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Current policies are insufficient to protect or restore Brazil's cost-effective conservation priority zones

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Abstract

In Brazil, conservation priority zones, in spite of their key role in preserving natural vegetation and its environmental resources are frequently located outside the country's public network of protected areas (PAs). Here we present the first study on land-use impacts inside Brazil's unprotected (i.e. outside PAs) Cost-Effective conservation priority Zones (CEZs), for the period 2020–2050. CEZs are conservation priority zones that had experienced low levels of human impact in 2020. In this study, we consider various governance scenarios, including different deforestation control and native vegetation restoration policies. To this end, a land-use change model is combined with a downscaling method to generate natural vegetation cover projections at a 0.01° resolution. Results, which include the effects of climate change on the expansion of the Brazilian agriculture, project native vegetation losses (through deforestation) or gains (through restoration) inside unprotected CEZs. If the current pattern of disregard for the environment persists, our results indicate that a large share of the native vegetation inside Brazil's CEZs is likely to disappear, with negative impacts on biodiversity preservation, green-house gas emissions and ecosystem services in general. Moreover, even if fully implemented and enforced, Brazil's current Forest Code is insufficient to adequately protect CEZs from anthropization, especially in the Cerrado biome. We expect that this study can help improving the conservation and restoration of CEZs in Brazil.

1. Introduction

Brazil is a megadiverse country. However, this rich heritage is under increasing threat, largely as the result of the conversion of natural habitats into farmland, for the production of beef, soybeans, corn, sugarcane, and other commodities. Globally, the continuous degradation of intact ecosystems for the extraction of timber or the production of food and other agricultural commodities has put an enormous strain on ecosystems everywhere, resulting in rapidly increasing rates of species loss [20]. With anthropization levels affecting more than half of the world's land surface [31, 48], protecting remaining wilderness areas and restoring degraded natural habitats is key for stopping or even reversing this alarming trend.

Based on the Convention on Biological Diversity's Aichi targets, Brazil set in 2013 its national biodiversity goals [24] for significantly reducing the risk of extinction of threatened species. In particular, Goal 11 foresaw the expansion of the country's network of protected areas (PAs), which includes both conservation units and indigenous lands [8], to cover at least 30% of the Amazon and 17% of each of its remaining terrestrial biomes (Cerrado, Caatinga, Atlantic Forest, Pantanal and Pampa). With the exception of the Amazon, this goal was still not attained in other biomes [46], and is now being challenged by more ambitious post-2020 targets, which include recent proposals for protecting 30% of the planet (land and oceans) by 2030 [12], half the terrestrial biosphere by 2050 [11, 21, 49]. In addition, by adhering to the 2022

Kunming-Montreal Global Biodiversity Framework [1], Brazil agreed to, by 2030, bring the loss of areas of high biodiversity importance, including ecosystems of high ecological integrity, close to zero, to protect 30% of Earth's lands, oceans, coastal areas, inland waters, and to restore at least 30% of areas of degraded terrestrial, inland water, and coastal and marine ecosystems.

Even though several recent studies [11, 12, 20, 21, 25, 49] have attempted to identify a global network of priority areas for conservation, there is still no consensus on how to invest the limited resources available for preserving or restoring natural habitats and related environmental resources, such as biodiversity [25]. Crucially, conservation strategies diverge in how they take into account the degree of anthropization of proposed areas [51]. Compared to pristine regions, areas that have already been impacted by human activities are generally more difficult to be designated as PAs, regardless their importance for biodiversity conservation. To address this issue, Yang and collaborators [51] combined seven global biodiversity conservation templates [14, 26, 29, 33, 41, 48, 50] with data on low-human impact areas (LIAs) [19] to identify cost-effective conservation priority zones (CEZs) more suitable for PA designation.

In Brazil, CEZs are frequently situated on private property, outside the legal protection of the country's public network of PAs. Although, in general, PAs are the most effective instruments of public policy for protecting natural ecosystems, they require appropriate funding for land expropriation, and management. Moreover, given currently existing funding gaps for both PA expansion and management, investments in management are frequently the best way to protect biodiversity [2]. In 2016, 76.6% of federal PAs in Brazil were threatened by funding deficits, with the network-wide deficit reaching 84.4% of the estimated management costs [9]. As a result, rather than focusing on the creation of new PAs to protect Brazil's CEZs, this study examines the efficiency of Brazil's Natural Vegetation Protection Act (Law n° 12 651, also known as the 'Forest Code', FC) in preserving and restoring the country's unprotected CEZs. The FC is Brazil's primary instrument for regulating changes in land use on private lands. It was revised in 2012 and establishes region-specific legal restrictions on the amount of deforestation permitted on private property; see supplementary material (SM) for a description of Brazil's FC. On each private property, the FC mandates the protection of environmentally sensitive areas, such as riverbanks and springs, as well as a percentage of native vegetation, which ranges from 80% in the Amazon to 20% in the Caatinga, for example. These areas account for more than one-third of Brazil's original vegetation and contribute to biodiversity preservation [23]. Here, we present the first evaluation of projected anthropization in unprotected CEZs at a high spatial resolution from 2020 to 2050. By anthropization we mean any area of original native vegetation (forested or not) that has been converted to cropland, pasture, or other uses. Our research focuses on Brazil's entire territory and its four biggest biomes (Amazon, Cerrado, Atlantic Forest and Caatinga); see SM.

We have three basic research questions. First, how effective is Brazil's FC at safeguarding or rehabilitating vulnerable CEZs? Second, how may the FC be adjusted or supplemented to protect and recover CEZs effectively? Finally, how the protection and restoration of CEZs may affect agricultural production in Brazil. To answer these questions, we used the GLOBIOM-Brazil land-use change model in conjunction with a downscaling approach to construct estimates of natural plant cover at a spatial resolution of 0.01° under five scenarios. In addition to a business-as-usual (BAU) scenario, four implementations of Brazil's current FC with varying native vegetation restoration standards and a regional zero-deforestation policy are considered. In all our projections, we additionally account for the impact of climate change on Brazil's agriculture, including the spatial displacement of crops due to shifting productivity patterns. Comparisons among these projections are used to help identify gaps in the current legislation and evaluating new policies for better conservation and restoration of unprotected CEZs in Brazil.

Previous modeling studies [7, 36, 38] and reviews [5] have investigated the potential implications of the FC on land use change, or the impact of land use change on Brazilian species [4, 10, 37, 42]. Other research has looked at the influence of the FC on biodiversity in certain biomes or regions [6, 32, 43, 47]. However, no previous research has looked into the possible contribution of FC implementation and enforcement to the protection and restoration of CEZs in Brazil. Furthermore, given the increasing annual rate of deforestation in the Amazon [17], new plans to develop transportation infrastructure that threatens remaining intact ecosystems [44], and recent reductions in environmental regulations [34], there is urgent need to assess the future potential risks and benefits on unprotected CEZs of implementing (or not) the FC, and investigate possible mitigating policies.

2. Materials and methods

2.1. Cost-effective conservation priority zones (CEZs)

Data on CEZs were generated by Yang *et al* [51] using a two-step procedure. In the first step, seven templates that identify global priority areas for biodiversity conservation were overlaid. The resulting map identified how many times an area appears in one or more templates: level 1, three or more times; level 2, two times; level 3, the area appears

Table 1. Total area of CEZs, area and percentage of unprotected CEZs, for Brazil, its largest biomes, and the MATOPIBA region; MATOPIBA comprises the Cerrado areas of the states of Maranhão, Tocantins, Piauí and Bahia.

Biome	Level 1, 2 and 3 CEZs (Mha)	Unprotected CEZs (Mha)	Unprotected CEZs (%)
Brazil	341.53	137.60	40.3
Amazon	280.49	95.46	34.0
Atlantic Forest	9.91	6.26	63.2
Caatinga	8.66	5.55	64.2
Cerrado	39.64	28.44	71.7
MATOPIBA	24.31	18.16	74.7

in only one template. These seven templates represented different approaches or criteria for biodiversity conservation: crisis ecoregions [48], biodiversity hotspots [26], Endemic Bird Areas [41], Key Biodiversity Areas [14], Centers of Plant Diversity [50], Global 200 Ecoregions [29], and Intact Forest Landscapes [33]. In the second step, the resulting three-level global map was compared with data of LIAs [18] to identify CEZs. LIAs are landscapes with minimal human density and impacts that are not primarily maintained for human needs (e.g. agricultural production, logging, etc). Natural processes predominate in these locations, however they may not necessarily have intact natural vegetation, ecosystem processes, or faunal assemblages. The LIA map rely on recent, high-resolution, publicly available worldwide data on human impacts such as human population, livestock density, forest change, land cover, and nighttime lighting [18].

As shown in table 1, CEZs cover 341.53 Mha or 40% of Brazil's land surface, with level 1, 2 and 3 areas covering 8%, 19%, and 13%, respectively. In terms of Brazil's main biomes, CEZs cover 67% (280.49 Mha) of the Amazon, 20% (39.64 Mha) of the Cerrado, 10% of the Caatinga (8.66 Mha), and 9% (9.91 Mha) of the Atlantic Forest. Although CEZs are in principle more suitable for PA designation, there are large areas of PAs that do not overlap with any CEZ. Conversely, 40.3% (137.60 Mha) of the surface of CEZs is not covered by any PA, with 34% (95.46 Mha) in the Amazon, 71.7% (28.44 Mha) in the Cerrado, 64.2% (5.55 Mha) in the Caatinga, 63.2% (6.26 Mha) in the Atlantic Forest.

2.2. GLOBIOM-Brazil land-use change model

An adaptation of the well-known land-use model GLOBIOM [15] to Brazil's specificities, GLOBIOM-Brazil [38, 39] is a global partial equilibrium model that simulates the competition for land among the agricultural, forestry and bioenergy sectors, subjected to resource, technology and policy restrictions. Mathematically, the competition for land is simulated at the pixel level by maximizing the sum of consumer and producer surpluses. Within Brazil, spatially explicit variables such as crop area or deforestation are geographically represented over a uniform grid of 0.5 by 0.5° (or approximately 50 km by 50 km around the Equator). Simulations are recursively run from 2000 (baseline year) to 2050, in 5 year time steps.

The initial baseline map of land cover and land use is provided by MapBiomas Collection 4.1 [40], issued in March 2020. The difference between Collection 4.1 and the most recent, Collection 7 (released in August 2022). is small in terms of level 1 general accuracy (90.2 and 91.3%, respectively), area discrepancy (1.3 and 1.5%), and allocation discrepancy (8.5 and 7.0%) is small. Statistics on crop and animal production are taken from Brazil's official yearly agricultural surveys [16]. Exogenous drivers, such as gross domestic product growth, population growth, and technological and dietary trends, follow the assumptions from the 'middle-of-the-road' shared socioeconomic pathway (SSP2) [30]. More details can be found in the SM.

2.3. Downscaling approach

The downscaling procedure is performed as a post-processing step, using GLOBIOM-Brazil 0.5° results as input. MapBiomas Collection 4.1 [40] maps, converted to 0.01° resolution and GLOBIOM land-use/cover classes, provide further constraints and information to the downscaling algorithm. For any given 0.5° input pixel, the algorithm generates a new set of 50 by 50 0.01° pixels containing the proportion relative to the new pixel area of the original land-use classes. This allocation is modeled and solved as a mathematical programming problem, in which class proportions are allocated such as to minimize a cost function, subject to a series of constraints. This cost function is partially composed of a gravity-type function that favors allocation patterns similar to the ones observed in the past. In addition, a second component of the cost function is included to enforce spatial similarity, following Tobler's First Law of Geography that 'everything is related to everything else, but near things are more related than distant things' [45]. Constraints serve to enforce general mathematical properties (e.g. land-use proportions must be positive and add to 1) and to represent assumed physical or legal restrictions (e.g. no farming in PAs).

Finally, restored native vegetation is allocated according to the specific scenario being run. In the case of the FC, FC + SFR and FCZD scenarios, the amount of restoration required by the spatial distribution of environmental debts (in legal reserves (LRs) and areas of permanent preservation (APPs)) is allocated following three criteria, the distribution of existing native vegetation (i.e. new growth is near old growth), hydrography (i.e. vegetation tends to concentrate around water bodies) and pasture (i.e. vegetation will tend to grow over former pasture), with no order of priority among them. To this end, gravity

Table 2. Scenario assumptions. Main assumptions for the various scenarios, including governance (illegal deforestation control (IDC) and native vegetation restoration), and zero-deforestation policy (ZD).

	Deforestation control				
Scenarios	Atl. Forest	Amazon	Cerrado	Rest of Brazil	Restoration
BAU	ZD	Partial IDC	Partial IDC	No	No
FC	ZD	Full IDC	Full IDC	Full IDC	Yes
FC+SFR	ZD	Full IDC	Full IDC	Full IDC	Yes
FC+CEZ	ZD	Full IDC	Full IDC	Full IDC	Yes
FCZD	ZD	Full IDC	ZD (>2025)	Full IDC	Yes

functions are constructed for each criterion, and, after normalization, multiplied together into a single cost function. In the case of the FC + CEZ scenario, restoration concentrates at anthropized areas inside or at the near vicinity of CEZs. Further details on the downscaling methodology can be found in the SM.

2.4. Simulation scenarios

Under various preservation/restoration policy limitations, five scenarios are used to capture anthropization in CEZs. Table 2 provides a summary of all scenarios. The BAU scenario maintains existing rates of native vegetation conversion to pasture and agriculture across Brazil's major biomes, with no restoration of illegally deforested areas, and little illegal deforestation control, which is calibrated by means of a probability of enforcement (see SM). Key parts of Brazil's FC are enforced in the FC scenario, including a deforestation prohibition on farms' LRs and permanent protection areas (APPs) after 2000, and mandatory restoration of illegally deforested areas of native vegetation after 2020. The FC + SFR (FC plus small farms restoration) scenario is based on the FC but includes mandatory restoration of illegally deforested areas prior to 2008 that were exempted from mandatory restoration by the Brazilian Parliament's small farms amnesty. The FC + CEZ scenario is essentially the FC scenario with a different restoration requirement: any places within unprotected CEZs that had experienced some degree of anthropization by 2020 must be restored. Note that there can be legal deforestation inside unprotected CEZs in the FC + CEZ, just like in the FC and FC + SFR scenarios. Finally, in addition to the FC requirements, the FCZD scenario contains a zero-deforestation strategy in the Cerrado beginning in 2025.

3. Results

3.1. Anthropization of unprotected CEZs by 2020

Table 3 presents the level of anthropization (in Mha and %) inside unprotected CEZs by 2020, estimated from MapBiomas Collection 4.1 data. In Brazil, CEZs cover 341 Mha, 57% (194 Mha) of which legally protected by Brazil's network of PAs. Of the 137.6 Mha of CEZs outside PAs (i.e. unprotected), 10.2 Mha (6.9%) have already suffered some degree of anthropization by 2020. In the largest Brazilian biomes, the level of CEZ anthropization is 12.3% (3.55 Mha) in the Cerrado, 3.3% (3.38 Mha) in the Amazon, 35.7% (2.34 Mha) in the Atlantic Forest and 10.4% (0.63 Mha) in the Caatinga. At level 1, the highest conservation priority level globally (see section 2), 12.7% (6.68 Mha) of unprotected CEZs in Brazil had been anthropized by 2020. Figure 1(a) presents the spatial distribution of anthropization inside unprotected CEZs by 2020. Red pixels indicate where anthropization exceeds 20% of the pixel area. Observe that in the Amazon anthropization areas inside unprotected CEZs follow the pattern of the main rivers (specially, the Amazon) and of the main roads that cross the biome. In the Cerrado, most anthropization is concentrated in the MATOPIBA region, and in the biome's east and northwest regions, along the borders with the Atlantic Forest and the Amazon, respectively. MATOPIBA is a region located along the border between the Cerrado and the Caatinga biomes, which comprises the Cerrado areas of the states of Maranhão, Tocantins, Piauí and Bahia (hence its acronym), and where the largest undisturbed remnants of the Cerrado vegetation are located [39]. These are areas that are now under intense pressure due to the rapid expansion of the agricultural frontier.

3.2. Projected anthropization of unprotected CEZs between 2020 and 2050

3.2.1. Brazil level

Table 4 presents numerical values for the projected amount of anthropization growth or decrease inside unprotected CEZs between 2020 and 2050, for all scenarios. In Brazil, under the BAU scenario, anthropization is projected to increase by 20.7 Mha, attaining 13.9% of the total surface of unprotected CEZs. Note that most of the anthropization increase occur inside level 1 CEZs. Results improve for scenarios FC, FC + SFR, FC + CEZ and FCZD, which include a ban on illegal anthropization of LRs and APPs in all biomes, and different restoration strategies of anthropized areas. The FZCD also includes a zero-deforestation policy in the Cerrado after 2025. Maps of accumulated anthropization and restoration inside unprotected CEZs between 2020 and 2050, for all scenarios, are presented in figures 1(b)–(f) and S1, respectively. Red and purple

Table 3. Anthropization inside unprotected CEZs by 2020, estimated from MapBiomas Collection 4.1 data, in Mha and %.

	CEZ level			
Biome	Level 1	Level 2	Level 3	All
Brazil	6.68 (12.7%)	1.21 (1.9%)	2.31 (7.9%)	10.20 (6.9%)
Amazon	0.44 (3.1%)	0.86 (1.4%)	2.09 (7.6%)	3.38 (3.3%)
Atlantic forest	2.19 (35.1%)	0.09 (41.3%)	0.06 (73.2%)	2.34 (35.7%)
Caatinga	0.39 (10.9%)	0.16 (9.2%)	0.08 (10.3%)	0.63 (10.4%)
Cerrado	3.52 (12.4%)	0.02 (13.0%)	0.01 (8.8%)	3.55 (12.3%)
MATOPIBA	1.50 (8.3%)	0.01 (9.1%)	0.01 (16.1%)	1.53 (8.4%)

Table 4. Projected amount of anthropization growth or decrease inside unprotected CEZs by 2050, for all scenarios, in Mha and %.

		CEZ level			
Scenario	Biome	Level 1	Level 2	Level 3	All
BAU	Brazil	10.52 (41.5%)	4.96 (7.7%)	4.60 (16.1%)	20.07 (13.9%)
	Amazon	1.54 (11.2%)	4.81 (7.8%)	4.31 (16.2%)	10.66 (10.5%)
	Atlantic Forest	0.00 (0.0%)	0.00 (0.0%)	0.00 (0.0%)	0.00 (0.0%)
	Caatinga	0.09 (2.8%)	0.03 (2.2%)	0.09 (12.6%)	0.23 (3.9%)
	Cerrado	8.87 (32.1%)	0.01 (4.6%)	0.03 (24.5%)	8.9 (31.9%)
	MATOPIBA	7.39 (41.5%)	0.00 (1.9%)	0.03 (34.0%)	7.42 (41.1%)
FC	Brazil	4.98 (9.7%)	1.21 (1.8%)	0.83 (2.9%)	7.02 (4.9%)
	Amazon	0.19 (1.4%)	1.10 (1.8%)	0.68 (2.6%)	1.97 (1.9%)
	Atlantic Forest	−0.69 (−10.9%)	−0.01 (−6.6%)	−0.01 (−9.1%)	−0.71 (−10.7%)
	Caatinga	0.37 (10.6%)	0.09 (5.5%)	0.08 (11.1%)	0.55 (9.3%)
	Cerrado	5.10 (18.4%)	0.00 (−5.0%)	0.02 (15.4%)	5.11 (18.3%)
	MATOPIBA	3.96 (22.2%)	−0.01 (−5.3%)	0.02 (18.0%)	3.97 (22.0%)
FC + SFR	Brazil	4.37 (8.5%)	0.95 (1.4%)	0.60 (2.1%)	5.92 (4.1%)
	Amazon	0.08 (0.6%)	0.88 (1.4%)	0.46 (1.8%)	1.42 (1.4%)
	Atlantic Forest	−0.81 (−12.9%)	−0.02 (−9.6%)	−0.01 (−13.3%)	−0.84 (−12.8%)
	Caatinga	0.37 (10.8%)	0.06 (3.9%)	0.09 (11.8%)	0.53 (9.0%)
	Cerrado	4.72 (8.5%)	0.95 (1.40%)	0.60 (2.1%)	5.92 (21.2%)
	MATOPIBA	3.80 (21.3%)	−0.02 (−9.5%)	0.02 (13.09%)	3.80 (21.0%)
FC + CEZ	Brazil	−2.52 (−4.8%)	−0.07 (−0.1%)	−0.67 (−2.4%)	−3.27 (−2.2%)
	Amazon	−0.54 (−3.9%)	0.09 (0.1%)	−0.59 (−2.2%)	−1.05 (−1.0%)
	Atlantic Forest	−1.44 (−22.9%)	−0.03 (−16.5%)	−0.05 (−57.4%)	−1.52 (−23.1%)
	Caatinga	−0.12 (−3.4%)	−0.11 (−6.7%)	−0.05 (−6.6%)	−0.28 (−4.7%)
	Cerrado	−0.43 (−1.5%)	−0.01 (−16.3%)	0.0 (4.0%)	−0.45 (−1.6%)
	MATOPIBA	1.66 (9.4%)	−0.02 (−12.2%)	0.01 (8.4%)	1.66 (9.2%)
FCZD	Brazil	1.11 (2.2%)	1.17 (1.8%)	0.81 (2.8%)	3.09 (2.2%)
	Amazon	0.18 (1.3%)	1.06 (1.7%)	0.66 (2.5%)	1.9 (1.9%)
	Atlantic Forest	−0.69 (−10.9%)	−0.01 (−6.6%)	−0.01 (−9.0%)	−0.71 (−10.7%)
	Caatinga	0.31 (9.0%)	0.10 (5.9%)	0.10 (13.0%)	0.51 (8.6%)
	Cerrado	1.29 (4.7%)	0.00 (6.1%)	0.00 (4.6%)	1.28 (4.6%)
	MATOPIBA	1.11 (6.2%)	−0.01 (−5.6%)	0.01 (3.3%)	1.10 (6.1%)

indicate pixels with more than 20% of their area anthropized or restored, respectively.

Compared to BAU, anthropization inside unprotected CEZs decreases to 7.02 Mha (4.9%), for the FC scenario between 2020 and 2050. As one increases the area of restored native vegetation from 12.4 Mha (FC) to 34.9 Mha (FC + SFR), anthropization decreases to 5.92 Mha (4.1%). Comparing FC to FC + SFR shows that the large increase in restoration area (more 22.5 Mha) has a surprisingly small impact on anthropization inside unprotected CEZs (less 1.10 Mha). This result can be explained by the fact that the spatial distribution of restored vegetation under the FC and FC + SFR (and, also, FCZD) scenarios follows from FC legal requirements (restoration of LRs and APPs), which are blind to the location of CEZs. To address this issue, in the FC + CEZ scenario, we prioritize restoration of areas within unprotected CEZs that have already been anthropized by 2020 (red pixels in figure 1(a)). Compared to 2020, this strategy decreases anthropization by −3.27 Mha (−2.2%) in 2050, the best result among all scenarios.

However, it is important to note that more restoration may result, through displacement of agricultural activity, in more loss of biodiversity-rich, old-growth native vegetation areas. This explains why by

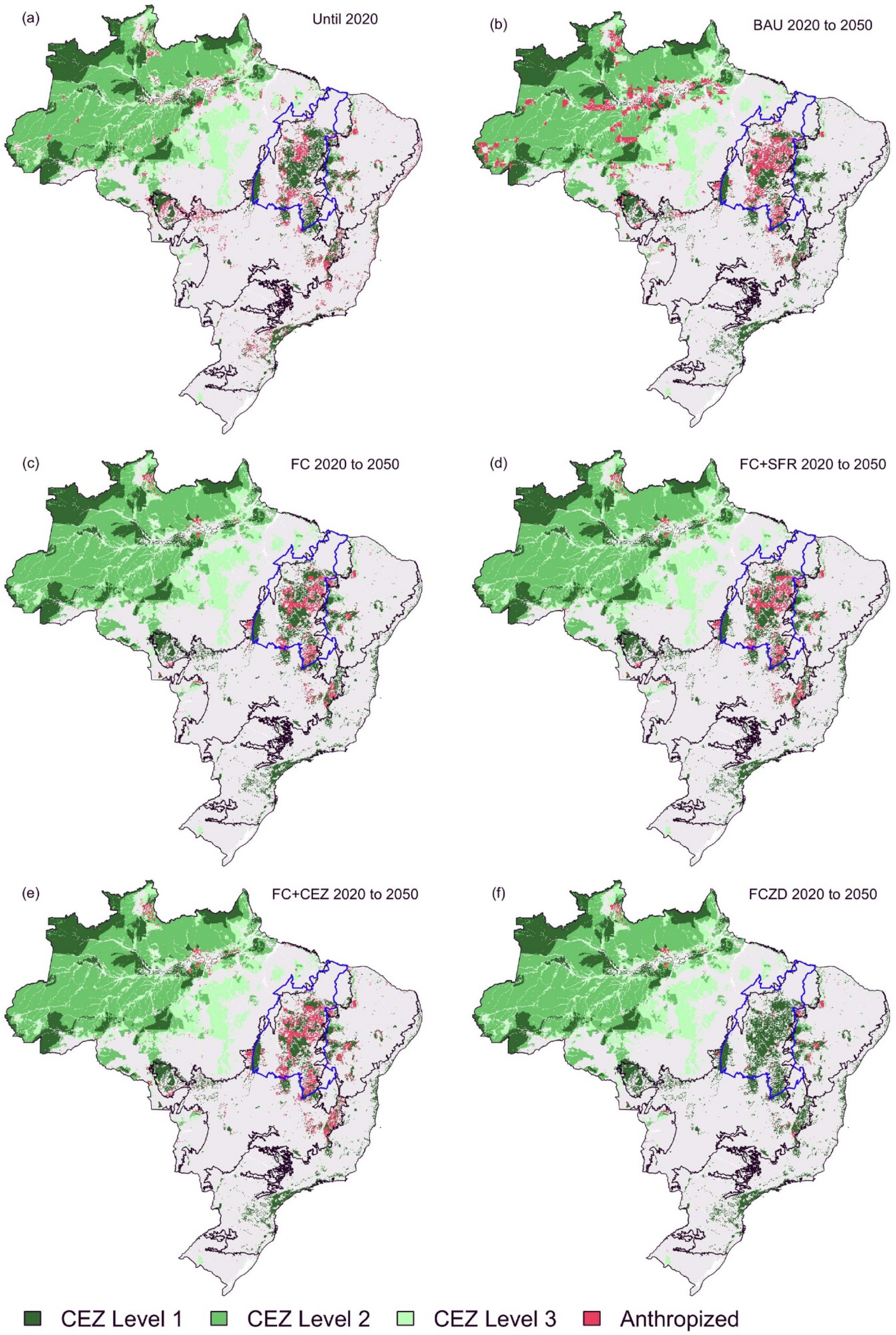

Figure 1. Spatial distribution of anthropization inside unprotected CEZs by 2020 (a), and of projected accumulated anthropization between 2020 and 2050, for scenarios BAU (b), FC (c), FC + SFR (d), FC + CEZ (e) and FCZD (f). Red pixels indicate where anthropization exceeds 20% of the pixel area. Black lines indicate the borders of Brazil's biomes; the blue line delimitates the MATOPIBA region; areas outside CEZs are colored in grey.

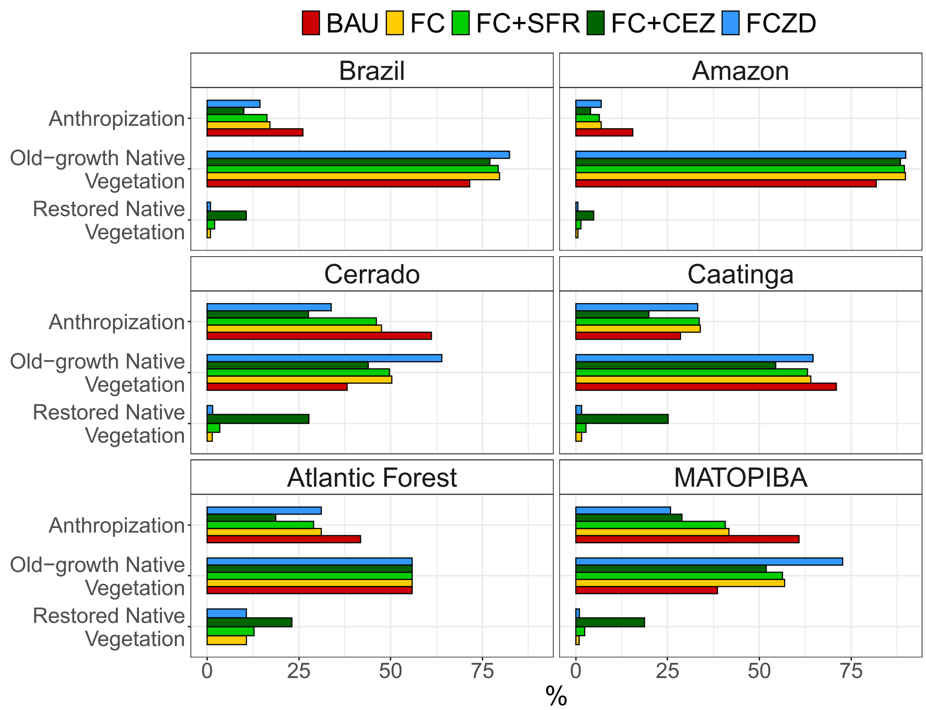

Figure 2. Percentage of anthropized area, and old-growth and restored native vegetation areas inside unprotected CEZs between by 2050, for all scenarios, in %.

2050 the percentage of old-growth native vegetation inside unprotected CEZs in the FC + CEZ scenario is the smallest among all FC-based scenarios (figure 2). The FCZD scenario is an attempt to mitigate this problem by introducing a zero-deforestation policy in the Cerrado, the most threatened biome, from 2026 onward. This scenario permits to maintain a large share of Brazil's old-growth native vegetation inside unprotected CEZs, while keeping almost constant the level of anthropization between 2020 and 2050.

3.2.2. Biome level

Under the BAU scenario, the Cerrado and the Amazon biomes are the most vulnerable. In the Cerrado, anthropization level inside unprotected CEZs increases to 31.9% (8.9 Mha) in 2050, mostly inside the MATOPIBA region (7.42 Mha). In comparison, in the Amazon, where the network of PAs covers more than 50% of the biome, anthropization level remains relatively low (10.5%). However, in terms of area, accumulated anthropization in the Amazon inside unprotected CEZs reaches 10.66 Mha, a larger area than in the Cerrado. Overall, under the BAU scenario, these two biomes account for more than 97% of the anthropization projected to occur inside unprotected CEZs in Brazil between 2020 and 2050.

For the other scenarios, results depend on the peculiarities of each biome. In the Atlantic Forest, a biome where highly-fragmented, intact remnants outside PAs are protected by a deforestation ban, FC-based scenarios work well, and reduce through restoration the anthropization level inside unprotected CEZs: −10.7% (FC and FCZD), −12.8% (FC + SFR) and −23.1% (FC + CEZ), between 2020 and 2050.

In the Amazon biome, strongly pressured by the advance of large-scale agriculture (mainly, cattle ranching), all four FC-based scenarios are able to, in three decades, to keep almost constant or even reduce anthropization inside unprotected CEZs to percentages that ranges from −1% (FC + CEZ) to 1.9% (FC), compared to 10.5% in the BAU scenario. It is important to note that, differently from other biomes, in the Amazon anthropization growth inside unprotected CEZs occurs mostly on level 2 areas, for all but the FC + CEZ scenario.

In the Cerrado, the powerhouse of Brazil's agribusiness, the situation is different. Scenarios FC, FC + SFR and, obviously, BAU are not able to stop the growth of anthropization inside unprotected CEZs. For these three scenarios, anthropization inside unprotected CEZs increases between 2020 and 2050 to 31.9% (8.9 Mha) in BAU scenario, 18.3% (5 Mha) in the FC scenario, and 21.2% (6 Mha) in the FC-SFC scenario. Note that 83% (BAU), 78% (FC) and 64% (FC + SFR) of this expansion of anthropization occurs in the MATOPIBA region. Drivers of anthropization in the Cerrado are its aptitude for agriculture, demand for agricultural products (mainly, beef and soybeans/maize), proximity to markets, transport and processing infrastructure, and, mainly, lower level of protection relative to the Amazon and Atlantic Forest biomes. As expected, the scenario FCZD manages to stabilize the level of anthropization in the Cerrado. Inside unprotected CEZs in Cerrado,

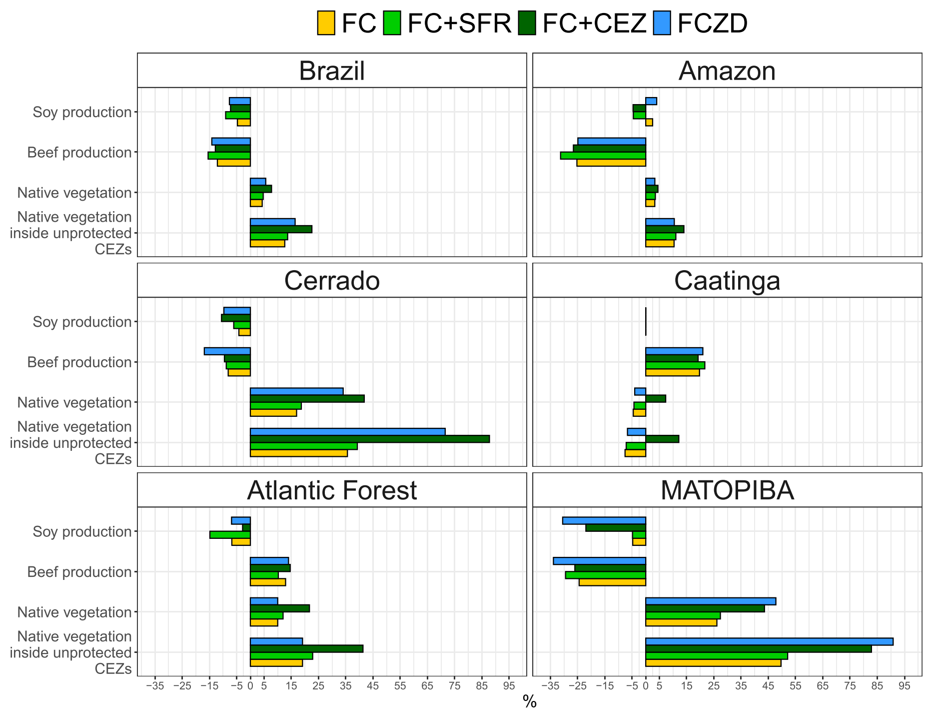

Figure 3. Percentage of gain or loss relative to the BAU scenario of beef and soybeans production (in volume), total native vegetation area, and native vegetation area inside unprotected CEZs by 2050, for all scenarios.

anthropization increases only 4.6% (or 1.28 Mha) in three decades. In fact, this result corresponds to anthropization that happened before the implementation of the zero-deforestation policy in 2025. With its policy of CEZ-targeted restoration, the FC + CEZ achieves contradictory results in the Cerrado biome: −1.6% reduction on the level of anthropization but with the smallest area of old-growth native vegetation after the BAU scenario.

Caatinga's arid climate reduces its aptitude for large-scale agricultural activity. Caatinga is also relatively less protected by the environmental legislation than its neighboring biomes, the Cerrado and the Atlantic Forest. In this context, the FC + CEZ scenario is the only one that performs well, managing to reduce the level of anthropization inside unprotected CEZs by −4.7% (−0.28 Mha), between 2020 and 2050. Finally, it is worth mentioning that, regardless the scenario and region.

3.2.3. Conservation versus production

Naturally, policies like the ones modeled by our scenarios, in addition to their positive impacts on the environment, may also affect agricultural production. In figure 3, we present the percentage of gain or loss (in volume) by 2050, relative to the BAU scenario, of the production of beef and soybeans, used here as proxies of Brazil's agribusiness sector dynamism. These results are compared to two proxies of conservation: the total area of native vegetation and the total area of native vegetation inside unprotected CEZs, in Brazil and its four largest biomes (plus the MATOPIBA region).

At the country level, we observe that policies to preserve and restore Brazil's CEZs, at least the ones represented by our scenarios, incur in production losses due to higher restrictions on access to land for agricultural expansion. For the FCZD scenario, for an increase of 17% of native vegetation area inside unprotected CEZs, there is a loss of approximately 15% in the beef production and of 7% in the soybeans production, relative to the BAU scenario by 2050. Losses and gains of the same magnitude are obtained with the FC, FC + SFR and FC + CEZ scenarios.

At the regional level, the picture is more complex due to production and deforestation leakages across biomes. In the Cerrado, for the FCZD scenario, losses in beef and soybeans production are, respectively, 18% and 10%, but the environmental gains are impressive, ranging from around 35% for native vegetation to more than 70% for native vegetation inside CEZs (respectively, 48% and 92% in the MATOPIBA region). In the Atlantic Forest, compared to BAU, losses in beef production, seen in the Cerrado, are replaced by gains of up to 15%, depending on the scenario. Moreover, the variation in native vegetation area inside unprotected CEZs is still positive, reaching 42% in the FC + CEZ scenario, and 20% in the FCZD. In the Amazon, losses relative to BAU on the soy production are the smallest (there is even some gain for the FC and FCZD scenarios) but are the highest on the beef production among all biomes. In the Caatinga biome, a biome with low agricultural output, our scenarios produce no production losses but also no environmental gains relative to BAU. The exception is the FC + CEZ, with a gain by 2050 of 7% and 13% in the area of native vegetation and of native vegetation inside CEZs, respectively.

4. Discussion

More than half of Brazil's 1172 endangered species are placed on the Red List [3] due to the ongoing reduction in size, extent, and/or quality of their habitats as a result of the expansion of the agricultural activity [3, 22]. In this context, it makes sense to preserve and restore CEZs, which by construction are biodiversity-rich areas, until recently relatively spared by human activities like agriculture. However, from the above presented results, it is clear that keeping the current situation represented by the BAU scenario (almost no illegal deforestation control, and no restoration of illegally deforested areas), Brazil is in route to loose a large share of its unprotected CEZs in the coming decades, with dire consequences for its biodiversity and other ecosystem services.

The election and inauguration of President Luiz Inácio Lula da Silva (January 2023), who pledged a fundamental departure from his predecessor's environmental policies, provides some cause for optimism. In terms of its legal framework, Brazil already possesses, if there is political will, some of the means for quick action. The FC, which is the primary legal document governing the protection and restoration of native vegetation on rural private lands in Brazil, has been promulgated in 2012. Since 2017, the government also oversees the National Plan for Native Vegetation Recovery (PLANAVEG), which has the stated goal of achieving the 12 Mha restoration objective announced in Brazil's NDC and Bonn Challenge pledge.

Indeed, our results with the FC scenario show that truly enforcing Brazil's FC is capable in the Amazon and the Atlantic Forest biomes to stop or even revert the loss of native vegetation inside unprotected CEZs. The code requires landowners to conserve and restore native vegetation inside APPs and LRs. LRs account for more than one-third of the country's original vegetation and contribute to biodiversity preservation [23]. In the Amazon, LRs cover up to 80% of total property area, explaining why the FC scenario fared well in maintaining the biome's unprotected CEZs, with fewer than 2 Mha (out of 95 Mha) anthropized in three decades. Since protected and unprotected CEZs together cover 67% of the Amazon, enforcing the FC represents a great step towards the overall conservation of the biome. The situation is different in the Atlantic Forest biome. Although landowners are required to protect only 20% of their properties as LR, the Atlantic Forest is protected by federal law 11.428/2006, which imposed since 2006 a de facto ban on deforestation in the biome. By 2050, 0.7 Mha of Atlantic Forest will be recovered inside unprotected CEZs. However, this good result may hide the destruction of older forests and their replacement by younger ones [35].

In two biomes, the Caatinga and, above all, the Cerrado, the FC scenario alone was not able to stop the destruction of native vegetation inside unprotected CEZs. In other words, these two biomes require the creation (and the effective implementation) of additional, specific policies. Ideally, these policies should combine targeted restoration, as in the FC + CEZ or FC + SFR scenarios, with increased protection against deforestation, as in the FCZD. Targeted restoration (i.e. outside the FC framework) may need to be undertaken as part of a program that pays landowners directly for restored ecological services. The REDD+ (Reducing Emissions from Deforestation and Forest Degradation) system is a well-known example. The Brazilian National REDD+ Strategy (ENREDD+) was introduced in 2016, and focuses on initiatives that prevent deforestation and support forest recovery and conservation. Currently, national funds such as the Amazon and the Climate Fund form the backbone of the ENREDD+ financial architecture [13].

In the Caatinga biome, the FC + CEZ scenario allows by 2050 the restoration of almost half (0.38 Mha) of the area already anthropized by 2020. In the Cerrado, currently the epicenter of Brazil's agrobusiness expansion, 8.9 out 28.4 Mha of native vegetation inside unprotected CEZs may be anthropized between 2020 and 2050, according to the BAU scenario. In the FC + CEZ scenario, this loss is transformed into a net gain of 0.45 Mha. However, as a side effect, the FC + CEZ scenario generates an increased loss of biodiversity-rich, old-growth native vegetation areas, which are replaced by restored areas elsewhere.

Overall, only the FCZD scenario permitted to effectively protect the biome, and its threatened biodiversity. Basically, the FCZD scenario extends to the Cerrado from 2026 onwards the same level of protection granted by law to the Atlantic Forest in 2006. This initiative may be politically and economically difficult to implement biome-wide (not to mention Brazil-wide). Zeroing or even slowing deforestation requires advances in frontier governance, law enforcement, and mechanisms for punishing deforesters, and persuasive measures to engage producers [27, 28]. An alternative approach would be to extend the zero-deforestation policy initially to the MATOPIBA region, which covers 36% of the Cerrado but contains within its borders 64% of the biome's unprotected CEZs. Private-sector initiatives, like the Soy Moratorium in the Amazon [39], to combat deforestation and the conversion of native vegetation into pasture or cropland could also be an option, but implementing a similar agreement in the Cerrado faces major political and geographical obstacles [28].

The creation of new PAs to avoid the collapse of key ecosystem services, or the habitat loss of critically endangered species, although not the focus of this study (PAs are public land), should also be considered as a policy option. Creating PAs for strict protection or sustainable use at all CEZ locations would most likely be the optimal scenario. This measure would add 137.6 million ha (42.1 million ha outside the Amazon) to the country's public network of PAs. However, the proportional financial implications in terms of land expropriation and management, and commensurate political and social repercussions in terms of land use limitations should also be considered. More realistically, given Cerrado's critical situation [43], the creation of conservation areas at all level 1, unprotected CEZs would bring a much needed respite to this hotspot of biodiversity by adding 28.4 Mha to the current network (17.5 Mha, excluding indigenous lands) of PAs in this biome. A similar measure in the Caatinga, would add 3.6 Mha of protected land to the biome.

Summarizing, the complexity and magnitude of the task of protecting and restoring Brazil's unprotected CEZs requires a mix of additional policies, like targeted restoration, zero-deforestation, creation of PAs, built upon the existing legal framework defined by the (strictly enforced) FC. Naturally, the policies investigated here may also imply in production losses *relative* to the BAU scenario, as they more or less restrict access to land. Therefore, a careful political negotiation is needed to find the best balance between conservation measures and the economic interests of land owners. At stake are biodiversity conservation, climate change, food and energy production, and social justice in Brazil. Note that previous studies ([4–7, 10, 32, 36–38, 42, 43, 47]), using different methodologies, and with different goals, arrive to similar findings: deforestation is a threat to Brazil's rich biodiversity, be it a whole biome, a class or a single species; Brazil's current environmental legal framework needs improvements; and a compromise between agricultural production and preservation/restoration is possible.

Finally, it is important to note that, per construction, CEZs are a subset of the larger set of conservation priority zones (CPZs), which includes disturbed and undisturbed biodiversity-rich areas, and covers 89.1% of the Brazilian territory [51]. Since, with the exception of the FC-CEZ restoration strategy, all our scenarios (BAU included) do not depend on the location of both CPZs and CEZs (see table 2), most of the qualitative findings discussed in this section are also applicable to CPZs.

5. Conclusion

In this study, we provided the first high-spatial resolution evaluation of the evolution of anthropization inside Brazil's unprotected CEZs, for the period 2020–2050. Our results indicate that Brazil will loose a large share of its CEZs in the coming decades, if the almost complete disregard for the environment persists. However, there are ways to improve the current situation. The FC scenario demonstrates how native vegetation loss inside unprotected CEZs in the Amazon and Atlantic Forest biomes can be stopped or even reversed by effectively enforcing Brazil's FC. Additional policies are needed for the Cerrado and Caating biomes that combine enhanced deforestation protection with targeted restoration, as in the FC + CEZ or FC + SFR scenarios. The establishment of PAs in all level 1, unprotected CEZs in these two biomes should also be taken into consideration, at least in the most vulnerable areas, like the MATOPIBA.

Overall, we observed that there is no universal policy that fits the varying preservation and production constraints and needs of Brazil's different biomes. Optimally, for a continental-sized, highly diverse country like Brazil, preservation policies should be designed at least at the biome level, to increase their effectiveness and avoid unnecessary costs. We expect that the results of this study can help improving the conservation and restoration of CEZs, providing valuable support for the protection of Brazil's unique biodiversity resources.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://figshare.com/s/fb5c3fc1652eed45023e [52].

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