha)**	**Area 2019 (Mha)**	**Difference**	**Delta (%)**
Amazônia	419.92	421.59	+1.67	+0.40
Caatinga	82.72	86.27	+3.55	+4.29
Cerrado	204.00	198.47	–5.53	–2.71
Mata Atlântica	112.01	110.72	–1.29	–1.15
Pampa	16.50	18.10	+1.60	+9.70
Pantanal	15.10	15.10	+0.00	+0.00
Brazil	850.25	850.25	+0.00	+0.00

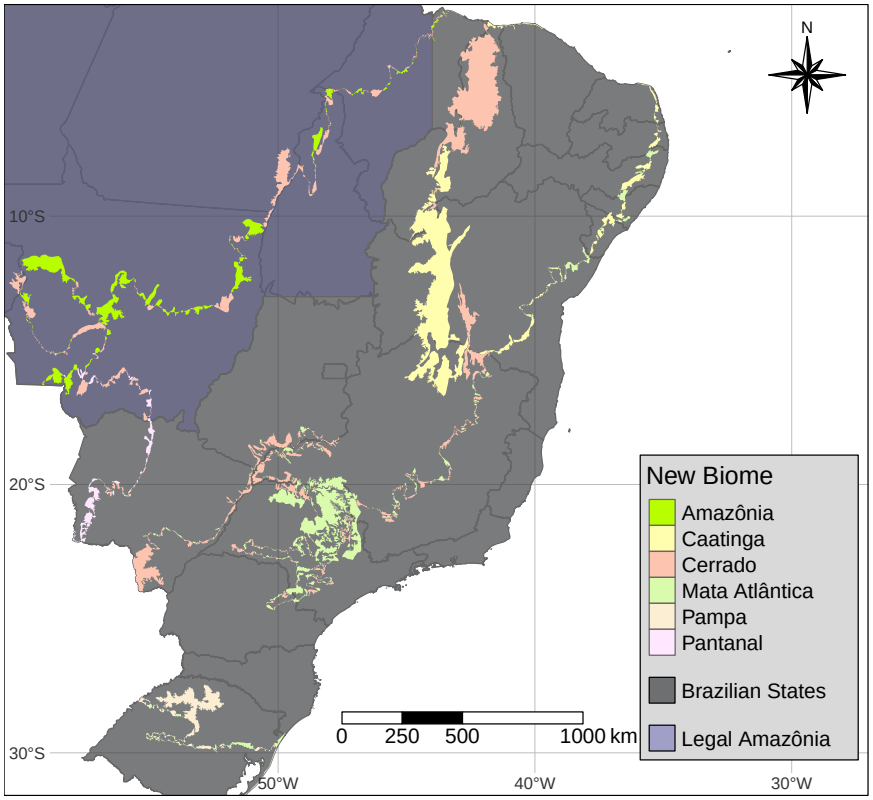
Source: The authors (2024).

Figure 3 – Brazilian biomes in 2004 (left) and 2019 (right) after processing.



Source: The authors (2024).

Figure 4 – Areas that changed between biomes on top of Brazilian states.



Source: The authors (2024).

Although most biomes did not significantly change their areas in the final balance, there were notable changes in their borders as they exchanged limits with their neighbors. Table 2 shows the gains and losses of each biome's related areas. For example, Amazônia gained 4.05 Mha from Cerrado and 0.47 Mha from Pantanal but lost 2.79 Mha to Cerrado and 0.06 Mha to Pantanal. All zero values in the table indicate that the respective biomes do not share borders. The main diagonal represents areas that did not change between versions.

Table 2 – Changes in area of the Brazilian biomes (in Mha).

Biome	Amazônia	Caatinga	Cerrado	M. Atlântica	Pampa	Pantanal	Total 2019
Amazônia	417.07	0.00	4.05	0.00	0.00	0.47	421.59
Caatinga	0.00	75.45	9.42	1.40	0.00	0.00	86.27
Cerrado	2.79	6.73	183.91	4.41	0.00	0.63	198.47
M. Atlântica	0.00	0.54	5.58	104.30	0.30	0.00	110.72
Pampa	0.00	0.00	0.00	1.90	16.20	0.00	18.10
Pantanal	0.06	0.00	1.04	0.00	0.00	14.00	15.10
Total 2004	419.92	82.72	204.00	112.01	16.50	15.10	850.25

Source: The authors (2024).

Figure 4 shows the areas that changed between biomes on top of the Brazilian state limits highlighting the areas gained in each biome. For example, along the border between the Caatinga and Cerrado biomes, the gained areas in Caatinga are highlighted in yellow, and the gained areas in Cerrado are in salmon.

3.2 States

Table 3 quantifies the states that had more than 5% of change. Rio Grande do Sul is on the list as it contains the entire Pampa biome. However, on this scale, other states also had some effects, some even more than Rio Grande do Sul. It is worth mentioning that more than 30% of the Piauí state changed biome, primarily

moving from Caatinga to Cerrado. São Paulo had almost 20% of change, transitioning from Cerrado to Mata Atlântica. Sergipe and Bahia had more than 10%, mainly moving from Cerrado to Caatinga and Mata Atlântica to Caatinga, respectively. Studies that rely on the previous definition of biomes in these states could have a considerable effect.

Table 3 – Overlaps of changing biomes within states (in Mha).

State	Total area	Area that changed between biomes	Percentage (%)
Piauí	25.16	7.57	30.09
São Paulo	24.82	4.87	19.62
Sergipe	2.19	0.27	12.33
Bahia	56.47	6.71	11.88
Minas Gerais	58.65	5.02	8.56
Rio Grande Do Sul	26.88	2.20	8.18
Mato Grosso Do Sul	35.71	2.48	6.94
Mato Grosso	90.34	5.87	6.50
Alagoas	2.78	0.18	6.47
Pernambuco	9.82	0.52	5.30

Source: The authors (2024).

3.3 Municipalities

Considering the Brazilian municipalities, although the number of municipalities in each biome does not change significantlyy (except for Pampa), there are significant changes in Caatinga, Cerrado, and Mata Atlântica, as shown in Table 4 (note that the sum of the municipalities in each biome is greater than the number in Brazil as municipalities can belong to more than one biome). Cerrado is the biome that gained and lost most municipalities, as it shares its border with all other biomes, except Pampa. Therefore, studies at the municipal level using biomes might have significant changes if changing the biomes map.

Table 4 – Number of municipalities in each biome that changed from 2004 to 2019.

Biome	Total 2004	Added	Removed	Total 2019
Amazônia	556	+8	–4	560
Caatinga	1223	+89	–102	1210
Cerrado	1399	+157	–122	1434
Mata Atlântica	3057	+119	–94	3082
Pampa	173	+86	–26	233
Pantanal	28	+1	–7	22

Source: The authors (2024).

Looking at the municipalities themselves, 160 have 100% of change in their biomes. Table 5 shows the results for municipalities grouped by states. Beyond the previous states, Tocantins, Sergipe, Paraiba, and Rio Grande do Norte states have municipalities with more than 90% of change in their biomes. São Paulo and Minas Gerais, the two states with more municipalities, were the ones with more municipalities with more than 5% of change in the biome. A total of 879 municipalities, or 15.7% of Brazil, have some effect related to the newest version of the biomes.

Table 5 – Number of municipalities per state with more than 5%, 50%, and 90% of change in their biomes.

State	n ≥ 5%	n ≥ 50%	n ≥ 90%
São Paulo	199	114	44
Minas Gerais	129	50	14
Piauí	116	87	56
Rio Grande do Sul	100	59	19
Bahia	77	22	12
Pernambuco	31	23	12
Mato Grosso do Sul	26	5	2
Tocantins	22	4	3
Sergipe	17	11	3
Alagoas	13	6	1
Paraíba	11	9	5
Rio Grande do Norte	8	4	2
Total	749	394	173

Source: The authors (2024).

3.4 Policy implications

To better understand the policy implications, it is necessary to analyse the native vegetation within areas that changed their biomes. Table 6 shows the changes in native vegetation for the year 2022 according to MapBiomas Collection 8. The increase reflects areas of native vegetation that moved to the respective biome, while the decrease represents areas that moved out of the biome. It is necessary to clarify that positive values do not indicate restoration of native vegetation, but the vegetation located in one biome that moved to another. Cerrado biome experienced the most significant changes in native vegetation, gaining 8.42 Mha and losing 9.49 Mha, as it shares borders with all other biomes but Pampa. Although there are significant areas of native vegetation that moved from one biome to another, the net change was considerably low. Both Cerrado and Mata Atlântica showed a net loss of native vegetation, losing 1.07 Mha and 0.64 Mha, respectively. These 1.71 Mha correspond the net gain of the other biomes.

Table 6 – Native vegetation increase, decrease, and change per biome for year 2022 (Mha).

Biome	Increase	Decrease	Change
Amazônia	+2.37	–1.59	+0.78
Caatinga	+6.08	–5.68	+0.40
Cerrado	+8.42	–9.49	–1.07
Mata Atlântica	+1.22	–1.86	–0.64
Pampa	+0.49	–0.15	+0.34
Pantanal	+0.63	–0.44	+0.19

Source: The authors (2024).

Looking at the transitions between biomes, the changes were highly heterogeneous, as shown in Table 7. The table ranks the areas with the most to the least percentage of native vegetation within them. The transition from Caatinga to Cerrado has an area with more than 80% of native vegetation, while the transition from Cerrado to Mata Atlântica has only 17.22% of native vegetation.

We can see that almost all areas that changed the biome follow the minimum requirement of 20% protection as defined by Brazil's Native Vegetation Protection Law (No. 12,651/2012), also known as the Forest Code. However, areas within Legal Amazônia are more restricted, requiring up to 80% of protection in their legal reserves. As shown in Figure 4, the areas most susceptible to change are the ones transitioning between Amazônia, Cerrado, and Pantanal. The areas that have potentially increased their legal reserve requirements are the ones that moved from Cerrado or Pantanal to Amazônia. The area that moved from Cerrado to Amazônia amounts to 4.07 Mha, while the area that moved from Pantanal to Amazônia amounts to 0.47 Mha. The conservation of these areas may be subject to legal action, since producers established themselves in these regions before the change in the law, which could characterize a guaranteed right not to need to protect more than 20%. On the

other hand, areas that left Amazônia are now able to be deforested up to 80%, such as the 2.80 Mha that moved from Amazônia to Cerrado. Special attention in terms of conservation must be paid to such areas. The area of Amazônia biome that was outside Legal Amazônia was kept around 0.3 Mha, within the state of Maranhão, in the Northeast region. As it was already outside the Legal Amazônia, the protection of this area is kept at 20%.

Table 7 – Native vegetation in the areas that changed biome.

From	To	Total area (Mha)	Native vegetation (Mha)	Percentage of area with native vegetation
Caatinga	Cerrado	6.76	5.57	82.37
Amazônia	Pantanal	0.06	0.04	69.78
Cerrado	Caatinga	9.45	5.66	59.89
Cerrado	Amazônia	4.07	2.28	56.14
Cerrado	Pantanal	1.05	0.59	56.04
Pantanal	Cerrado	0.63	0.35	55.93
Amazônia	Cerrado	2.80	1.55	55.57
Pampa	Mata Atlântica	0.30	0.15	50.53
Mata Atlântica	Caatinga	1.40	0.42	29.91
Mata Atlântica	Pampa	1.91	0.49	25.67
Mata Atlântica	Cerrado	4.42	0.95	21.48
Caatinga	Mata Atlântica	0.55	0.11	20.33
Pantanal	Amazônia	0.47	0.09	19.72
Cerrado	Mata Atlântica	5.60	0.96	17.22

Source: The authors (2024).

The recently created Laws of Pantanal (Law No. 11,861/2022 for the Mato Grosso state and Law No. 6,160/2023 for Mato Grosso do Sul state) establish that private properties must have up to 40% of their areas covered by cultivated pasture, keeping the rest of the properties covered by native vegetation, including native pasture. The transitions from Amazônia and from Cerrado to Pantanal have, respectively, 69.78% and 56.04% of their areas as native vegetation. In general terms, most private properties within those areas will not have significant impact by changes in the definitions of biomes. However, individual properties within such regions with environmental deficits might exist, although they might be compensated by other properties with surpluses in the same region as they belong to the same biome. Because of this, the results presented in this section are exploratory and further analysis is required.

4 CONCLUSIONS

Depending on the political-administrative scale, the changes in the official delimitation of the Brazilian biomes might have significant effects, especially in the following areas: Pampa biome; Caatinga, Mata Atlântica, and Cerrado biomes, particularly within the municipality level; Piauí, São Paulo, Sergipe, and Bahia states, but also in Minas Gerais, Rio Grande do Sul, Mato Grosso do Sul, Mato Grosso, Alagoas, and Pernambuco; and municipalities in the previous states and also from Tocantins, Paraíba, and Rio Grande do Norte. Other spatial representations might not produce significant changes (less than 5%). Different scales would require further investigation, as the results described in this article present an initial analysis and potential areas with implications for the enforcement of Brazil's Forest Code.

Studies that examine more than one contiguous biome at the municipality level might have reduced effects, as the changes in one biome are directly related to its neighbors. The borders between Caatinga and Cerrado and between Cerrado and Mata Atlântica have more changes in municipalities. Studies that use these two combinations of biomes might have smaller effects on the changes in municipalities.

Changes in biome boundaries have a significant impact on studies, land use planning of priority areas for conservation, ecological connectivity, zoning, the establishment of conservation units and enforcement of national legislation. Many of these decisions are made at the level of Federative Units. This research contribute to a better understanding of these changes, facilitating the potential adaptation of ongoing projects and initiatives.

It is worth noting that, as other biophysical cartographic bases are updated, the limits of biomes will also require adjustments. Brazilian institutions must be prepared to adapt to these changes.

Studies seeking to investigate new definitions of biomes for Brazil could benefit from the methodology presented in this work. The scripts that implement the method of this study were written in R using the sf package (PEBESMA et al., 2018). All scripts and data presented in this paper are available on GitHub[5].

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Authors contribution

P.R.A.: Conceptualization, Methodology, Software, Validation, Writing - Original Draft, Writing - Review & Editing; A.C.S.: Conceptualization, Methodology, Writing - Original Draft, Writing - Review & Editing. G.F.B.A: Conceptualization, Methodology, Writing - Original Draft, Writing - Review & Editing. M.I.S.E: Conceptualization, Methodology, Writing - Original Draft, Writing - Review & Editing.

Conflicts of interest

The authors declare that there are no conflict of interest.

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