

Article

Threats and Opportunities for Biodiversity Conservation and Sustainable Use in the Buffer Zones of National Parks in the Brazilian Cerrado

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Abstract

In recent decades, the Brazilian Cerrado has faced rapid land conversion, resulting in the loss of approximately half of its original vegetation cover. Most existing conservation units within the biome are increasingly threatened by the expansion of land use around their boundaries. The establishment of buffer zones with land use regulations may protect biodiversity within these protected areas. In this study, we evaluated and ranked the 10 km buffer zones of 15 national parks (NPs) located in the Cerrado biome, identifying their priority for biodiversity conservation and sustainable land use interventions. The analysis considered the following data: land use and land cover change from 2012 to 2020, extent of natural vegetation fragments, presence or absence of state and municipal conservation units within the buffer zones, and drainage density. Two multicriteria analysis methods, the analytic hierarchy process and the weighted linear combination, were applied to classify the buffer zones into five levels of threat: very high, high, moderate, low, and very low. Among the 15 buffer zones analyzed, 11 were classified as having high to very high priority for conservation actions. The buffer zones surrounding the Serra da Bodoquena, Emas, Canastra, and Brasília NPs were ranked as having very high priority. Between 2012 and 2020, the most severe reductions in ecological connectivity were observed in the buffer zones of Grande Sertão Veredas (44.5%), Nascentes do Rio Parnaíba (40.4%), and Serra das Confusões (36.7%). Given the relatively high proportion of natural vegetation in the buffer zones located in the northern Cerrado, we recommend prioritizing conservation efforts in this region. In contrast, in the southern portion of the biome, where land occupation is more intense, strategies should focus on promoting environmentally sustainable land use practices.

Keywords: conservation units; protected areas; buffer zones; land use and land cover; tropical savanna



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1. Introduction

Previous studies have shown that global species richness and abundance are approximately 10% and 15% higher in protected areas than in unprotected ones [1]. Territorial conservation initiatives are among the most effective strategies for the sustainable use of biodiversity, aligning with the concept of “living in harmony with nature” [2]. In Brazil, the establishment of protected areas (PAs) has been the primary approach for biodiversity conservation, which is ruled by the National System of Protected Areas (SNUC) [3,4].

One effective strategy to mitigate the negative impacts of land conversion in protected areas is the creation of buffer zones, which increase the resilience of these ecosystems [5,6]. Buffer zones are widely recognized for providing ecological, social, economic, and institutional benefits. Ecologically, they help restrict human access and illegal activities, protect permanently preserved areas from invasive species, and serve as habitat extensions for wide-ranging species inhabiting conservation areas [7].

The SNUC mandates the establishment of buffer zones to reduce negative environmental impacts on conservation units (Article 2, Clause XVIII, Federal Law No. 9985/2000). Exceptions to this requirement include Environmental Protection Areas and Private Natural Heritage Reserves. A buffer zone is defined as the surrounding area of a conservation unit where human activities are subject to specific rules and restrictions aimed at minimizing adverse effects on the unit. These effects include environmental fragmentation, the spread of invasive exotic species, edge effects on the interior of conservation units, and pressures from urbanization [8,9]. Numerous studies have indicated that many of challenges faced by conservation units involve land use changes and activities occurring in adjacent areas (e.g., [10]). The primary functions of buffer zones are to support the sustainable use of natural resources and to mitigate adverse environmental impacts on conservation units. The regulation of these units and their buffer zones is detailed in a technical document known as the Management Plan.

The Brazilian tropical savanna (Cerrado biome) covers approximately 204 million hectares in the central part of the country [11]. Nearly half of the Cerrado natural vegetation, encompassing grasslands, shrublands, and forestlands, has already been suppressed, mainly for agricultural and livestock activities [12]. The current Native Vegetation Protection Law, popularly known as the Brazilian Forest Code, has been in effect since April 2012, establishing regulations for the exploitation, conservation, and restoration of natural vegetation across the country [13]. Compared to the Brazilian Amazon, the Forest Code is less restrictive for the Cerrado: only 20% of natural vegetation on rural properties must be preserved in the Cerrado, whereas 80% must be preserved in the Amazon. This discrepancy highlights the need for effective law enforcement procedures in the Cerrado through actions that include enhanced monitoring, inspection, and effective application of administrative and criminal penalties for violators [14]. Such measures are critical given the Cerrado's ecological importance. The biome hosts numerous endemic plant species, encompasses 10 of Brazil's 12 major hydrographic regions, and provides a wide range of ecosystem services, including genetic resource provision, carbon sequestration, pollination support, and cultural services such as tourism and recreation [15]. Unsustainable land use in the Cerrado risks pushing the biome toward an ecological tipping point, leading to irreversible fragmentation, biodiversity loss, spread of invasive species, soil degradation, and water pollution [16]. Since 1986, vegetation loss has led to a 20% increase in habitat fragmentation within this biome [17].

Only 8.6% of the Cerrado biome is covered by federal conservation units, compared to 28% in the Brazilian Amazon. In the Cerrado, the main purpose of these protected areas is the biodiversity conservation. This contrasts with protected areas in the Brazilian Amazon, which are designed not only to preserve biodiversity but also to serve as a green barrier against the expansion of the agricultural frontier from south to north [18]. Despite their importance, only 16% of the federal conservation units in the Cerrado have established management plans [19,20]. Furthermore, the buffer zones surrounding these conservation units present a high degree of native vegetation fragmentation [21–23], which directly affects local fauna, as many species do not remain confined within PAs. State and municipal conservation units have also been ineffective in preventing disruptions to the natural processes of native plant species dispersion and colonization [24]. Despite recent

advances in Brazil's environmental legislation aimed at promoting the sustainable use of natural resources, there remains a significant gap in strategic planning to identify and prioritize regions where conservation efforts can reconcile biodiversity protection with socioeconomic development [25]. Conducting environmental characterizations, especially within and around conservation units, can contribute to the formulation of strategies and public policies for the effective establishment, governance, management, and conservation of these areas [9]. In other words, the mere designation of a conservation unit does not guarantee effective biodiversity conservation. Therefore, it is essential to assess both threats and opportunities for biodiversity conservation and sustainable use, especially in the buffer zones surrounding conservation units. To date, no studies have quantified the extent of anthropogenic pressure in areas surrounding Cerrado conservation units, that is, there is no study addressing the magnitude of land use pressure in areas surrounding the NPs in this biome.

Connectivity analyses are widely applied in the management, planning, establishment, research, and monitoring of conservation units. Connectivity refers to the ability of a landscape's structure and composition to facilitate or hinder the movement and dispersal of genes, individuals, and populations [24,26]. To minimize conflicts between agricultural production and biodiversity conservation, it is essential to identify areas with high functional connectivity, which serve as biodiversity preservation hotspots [27]. Several indices are available to assess landscape connectivity, including the Integral Index of Connectivity (IIC), which is sensitive to different types of landscape changes [27–29]. Landscape connectivity reflects the extent to which a landscape promotes or inhibits the movement of organisms or ecological processes [30]. The IIC evaluates the contribution of each habitat fragment to overall connectivity by combining fragment characteristics with the number of connections in the shortest paths between pairs of fragments [11]. Previous studies conducted, for example, by Manes et al. [27] and Schwaida et al. [31], have demonstrated the effectiveness of the IIC in identifying priority areas for biodiversity conservation and environmental compensation within the Cerrado biome.

Another important tool in conservation planning is the multicriteria analysis, which has been applied to identify priority areas for biodiversity conservation, evaluate the effectiveness of environmental policies, designate areas for ecological restoration, create ecological corridors, and assess risks of environmental degradation [31–34]. Among the various multicriteria analysis techniques, the analytic hierarchy process (AHP) allows structured decision-making through spatial analysis integrated with geographic information systems (GIS) [35]. In the Cerrado biome, AHP has been successfully employed, for example, by Morandi et al. [36] to delineate ecological corridors between two conservation units located in the Cerrado biome.

An important yet often overlooked attribute in multicriteria analyses for biodiversity conservation, especially within conservation units and their surrounding areas, is drainage density (Dd), mainly in regions under strong anthropogenic pressure (e.g., [1]). The quality of water resources in protected areas can be affected to varying degrees depending on the configuration of the Dd network and the direction of water flow, whether entering or exiting the protected areas. Dd in a given region is influenced by factors such as soil infiltration capacity, terrain resistance to erosion, precipitation patterns, topography, and vegetation cover [37–39]. The objective of this study was to identify both threats and opportunities for biodiversity conservation in the buffer zones of NPs in the Brazilian Cerrado and to develop a ranking of the most threatened parks through multicriteria analysis. The novelty of this study lies in its application of a multicriteria approach to assess the status of buffer zones around the Cerrado's NPs, a region that has received comparatively less attention than the Brazilian Amazon from both scientific community and policymakers.

2. Materials and Methods

2.1. Study Area

The study area encompasses the buffer zones of 15 NPs located in the Cerrado biome (Figure 1). These NPs are fully protected, with strict regulations for activities that could cause high environmental impact, both within and around their boundaries. Each park's specific regulations are outlined in its respective management plan, which prohibits the direct use of natural resources within park boundaries and mandates the establishment of buffer zones [3].

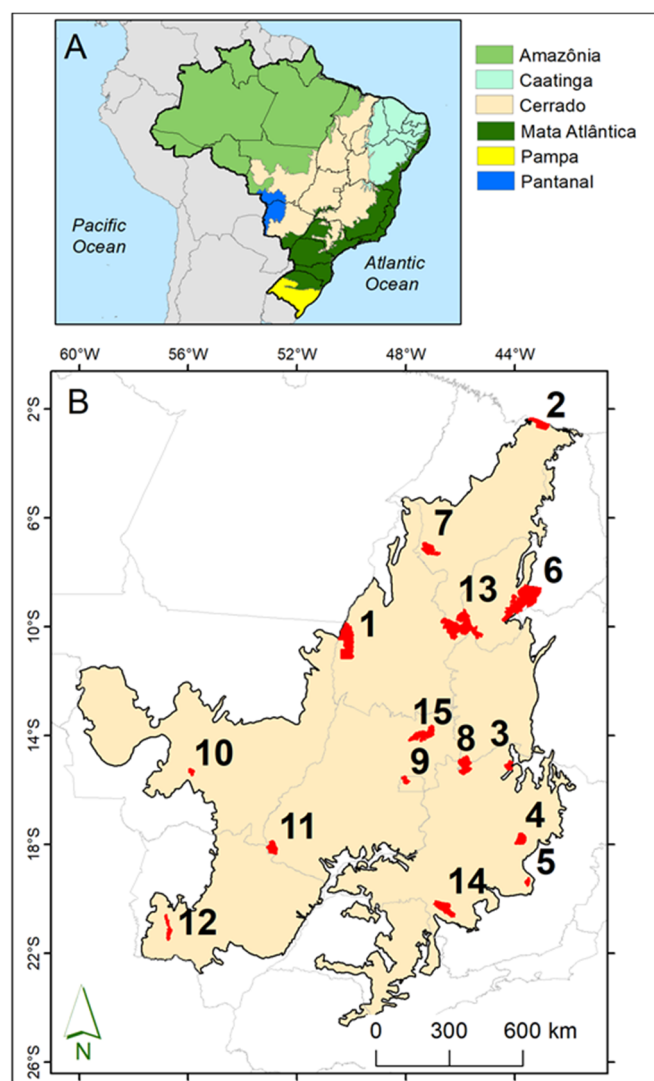


Figure 1. Location of the Cerrado biome in Brazil (A) and the 15 national parks included in the study area within the Cerrado biome (B). National parks identification: 1—Araguaia; 2—Lençóis Maranhenses; 3—Cavernas do Peruaçu; 4—Sempre-Vivas; 5—Serra do Cipó; 6—Serra das Confusões; 7—Chapada das Mesas; 8—Grande Sertão Veredas; 9—Brasília; 10—Chapada dos Guimarães; 11—Emas; 12—Serra da Bodoquena; 13—Nascentes do Rio Parnaíba; 14—Serra da Canastra; and 15—Chapada dos Veadeiros.

Although all 15 parks included in this study have approved management plans, only seven have officially designated buffer zones. To ensure consistency in the analysis, a standardized 10 km buffer was applied around each park, based on CONAMA Resolution No. 13, dated 6 December 1990. The Serra das Confusões NP, although primarily located in the Caatinga biome, was included in this study due to its strategic location within an

important ecotone between the Caatinga and Cerrado biomes. For the Lençóis Maranhenses NP, located along the coast of Maranhão State, only the continental portion of its 10 km buffer zone was considered.

2.2. Methods

Figure 2 shows the main steps of the analyses conducted in this study. The multitemporal analyses covered the period from 2000 to 2020. The year 2000 was selected because it corresponds to the establishment of the SNUC, while 2020 was the most recent year for which annual land use and land cover (LULC) maps were available from the MapBiomas Project, coinciding with the beginning of this study. The main analytical steps included assessing temporal changes in LULC; evaluating the functional connectivity of the landscape; and developing a ranking to guide conservation and sustainable land use actions in the buffer zones. The main datasets used in this study were the map of Brazilian biomes [40]; the maps of federal, state, and municipal conservation units [41]; the LULC maps of Brazil [12]; and the national drainage network map [42].

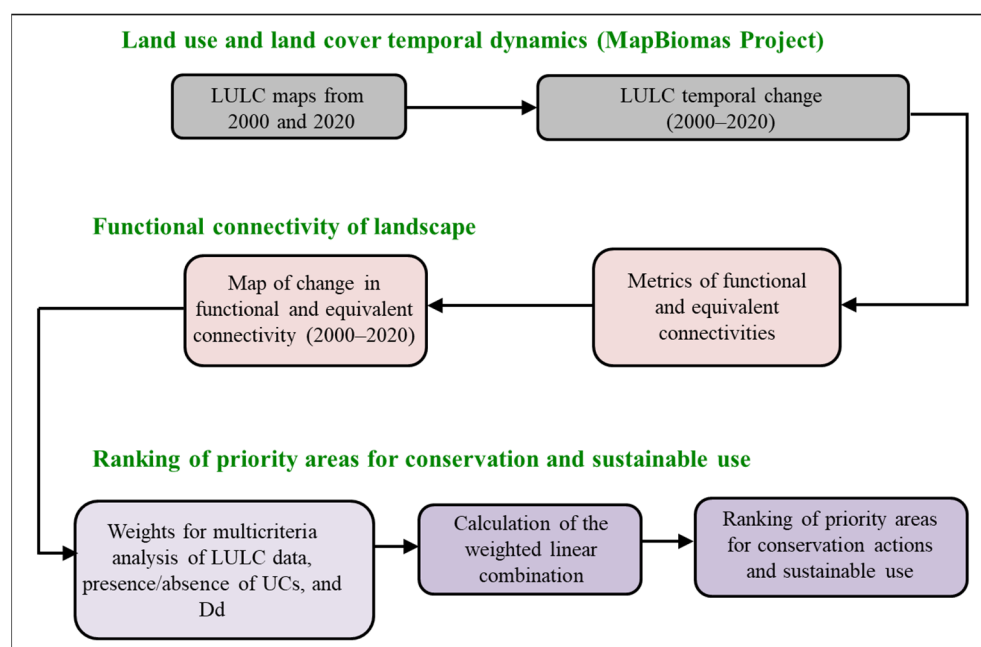


Figure 2. Flowchart showing the main analytical steps conducted in this study. LULC = land use and land cover; UCs = conservation units; and Dd = drainage density.

2.2.1. Land Use and Land Cover Data

The MapBiomas Project is a multi-institutional initiative that produces annual LULC maps of Brazil. These maps are generated through pixel-by-pixel classification of Landsat satellite images with a spatial resolution of 30 m. The classification process is fully automated using the Random Forest machine learning algorithm implemented on the Google Earth Engine platform, which allows cloud-based spatial analysis [12]. In this study, the 21 LULC classes identified in the study areas were grouped into four main categories: agriculture, non-vegetated area, water bodies, and natural vegetation. The 12 potential LULC changes were further classified into five groups: natural vegetation increase; anthropogenic area increase; water body decrease; natural vegetation suppression; and abandoned agricultural areas. Areas where no change occurred were labeled as unchanged. These changes were detected using the land cover change tool available in the Semi-Automatic Classification plug-in for QGIS Desktop 3.26.2 [43].

2.2.2. Functional Connectivity

The functional connectivity of the landscape surrounding the parks was assessed by analyzing natural vegetation fragments within the 10 km buffer zones for the years 2000 and 2020. This analysis involved calculating changes in the integral index of connectivity (IIC) and its three components: *dIIC_intra*, *dIIC_flux*, and *dIIC_connector*. The IIC is a binary landscape ecology metric based on graph theory that evaluates the connectivity between habitat fragments by considering each fragment as a node and potential connections between them as edges [28]. This approach enables the assessment of the importance of individual fragments in maintaining overall landscape connectivity or serving as connectors between groups of fragments [44,45]. The IIC values range from 0, indicating no connectivity (completely isolated fragments), to 1, indicating full connectivity (all fragments are maximally connected) [46]. The calculation is given by Equation (1):

$$IIC = \frac{\sum_{i=1}^n \sum_{j=1}^n \frac{a_i \times a_j}{1 + n \times l_{ij}}}{A_L^2} \quad (1)$$

where n is the total number of nodes (fragments) in the landscape; a_i , and a_j represent the areas of fragments i and j ; l_{ij} is the number of links in the shortest path connecting fragments i and j ; and A_L is the total area of the landscape, including both areas with and without fragments.

The *dIIC* metric quantifies the relative importance of a specific fragment to overall landscape connectivity. In other words, *dIIC* estimates the percentage decrease in the IIC value when a specific fragment is removed from the landscape [46,47]. It is calculated as follows in Equation (2):

$$dIIC (\%) = \frac{IIC - IIC^i}{IIC} \times 100 \quad (2)$$

where *dIIC* represents the percent contribution of fragment i to the total connectivity; *IIC* is the integral index of connectivity considering all fragments; and IIC^i is the IIC value calculated without fragment i .

According to Saura and Rubio [46], the *dIIC* values can be partitioned into three ecological components, *dIIC_intra*, *dIIC_flux*, and *dIIC_connector*, based on the specific role that landscape elements (nodes or links) play in contributing to connectivity and habitat availability, Equation (3).

$$dIIC = dIIC_{intra} + dIIC_{flux} + dIIC_{connector} \quad (3)$$

The *dIIC_intra* component refers to intrapatch connectivity and depends on the size and habitat quality of the fragment. It is independent of connections between fragments, dispersal distances of focal species, and the isolation of fragments in the landscape. A large, high-quality fragment will have a high *dIIC_intra* value because it can support species populations without requiring movement to other patches. The *dIIC_flux* component refers to the direct interpatch connectivity and depends on the distance to other fragments as well as to the quality and size of other fragments. This component reflects how well a fragment is connected to others in the landscape, but it does not consider the fragment's role in maintaining connectivity between other pairs of fragments. Instead, it measures the contribution of a fragment or link to connectivity by serving as a source or destination for dispersal. A fragment connected to multiple others will have a high *dIIC_flux* value, facilitating species dispersal and migration. The *dIIC_connector* component captures stepping-stone connectivity, i.e., the extent to which a fragment contributes to indirect connections between other fragments. It reflects whether the removal of a fragment would break connections between other patches that are otherwise unreachable directly [46].

The IIC and dIIC metrics were calculated using the Conefor 2.6 application to quantify both structural and functional aspects of landscape connectivity in the buffer zones. Conefor is a spatial ecology tool designed to evaluate the importance of habitat fragments and the functional connections necessary for maintaining or improving landscape connectivity. It also allows for assessing the impact of changes in the surrounding matrix on connectivity [44]. Conefor requires two primary input files: the node file, which represents habitat fragments (nodes), and the link file, which defines potential connections (edges) between these nodes [45]. These landscape graphs were generated using vector files of natural vegetation cover within the 10 km buffer zones. The input parameters (node and link text files) were generated in ArcGIS for the years 2000 and 2020. Connections were calculated based on the edges of the fragments, with links defined by the Euclidean (linear) distance between nodes.

A dispersion distance of 1 km was arbitrarily selected for this study, consistent with the binary connection model, in which a link between two nodes is established based on a pre-defined dispersal threshold [44]. This distance reflects the movement capacity of a generic species capable of traversing at least 1 km through the landscape matrix. It is suitable for several found in the Cerrado, including the giant armadillo (*Priodontes maximus*), maned wolf (*Chrysocyon brachyurus*), giant anteater (*Myrmecophaga tridactyla*), and jaguar (*Panthera onca*), among others with varying dispersal capacities [48–51]. According to the IUCN Red List Categories and Criteria, Version 3.1 [52], the giant armadillo and giant anteater are classified as vulnerable, while the maned wolf and jaguar are listed as near threatened. Additionally, habitat fragments smaller than 1 hectare were excluded from the analyses due to the spatial limitations of Landsat imagery, which has 30 m resolution.

For each fragment located in the buffer zones in 2000 and 2020, the equivalent connectivity (EC) values were also calculated. EC(IIC) is defined as the size of a single, maximally connected habitat patch that would yield the same IIC value as the actual habitat configuration of fragmented habitat in the landscape [44,53]. In other words, it expresses the effective area of habitat that, if fully connected, would provide the same connectivity value as the existing fragmented landscape. This makes EC a particularly intuitive indicator, as it is expressed in area units, allowing for direct comparison with changes in the total habitat area in the landscape. The relative variation in EC, denoted as dEC, following spatial changes in the landscape, can be directly compared to the variation in the total habitat area (dA) after the same changes. These variations are given by Equations (4) and (5), respectively:

$$dEC = \frac{EC(IIC)^i - EC(IIC)}{EC(IIC)} \times 100 \quad (4)$$

$$dA = \frac{A^i - A}{A} \quad (5)$$

where dEC represents the relative change in EC, calculated as the difference between the EC(IIC) value after the change $EC(IIC)^i$, divided by the original EC(IIC) value; and dA represents the relative change in total habitat area, calculated as the difference between the area after the change (A^i) and before the change (A), divided by the original area.

The values of dEC and dA can be interpreted to understand the relative impacts of landscape changes on connectivity and habitat area. When transformations in the landscape result in increased isolation of fragments, the loss of connectivity tends to be higher than the loss of habitat area ($dEC < dA$). Conversely, if deforestation occurs in a spatial pattern that enables the remaining fragments to serve as corridors or stepping stones between other patches, connectivity may be maintained even with significant habitat loss ($dEC > dA$). When changes affect both connectivity and area proportionally, the values of dEC and dA are expected to be approximately equal ($dEC = dA$).

To determine the appropriate statistical test for comparing variations in functional connectivity, a normality test was first performed. Assessing normality is a crucial step for several parametric statistical methods, as it ensures the validity and reliability of inferences obtained from the data [54]. In this study, we selected the Anderson–Darling test to assess normality. This test operates under the null hypothesis (H_0) where the data follow a normal distribution (p -value > 0.05), while the alternative hypothesis (H_1) assumes that the data do not follow normal distribution (p -value < 0.05). The results indicated that the values of dIIC, dIIC_intra, dIIC_flux, and dIIC_connector for the 15 buffer zones did not follow a normal distribution. Consequently, the non-parametric Mann–Whitney test (also known as the Wilcoxon rank-sum test) was selected to compare these metrics between 2000 and 2020. This test assesses whether there is a statistically significant difference in a dependent variable between two independent groups. The hypotheses for the Mann–Whitney test, at a 5% significance level, where H_0 : dIIC, dIIC_intra, dIIC_flux, and dIIC_connector for 2000 do not differ from those in 2020; and H_1 : dIIC, dIIC_intra, dIIC_flux, and dIIC_connector for 2000 differ from those in 2020. Both the normality and the Mann–Whitney tests were conducted using RStudio software, version 2022.12.0+353 [55].

2.2.3. Ranking the Priority Areas for Biodiversity Conservation

The final step of this study involved developing a prioritization ranking for the buffer zones surrounding the parks, with the goal of guiding the implementation of targeted conservation and sustainable land use actions. This process followed a structure method, consisting of the following steps: (i) defining the decision criteria and their corresponding relative importance weights; (ii) analyzing the consistency of the assigned weights; (iii) normalizing the criteria to a common scale; (iv) performing a weighted linear combination (WLC) of the criteria; and (v) generating spatial maps of priority areas around the parks.

This analysis employed the AHP multicriteria decision-making tool designated to address complex problems involving multiple, often conflicting factors [56]. The AHP method is based on a pairwise comparison of criteria, where decision-makers assess the relative importance of each criterion using a standardized scale. As proposed by Saaty [56], this numerical scale ranges from 1 to 9: a score of 1 indicates equal importance between two criteria, while a score of 9 indicates that one criterion is considered absolutely more important than the other.

The criteria used in the hierarchical analysis included LULC classes from 2020, functional connectivity in 2020, Dd, and the percentage of protected area located within the buffer zones (Figure 3). The relative importance of each criterion was determined through pairwise comparisons, where importance scores were assigned based on expert judgments. The overall importance of each criterion was calculated by summing the scores assigned to it in the pairwise comparison matrix. This normalization was performed by computing the eigenvector (w), which involved dividing the sum of each column by the total sum of all columns in the matrix. The resulting eigenvector values represent the relative weights of each criterion, reflecting their contribution to the prioritization analysis.

For the calculation of Dd, the following formula proposed by Tarboton et al. [57] was used, Equation (6):

$$D_d = \frac{\sum L}{A} \quad (6)$$

where $\sum L$ is the total length of the watercourses, whether perennial, intermittent, or ephemeral, and A is the area of the basin.

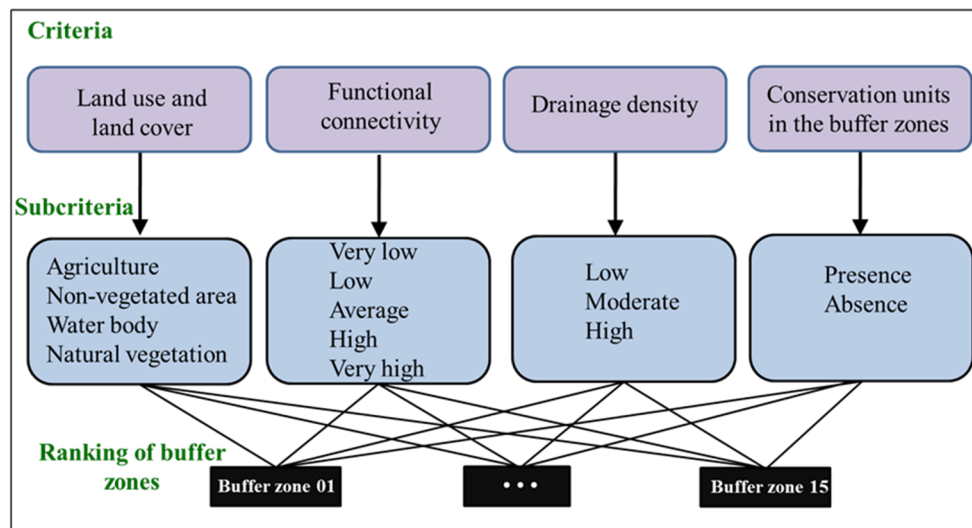


Figure 3. Criteria and sub-criteria used in the analytic hierarchy process (AHP) for prioritizing buffer zones around national parks found in the Brazilian Cerrado biome.

The Dd is an important parameter in the morphometric analysis of drainage basins and is especially sensitive to anthropogenic disturbances [58]. This index reflects the degree of development of surface drainage networks and indicates the availability of linear water flow paths and detrital material transport in a given area [38,59]. Dd is considered a sensitive variable influenced by both climatic and human-induced changes [37]. According to Villela and Mattos [59], Dd can assume the following values: <math> <0.05 \text{ km km}^{-2}</math> (poorly drained basins); $0.5\text{--}3.5 \text{ km km}^{-2}$ (moderately drained basins); and $>3.5 \text{ km km}^{-2}$ (well-drained basins). Low-drainage density values are typically found in regions with permeable substrates and gentle slopes, whereas higher values are associated with less permeable substrates and steeper terrain [37].

The order of importance of the criteria was established through expert consultation with six specialists in biodiversity conservation. We provided a structured form for each expert in which they were asked to rank the four main criteria based on their perceived relevance for prioritizing conservation and sustainable land use actions in the buffer zones surrounding the NPs. Based on their responses, we assigned relative importance weights to both the main criteria and their corresponding sub-criteria. To assess the reliability of the pairwise comparisons, the consistency ratio (CR) was calculated as shown in Equations (7) and (8).

$$CR = \frac{CI}{RI} \tag{7}$$

$$CI = \frac{\lambda_{max} - N}{N - 1} \tag{8}$$

where CI is the consistency index, RI is the random consistency index, which varies depending on the number of criteria, λ_{max} is the maximum eigenvalue of the pairwise comparison matrix, and N is the number of criteria, i.e., the order of the matrix.

According to the AHP method, the assigned weights are considered acceptable only when the CR is less than 0.1. If the CR exceeds this threshold, the pairwise judgments must be reviewed and adjusted until the matrix reaches an acceptable level of consistency. The value of λ is calculated using Equation (9), and the corresponding random consistency index (RI) values for matrices of orders 3 to 10 are presented in Table 1.

$$\lambda = \frac{A \times W_n}{W_n} \tag{9}$$

where A represents the pairwise comparison matrix and W_n is the vector of normalized weights assigned to each criterion.

Table 1. Values of the random index according to the order of the comparison matrix.

Matrix Order	Random Index
3	0.52
4	0.89
5	1.11
6	1.25
7	1.35
8	1.41
9	1.45
10	1.49

To identify priority buffer zones through multicriteria analysis, it is necessary to normalize the data to enable meaningful comparisons. The four selected criteria were converted into raster format, and their corresponding sub-criteria were normalized to a standardized scale ranging from 0 to 1. In this scale, 0 represents very low importance, while 1 represents very high importance. Intermediate values of 0.25, 0.5, and 0.75 correspond to low, moderate, and high importance levels, respectively.

The map of the 10 km priority buffer zones for conservation and sustainable use was produced using the WLC method, which sums the normalized criteria values (scaled from 0 to 1), each multiplied by its respective weight, Equation (10).

$$WLC = \sum_{i=1}^n w_i \times x_i \quad (10)$$

where w_i is the weight of criterion i , and x_i is the normalized score of criterion i .

The pixel values of the raster layers for each criterion were multiplied by their respective weights derived from the AHP analysis, Equation (11). The weighted pixel values from the same locations across all four images were then summed to generate the final map of priority areas for conservation (PAC) [35].

$$PAC = (FC \times P1) + (Dd \times P2) + (LULC \times P3) + (PAUC \times P4) \quad (11)$$

where FC is the functional connectivity, Dd is the drainage density, $LULC$ is the land use and land cover data, $PAUC$ is the presence of conservation units, and $P1$ – $P4$ are the importance weights assigned to each criterion, according to the AHP method.

The priority levels of the buffer zones surrounding the parks for biodiversity conservation were categorized into five classes: very low, low, moderate, high, and very high. This classification was based on intervals derived from the Jenks natural breaks method applied to the values obtained through the WLC approach. Jenks natural breaks is a widely used unsupervised classification technique that aims to minimize variance within classes while maximizing variance between classes [60]. Data processing for this step was performed using QGIS 3.22.12 software.

3. Results

3.1. Weights for Hierarchical Analysis

The weights assigned to the criteria and sub-criteria used in prioritizing conservation and sustainable use in the buffer zones, based on the 2020 data, are presented in Table 2. The detailed results of the weighing process for each criterion and its respective sub-criteria

are shown in Table 3. The presence of agricultural and non-vegetated areas in the buffer zones emerged as the most influential contributors to the final prioritization.

Table 2. Pairwise comparison matrix of the analysis criteria and their corresponding weights of importance.

	Land Use and Land Cover	Functional Connectivity	Presence/Absence of Conservation Units	Drainage Density
Land use and land cover	1	3	7	8
Functional connectivity	1/3	1	5	7
Presence/absence of conservation units	1/7	1/5	1	2
Drainage density	1/8	1/5	1/2	1

Table 3. Weights of the criteria and sub-criteria used for prioritizing conservation and sustainable use in the buffer zones surrounding national parks in the Cerrado biome.

Criteria	Order of Importance	Weight	Sub-Criteria	Weight	Combined Weight
Land use and land cover	1st	0.58	Agriculture	1	0.58
Functional connectivity	2nd	0.28	Non-vegetated area	0.75	0.21
Presence/absence of conservation unit	3rd	0.08	Natural vegetation	0.25	0.02
Drainage density	4th	0.06	Water body	0.01	0.0006

3.2. Land Use and Land Cover Change

Figure 4 shows the percentage of natural vegetation loss between 2000 and 2020 in the buffer zones of the 15 national parks selected. The three parks with the highest percentages of suppression were Grande Sertão Veredas (17.4%), Cavernas do Peruaçu (12.2%), and Serra da Bodoquena (10.9%). These parks are located in the southern portion of the Cerrado biome, which is characterized by the lowest levels of remaining natural vegetation cover. Notably, Brasília NP, the only national park located within an urban area in Brazil, recorded a natural vegetation loss of 7.7%, exceeding the study area's average of 7.0%.

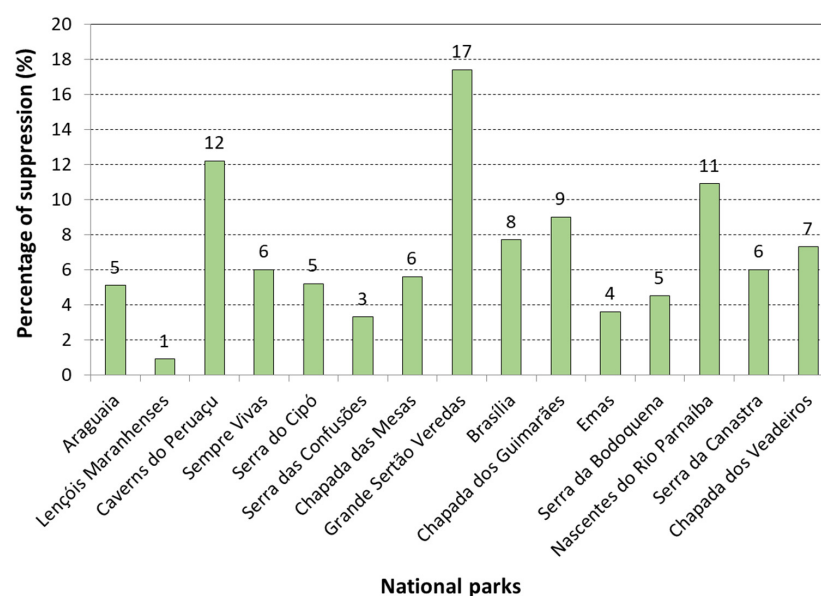


Figure 4. Percentage of natural vegetation loss in the buffer zones surrounding national parks in the Cerrado biome between 2000 and 2020.

3.3. Functional Connectivity of Landscape

Table 4 shows the variations in connectivity (*W*) and corresponding *p*-values for four key metrics across the 15 national parks: dIIC, which reflects the overall importance of a fragment to landscape connectivity; dIIC_connector, which measures the fragment's role as a stepping stone in connecting other patches; dIIC_intra, which indicates internal connectivity within the fragment; and dIIC_flux, which represents the fragment's contribution for facilitating flux between other fragments. A *p*-value < 0.05 indicates statistically significant changes. All four connectivity metrics were statistically significant for Brasília, Chapada das Mesas, Chapada dos Veadeiros, Grande Sertão Veredas, and Nascentes do Rio Parnaíba, suggesting that these parks play critical roles in maintaining landscape connectivity. On the other hand, Chapada dos Guimarães, Sempre Vivas, and Serra do Cipó showed no statistically significant values, indicating a limited role in connectivity. For Emas and Lençóis Maranhenses, only the dIIC_connector metric was statistically significant, highlighting their specific function as ecological stepping stones.

Table 4. Results of the Mann–Whitney test for the Integral Index of Connectivity Index (IIC) and its components: dIIC_connector, dIIC_intra, and dIIC_flux components in for the buffer zones around surrounding the national parks in the Cerrado biome. *W* represents the statistical test indicating the variation in connectivity. *p*-values in bold indicate that they are statistically significant differences (*p* < 0.05) between the years 2000 and 2020.

National Park	dIIC		dIICconnector		dIICintra		dIICflux	
	<i>W</i>	<i>p</i> -Value	<i>W</i>	<i>p</i> -Value	<i>W</i>	<i>p</i> -Value	<i>W</i>	<i>p</i> -Value
Araguaia	19,841,069	0.0242	18,982,208	1.5 × 10⁻⁵	19,099,633	0.1404	19,834,339	0.02637
Lençóis Maranhenses	6,103,413	0.4547	6,257,432	0.009721	6,084,750	0.3312	6,102,670	0.4494
Cavernas do Peruaçu	745,836	0.0436	753,373	0.00601	747,336	0.04837	749,238	0.06722
Sempre Vivas	5,583,801	0.1928	5,684,262	0.9306	5,640,191	0.5486	5,580,780	0.1802
Serra do Cipó	1,697,709	0.1254	1,795,463	0.5319	1,710,410	0.2504	1,697,818	0.1262
Chapada das Mesas	8,619,933	0.0007	8,930,303	0.03826	8,621,465	0.0006068	8,619,933	0.0007397
Grande Sertão Veredas	4,520,132	1.0 × 10⁻¹³	494,265	1.8 × 10⁻⁶	4,159,017	2.2 × 10⁻¹⁶	452,981	2.8 × 10⁻¹⁰
Brasília	6,103,639	2.5 × 10⁻⁵	625,416	0.01416	5,841,984	6.6 × 10⁻¹⁰	6,110,781	3.5 × 10⁻²
Chapada dos Guimarães	350,726	0.1452	35,491	0.1236	357,530	0.4278	350,647	0.1431
Emas	604,985	0.5628	188,494	2.2 × 10⁻¹⁶	570,818	0.08201	603,622	0.6268
Serra da Bodoquena	4,540,018	6.0 × 10⁻⁹	419,277	0.6014	4,436,806	2.6 × 10⁻¹⁰	4,547,414	3.0 × 10⁻⁶
Nascentes do rio Parnaíba	20,800,790	2.2 × 10⁻¹⁶	22,951,246	0.001226	21,341,104	2.2 × 10⁻¹⁶	20,827,769	2.2 × 10⁻¹⁶
Serra da Canastra	2,938,685	0.1389	29,957,057	0.1205	29,649,651	0.01208	29,955,653	0.1557
Chapada dos Veadeiros	25,308,696	0.0012	25,442,450	2.2 × 10⁻¹⁶	24,201,660	1.0 × 10⁻¹⁵	25,327,896	0.001623

The comparison between the variation in habitat area (dA) and equivalent connectivity (dEC) showed that all buffer zones experienced simultaneous losses in both natural habitat and spatial connectivity between 2000 and 2020 (Figure 5), with the exception of Serra da Bodoquena NP. In most cases, the reduction in habitat area surpassed the decline in connectivity (dA > dEC), indicating that natural vegetation fragments are shrinking more rapidly than they are becoming disconnected. The buffer zones surrounding Grande Sertão Veredas and Nascentes do rio Parnaíba showed the most severe declines in both natural cover and landscape connectivity. In contrast, the buffer zones of Araguaia, Serra do Cipó, and Serra da Canastra showed similar values of dEC and dA, suggesting that habitat loss of area in these areas directly translated into a proportional decline in landscape connectivity.

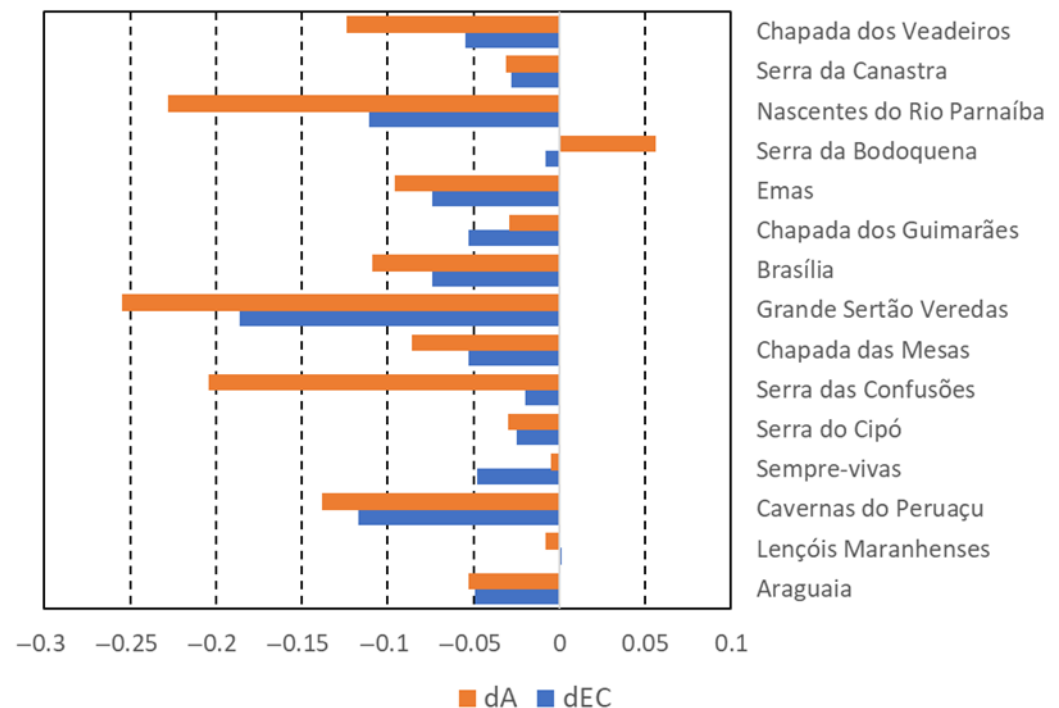


Figure 5. Variations in natural cover area (dA) and equivalent connectivity area (dEC) in the 10 km buffer zones of national parks in the Cerrado biome between 2000 and 2020.

3.4. Presence or Absence of Conservation Units

A total of 45 sustainable use conservation units (UCUS), covering 748,097 hectares, and 10 integral protection conservation units (UCPI), totaling 28,089 hectares, were identified within the buffer zones surrounding the parks. Notably, 4 of the 15 buffer zones had no conservation units. The most represented category was the Environmental Protection Area (APA), with 20 units accounting for 94.6% of the total area covered by conservation units. The second most frequent category was the Private Natural Heritage Reserve (RPPN), comprising 16 units but only 0.6% of the total area. State and municipal parks contributed with only four conservation units, representing 2.1% of the total area.

The parks with the largest proportions of protected areas within their buffer zones were Lençóis Maranhenses (98.9%), Chapada dos Guimarães (92.5%), Serra do Cipó (84.3%), Chapada dos Veadeiros (75.5%), and Brasília (75.0%). UCUS was the most extensive and widely distributed conservation units within the buffer zones.

3.5. Drainage Network

Table 5 presents the Dd values for the 15 parks and their corresponding buffer zones. The Dd values ranged from 0.234, indicating poor Dd, to 0.803, classified as regular Dd. None of the study areas showed a Dd considered good, and only four presented a regular Dd. Generally, high Dd values are associated with steep terrain, impervious soils, or deforestation, while low Dd values indicate flat terrain, permeable soils, or intact vegetation. Therefore, it can be inferred that the parks generally experience low surface runoff and possess higher infiltration capacity.

Table 5. Drainage density values within the national parks and their corresponding 10 km buffer zones. The classification of drainage density in “poor” and “regular” followed the criteria proposed by Villela and Mattos [59].

National Parks	Drainage Density (km km ⁻²)	Classification
Araguaia	0.329	Poor
Lençóis Maranhenses	0.409	Poor
Cavernas do Peruaçu	0.397	Poor
Sempre-Vivas	0.713	Regular
Serra do Cipó	0.803	Regular
Serra das Confusões	0.327	Poor
Chapada das Mesas	0.494	Poor
Grande Sertão Veredas	0.377	Poor
Brasília	0.397	Poor
Chapada dos Guimarães	0.735	Regular
Emas	0.234	Poor
Serra da Bodoquena	0.404	Poor
Nascentes do Rio Parnaíba	0.369	Poor
Serra da Canastra	0.705	Regular
Chapada dos Veadeiros	0.635	Regular

3.6. Prioritization for Conservation and Sustainable Use

The combined use of the AHP and WLC methods showed that 69% of the total area within the buffer zones is classified as having high to very high importance for conservation (Table 6). These priority areas are characterized by high functional connectivity, the presence of natural vegetation, and the absence of conservation units. Specifically, zones of very high importance accounted for 23% of the total buffer zones and are marked by intense anthropogenic pressure, very low functional connectivity, and LULC classes dominated by agriculture and non-vegetated areas, with varying presence of conservation units. Areas of moderate importance, which cover 31% of the buffer zones, generally show high functional connectivity, presence of conservation units, and remaining natural vegetation.

Table 6. Classification of priority areas for conservation actions, including the corresponding priority ranks by level of importance.

Priority Level	National Park	Area (%)	Area (ha)	Ranking
Very high	Serra da Bodoquena	88.46	159,890	1
	Emas	77.68	105,785	2
	Serra da Canastra	66.26	162,016	3
	Brasília	54.06	59,949	4
High	Serra das Confusões	82.42	468,871	1
	Chapada das Mesas	74.36	176,732	2
	Cavernas do Peruaçu	73.86	96,085	3
	Nascentes do Rio Parnaíba	64.88	379,018	4
	Grande Sertão Veredas	58.70	125,221	5
	Sempre-vivas	57.06	77,525	6
	Araguaia	55.28	188,867	7
Moderate	Lençóis Maranhenses	80.33	93,322	1
	Serra do Cipó	73.89	583,780	2
	Chapada dos Veadeiros	67.37	213,768	3
	Chapada dos Guimarães	66.26	56,400	4

4. Discussion

4.1. Key Findings

The main purpose of this study was to rank the buffer zones surrounding 15 NPs in the Cerrado biome based on the threats they face and the opportunities they offer for biodiversity conservation and sustainable land use. The results indicate that, in 2020, these buffer zones were composed of 74.5% natural vegetation, 22.8% agricultural areas, 1.5% non-vegetated natural areas, and 1.2% water bodies. Between 2000 and 2020, the loss of natural vegetation within these zones resulted in a 33% reduction in landscape connectivity. We identified around 670 thousand hectares in the buffer zones as high-priority areas for biodiversity conservation. By identifying areas with higher conservation value, this approach can assist direct restoration efforts toward more strategic locations, thereby reducing conflicts with stakeholder's interests in food and energy production, as also emphasized by Schuler and Bustamante [34].

The increase in natural vegetation fragmentation was especially pronounced in areas within or near MATOPIBA, the Cerrado's emerging agricultural frontier located in the northern portion of the biome. The expansion of grain production in this region has been driven by a combination of factors, including low land prices, favorable soil physical attributes for crop cultivation, favorable adequate precipitation, topography suitable for intensive mechanization, and proximity to the Porto of Itaqui in São Luís, Maranhão State. This port offers the most cost-effective option for grain export compared to other Brazilian ports [61]. MATOPIBA also contains some of the largest remaining preserved areas of the Cerrado [62,63]. As expected, the areas surrounding NPs in this region, especially Chapada das Mesas, Nascentes do Rio Parnaíba, and Serra das Confusões, have undergone intense natural vegetation fragmentation. Between 2000 and 2020, landscape changes in this region had a more pronounced impact on habitat loss than on the connectivity between fragments.

4.2. Recommended Strategies for High-Priority Buffer Zones

The prioritization process for biodiversity conservation highlighted the need for differentiated mitigation strategies. Buffer zones identified as having very high priority are highly anthropized, posing significant threats to biodiversity persistence in both short and long terms. On the other hand, buffer zones ranked as high and moderate priority still retain large fragments of natural vegetation, offering valuable opportunities for biodiversity conservation. However, these areas are mainly located in the northern portion of the biome, a region currently experiencing rapid agricultural expansion, which presents a considerable risk to their long-term preservation. As noted by Vieira-Alencar et al. [64], the largest priority areas for conservation in the Cerrado are concentrated in this northern region.

For the buffer zones surrounding NPs located in the northern Cerrado, we recommend strengthening the implementation of command-and-control measures, particularly law enforcement procedures to reduce illegal clearing of natural vegetation. Traditionally, government regulatory efforts are mostly focused on the Brazilian Amazon, which has historically resulted in limited effectiveness in the Cerrado because of lack of political prioritization [65]. As noted by Aragão et al. [66], the perspectives of soybean producers in the MATOPIBA region are largely economically driven, with little concern with environmental sustainability. These measures should account for varying socioeconomic contexts, land use patterns, and specific conservation objectives of each PA.

Buffer zones function as transitional areas that help mitigate external pressures on protected ecosystems [6] but outdated or rigid regulations often fail to address the diverse socioeconomic realities and dynamic land use patterns of surrounding communities, limiting their effectiveness. In other words, effective command-and-control measures must adopt a context-sensitive perspective that integrates local livelihoods, agricultural practices,

and land tenure, among other aspects. Recognizing the heterogeneity of stakeholders, ranging from smallholder farmers and indigenous communities to urban residents and private landowners, is essential for creating guidelines aligned with both conservation goals and human well-being. Regulations should be aligned with the specific conservation goals of each unit, whether they prioritize biodiversity protection, ecosystem services, or cultural heritage.

An example of a command-and-control measure is the expansion of the network of conservation units around NPs through the implementation of more strictly protected areas. This is a crucial strategy for enhancing ecological connectivity, mitigating edge effects, and avoiding increasing anthropogenic pressures. The strategic creation of additional conservation units can serve as ecological corridors and barriers, safeguarding core habitats from external disturbances. These new zones should be established in regions identified as ecological hotspots or under severe threat.

Another example is the maintenance of landscape connectivity through the identification of conservation corridors, which facilitates the movement of species and the flow of genetic material. Without such corridors, habitat fragmentation leads to isolated populations, reduced genetic diversity, and magnified extinction risks. Identifying priority areas for conservation corridors requires GIS-based spatial planning approaches that incorporate ecological, socioeconomic, and land use data. Additional command-and-control measures include the formal delimitation of buffer zones around NPs accompanied by the establishment of comprehensive management plans and the enhancement of monitoring efforts to ensure compliance in the buffer zones.

In the northern portion of the Cerrado biome, further studies are also needed to identify the presence of protected and endemic species to support discussions on strategies for maintaining and preserving ecological corridors. At the same time, it is important to consider the adoption of technologies aimed at increasing agricultural productivity, restoring degraded or abandoned lands, and introducing alternative land uses such as aquaculture [67]. Among the environmentally sustainable crop production, we can suggest the intensification of a crop–livestock integration system in the Cerrado (e.g., [4]), especially over moderate to highly degraded pastures [68,69].

4.3. Sustainable Land Use Opportunities in Highly Modified Areas

In the southern portion of the Cerrado biome, especially in the buffer zones of Semprevivas, Chapada dos Guimarães, and Serra da Bodoquena, vegetation loss has mostly affected the ecological connectors. This fragmentation pattern is typical of landscapes with a low proportion of natural areas and highly fragmented structures, as reported by Saura et al. [53] and Grande et al. [70]. In this region, where human occupation is already significant, it is recommended to promote the development of opportunities that have minimal impact on biodiversity. One such example is the study conducted by Rodrigues et al. [5], which proposed the implementation of sustainable cultural ecosystem services along the borders of eight Cerrado NPs featuring attracting scenic views.

Another interesting opportunity is the creation of information centers in the headquarters of each NP to foster conservation-oriented culture among local communities and visitors. These centers would serve as hubs for environmental education, providing accessible materials about the region's biodiversity, ecosystem services, and the importance of sustainable land use. These information centers can offer courses and workshops for varying audiences such as school groups and eco-tourists.

The development of educational and recreational activities, such as trails and bird watching may stretch the understanding of the importance of conservation units. Such activities offer the potential of combining learning with leisure for both local communities

and eco-tourists. The trails can be enriched with signages explaining the local ecology and cultural heritage. The bird watching activities can capitalize the Cerrado's rich avifauna, serving both scientific and recreational interests.

Promotion of cultural tourism by highlighting local traditions, such as traditional festivals, craft fairs, and regional cuisine, is another example of an excellent opportunity for enhancing local economies and preserving cultural heritage. Traditional festivals not only serve as seasonal attractions but also provide insight into local historical values and social customs. Craft fairs, on the other hand, support local artisans and encourage the continuation of heritage skills such as pottery and woodwork. Regional cuisine also provides tourists with the opportunity to keep in touch with historical and social dimensions of communities.

Fostering participatory management incentives in top-down governance models where local voices are not only heard but also are integrated into the planning, implementation, and monitoring activities, as well as engaging local stakeholders ensures that development strategies are grounded in local knowledge, priorities, and cultural values.

Additional opportunities include promoting visits to rural properties near NPs that adopt conservation practices, thereby attracting tourists interested in sustainability; implementing local composting systems for organic waste and encouraging material recycling to support circular economy initiatives; and conducting continuous biodiversity monitoring using remote sensing data to assess ecosystem health and support effective buffer zone management. Furthermore, local measures are essential to reduce wildlife mortality on highways and roads, along with biotechnical strategies aimed at protecting species with high conservation status and habitats vulnerable to fragmentation. Examples of biotechnical strategies include restoration of landscape connectivity such as the Jaguar Corridor Initiative [71], assisted natural regeneration of degraded habitats with native species, and riparian and wetland restoration to increase ecological corridors.

4.4. Limitations and Future Directions

This study can be further improved by incorporating additional datasets as input parameters for the AHP multicriteria analysis. For example, geodiversity data could be included, as the heterogeneity of physical environment, coupled with climatic interactions, strongly influences biodiversity patterns across different spatial scales [72]. Another potential refinement involves the integration of threatened species data from the International Union for Conservation of Nature (IUCN), as considered by Resende et al. [73], in their assessment of the role of protected areas and indigenous lands in safeguarding ecosystem services and biodiversity in the Cerrado. Additionally, the inclusion of socioeconomic data is essential to fully contextualize the ecological findings as those obtained in this study. This could involve data related to land tenure (e.g., private vs. state-owned lands), population density, Human Development Index (HDI), socioeconomic profiles of local communities, and the dominant local economic activities such as agriculture, logging, mining, and tourism.

Regarding LULC classes, the use of 30 m resolution Landsat dataset, although suitable for regional and national scale assessments, may limit the ability to detect small, fragmented patches of natural vegetation and fine-grained land use types, especially in heterogeneous or highly fragmented landscapes. This limitation may have led to an underestimation of habitat availability and connectivity. This is especially critical for species that depend on small habitat patches or linear features, such as riparian corridors or narrow forest strips, for movement. Therefore, our findings should be interpreted considering the spatial resolution of the input data. In this context, the use of higher spatial resolution remote sensing images, such as those provided by PlanetScope (4.7 m) and Sentinel-2 (10 m) satellites, offers a

valuable opportunity to capture smaller landscape fragments that may be overlooked by Landsat satellites.

We selected a 1 km diffusion distance as our reference value based on empirical data, aiming to provide a conservative estimate of landscape connectivity. However, we recognize that the use of a single diffusion distance may limit the generalizability of our results, especially for species with either shorter or longer dispersal capacities. In this context, we suggest that future research explores a range of diffusion distances (e.g., 500 m, 1 km, 2 km, and 5 km) to assess how connectivity metrics, such as dIIC, dIIC_connector, and dIIC_intra, respond to varying species-specific movement capabilities.

5. Conclusions

The establishment of a priority ranking for biodiversity conservation and sustainable use actions in the buffer zones of Cerrado NPs showed that none of the 15 parks were classified as having very low or low priority. On the other hand, four parks were identified as having very high priority. For parks located in the northern portion of the biome, priority should be given to actions centered on biodiversity conservation. Conversely, for those in the southern region, efforts should focus on promoting sustainable land use initiatives that balance ecological preservation with existing land use practices.

Although this study focused exclusively on NPs located in the Brazilian Cerrado biome, the approach developed here can be extended to other tropical regions characterized by species-rich ecosystems under intense pressure from land use conversion.

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