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Incorporating Agricultural, Socioeconomic, and Political Factors into Conservation Strategies for the Giant Armadillo (*Priodontes maximus*) in the Cerrado

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Abstract

Species distribution models are essential for proposing conservation strategies for large mammals. However, anthropogenic factors must be incorporated to enhance the effectiveness of these strategies. In this study we selected the Giant Armadillo (*Priodontes maximus*) as a target species. We mapped its distribution and analyzed the landscape structure in its potential occurrence area. Simultaneously, we mapped the socioeconomic, agrarian, and public governance dimensions of Cerrado municipalities, which were categorized into groups to assess the local context. Combining these results, we discussed conservation strategies for the species in the local-regional context. For the distribution modeling, 486 independent presence points and 14 predictor variables were utilized, resulting in a model with 695,367 km^2 of remaining habitat for the species. It corresponds to 33% of the Cerrado biome, with 7.6% of this area within protected areas or Indigenous Lands. Five anthropic variables were employed to classify the 1,434 municipalities in the study area, resulting in three distinct municipal profile groups. A map and a framework were then generated, combining municipal profile information and the amount of remaining habitat per municipality to guide decision-making on conservation strategies first steps. One group stood out due to the presence of large surplus of remaining native vegetation in both private properties and protected areas, indicating significant conservation opportunities.

Key words: Mammals, Species distribution models, anthropic, governance.

Resumo

Modelos de distribuição de espécies são essenciais para a proposição de estratégias de conservação para grandes mamíferos. No entanto, fatores antrópicos devem ser incorporados para que essas estratégias sejam mais efetivas. No presente estudo escolhemos o tatu-canastra (*Priodontes maximus*) como espécie alvo, mapeamos a sua distribuição e analisamos a estrutura da paisagem em sua área de potencial ocorrência. Paralelamente, mapeamos as dimensões socioeconômicas, agrárias e de governança pública dos municípios do Cerrado, que foram classificados em grupos a fim de se acessar o contexto local. A partir da combinação desses resultados, discutimos estratégias de conservação para a espécie em contexto local-regional. Para a modelagem de distribuição foram usados 486 pontos de presença independentes e 14 variáveis preditoras, resultando em um modelo com 695.367 km^2 de habitat remanescente para a espécie, o que corresponde a 33% do bioma Cerrado, com 7,6% dessa área no interior de Unidades de Conservação ou Terras Indígenas. Cinco variáveis antrópicas foram usadas para classificar os 1434 municípios da área de estudo, resultando em 3 grupos de perfis municipais distintos. Foram então gerados um mapa e um quadro que combinam as informações de perfil municipal e quantidade de habitat remanescente por município a fim de orientar os primeiros passos na tomada de decisão para estratégias de conservação. Um grupo se destacou devido a presença de grandes porções de áreas de vegetação nativa remanescente tanto em propriedades privadas quanto em áreas protegidas, indicando grande oportunidade de conservação

Palavras-chave: Mamíferos, Modelos de distribuição de espécies, antrópico, governança.

Introduction

The Cerrado is the world's largest tropical savanna, originally covering an area of 2 million square kilometers, 23.3% of the Brazilian territory. However, currently only 54.4% of native habitat coverage remains (Projeto MapBiomas, coleção 7), with approximately only 3% within Strictly Protected Areas, the Cerrado is one of the most threatened savanna on the planet (Silva & Bates 2002, Strassburg et al. 2017). Due to a high conversion and degradation rate, combined with its high biodiversity and endemism, this biome is considered one of the 25 global conservation hotspots (Mittermeier et al. 2004, Myers et al. 2000). It is located from northern/northeastern Brazil to Bolivia and northern Paraguay, connecting and bordering all Brazilian biomes except the pampas. Important ecosystem services are generated in the Cerrado, such as water supply, energy generation, and conditions for mechanized agriculture development due to its flat terrain and deep soils (Klink & Machado 2005).

The expansion of agricultural frontiers in this region and the consequent change in land use and land cover are main threats, and future projections indicate that landscape conversions are likely to continue at a significant pace in the coming years unless important changes on the biodiversity protection take place on the coming years (Carneiro-Filho & Costa 2016, Strassburg et al. 2017, Soterroni et al. 2019, Colman et al. 2021). Agreements and policies for the protection of the Amazon, which were effective in slowing deforestation in that biome, are not widely applied to the neighboring Cerrado (Soterroni et al. 2019), potentially contributing to even greater exploitation in the Cerrado as impactful activities migrate from the Amazon to the Cerrado biome (Fernandes et al. 2023). There is an urgent need for territorial planning and the implementation of Cerrado conservation initiatives. Twenty-five percent of threatened species in Brazil are present in this biome. Furthermore, the Cerrado holds 5% of all species in the world and 30% of the country's biodiversity. The five major emblematic and endangered large mammals in the Cerrado, known as the “Big Five”, are the giant armadillo (*Priodontes maximus*), giant anteater (*Myrmecophaga tridactyla*), jaguar (*Panthera onca*), maned wolf (*Chrysocyon brachyurus*), and tapir (*Tapirus terrestris*) (Klink & Machado 2005, WWF 2015). Conservation efforts for these mammals are strategically important due to their charisma, large home ranges and the need to preserve diverse habitats for their survival (Santos-Filho & Silva 2002), serving as umbrella species for other species across this biome.

When considering species conservation or territorial planning for conservation, information on Species Distribution Models (SDMs) are essential for this purpose. SDMs identify potential occurrence sites and the most important variables for the species' presence (Margules & Pressey 2000, Loiselle et al., 2003; Liu et al., 2013; Porfirio et al., 2014). Through these models, spatial and landscape analyses can be performed, indicating where conservation efforts should concentrate from a biodiversity and environmental perspective (Ferraz et al. 2012, Syfer et al. 2014, IUCN 2021). However, conservation strategies must go beyond models. An increasing number of studies highlight the need to explicitly incorporate the human dimensions — social, behavioral, economic, and cultural — to guide decision-making and define more effective conservation actions (O'Connor et al., 2003; Bode et al. 2008; Knight et al. 2010, Smith et al. 2010, Bennett et al. 2017). The agrarian, socioeconomic, and political contexts need to be understood, especially in a scenario where conservation resources are scarce and in need to be used wisely (Miller & McGee 2001, Polasky 2008, Moseley et al. 2013, Bennett et al. 2017).

Understanding the agrarian structure in areas where endangered species potentially occurs can facilitate the development of distinct conservation strategies tailored to the local context across regions. This involves the conservation of species remnant habitat in either public areas or private properties, depending on the presence or potential creation of

Conservation Units, Indigenous Lands, and lands associated with other traditional communities (Oliveira et al. 2017, De Marco et al. 2023). Furthermore, by taking into account the size and location of private properties and their Legal Reserves (portion of land that must be preserved with native vegetation within private properties in accordance with country-level laws for the protection of native vegetation), it becomes possible to anticipate the natural areas that may face deforestation in the coming years, in accordance with environmental legislation (Stefanes et al. 2018). This information can guide conservation strategies and public policies creation, extending beyond compliance with the Native Vegetation Protection Law (Soares-Filho et al., 2014; Lima & Bastos, 2020, de Mello et al. 2021). Lastly, an understanding of the agrarian structure can also inform whether conservation efforts should be directed towards large or small landowners (Michalski et al. 2010, Stefanes et al. 2018).

In addition to the agrarian structure, conservation planning requires an understanding of the social, political, and economic systems in which it operates. If these contexts are not adequately considered in conservation planning, it is likely to be inefficient, and its strategies can fail (Pressey et al. 2007, Knight et al. 2010, Bennett et al. 2017). This is because, despite the conservation goal being biological or environmental (e.g., maximizing the number of conserved species or resources quantity and quality), the means to achieve this goal are primarily socio-economic (Polasky 2008). Financial resources are needed to implement conservation strategies, such as land expropriation for Conservation Units, monitoring of protected areas, payment for environmental services, or restoration of degraded areas (Tisdell 2004, Mcneely 2006). Often, changes in the local, regional, or even national economic and social structure would be necessary to replace extremely environmentally degrading activities with more sustainable forms of natural resource exploitation. It is anthropogenic actions that have caused the biodiversity crisis we find ourselves in, and social changes will be necessary to adequately resolve it (Polasky 2008).

Finally, without effective public governance, the implementation of conservation strategies faces more obstacles. Good governance is fundamental to the development of any society, and simply put, governance refers to the ability of the government to develop goals and programs that allow it to achieve those objectives. "Public governance encompasses everything a public institution does to ensure that its actions are directed toward goals aligned with the interests of society" (Governo Federal 2018). Thus, a strong correlation can be found between public governance and the effectiveness of conservation strategies, particularly those that depend on public institutions for implementation, such as Conservation Units, monitoring, and the enforcement of laws and government incentives. Smith et al. (2003) and Eklund et al. (2011) found a correlation between low governance indicators and unsatisfactory outcomes of conservation initiatives; Wright et al. (2007) also demonstrated that corruption – a characteristic of areas with low governance – compromises the effectiveness of tropical protected areas in achieving their objectives.

Therefore, understanding both species spatial distribution and associated human dimensions is very advantageous for the successful planning and implementation of conservation strategies, particularly for species with large habitat requirements and limited population growth rates (Purvis et al. 2000, Hodgson 2011). The giant armadillo (*Priodontes maximus*) serves as a great case study for evaluation and refinement of conservation methods and tools as it is a species that occurs at low population density, with a low population growth rates and large home range. This species plays an important ecological role benefiting biodiversity (Desbiez & Attias, 2022), is rapidly losing habitat to anthropogenic activities and therefore requires attention and conservation strategies (Ferraz et al. 2021, Desbiez et al. 2020a).

Giant armadillo is the largest existing armadillo species, measuring on average 1.50 meters in length and weighing up to 60 kg (Carter et al. 2016, Desbiez et al. 2019). They control termite and ant populations and dig large burrows (Carter 1983, Anacleto 1997, Ceresoli & Fernandez-Duque 2012), which serve as shelters for several other animals, giving them the status of ecosystem engineers (Desbiez & Kluyber 2013). In the absence of this species, the lack of burrows can affect individuals or populations of certain species, and their interactions due to the disappearance of shelters and foraging sites (Fontes et al. 2020). Male sexual maturity is estimated to be reached at seven or eight years of age (Luba et al. 2020), while females have a gestation period of 5 months, giving birth to only one offspring, with an approximate three-year interval between births (Desbiez et al. 2020b). This slow reproduction rate increases the risk of local extinction (Desbiez et al. 2020b, Luba et al. 2020).

Giant armadillos are classified as "Vulnerable" to extinction according to the International Union for Conservation of Nature and Natural Resources (IUCN) Red List of Threatened Species (Anacleto et al. 2014) and by the Chico Mendes Institute for Biodiversity Conservation in Brazil (Chiarello et al. 2015). This species occurs in the Amazon, Atlantic Forest, and Cerrado biomes within Brazilian borders (IUCN, 2010). Habitat loss and fragmentation, roadkill, fire, hunting, and retaliation due to conflict with beekeepers are the main threats to the species (Banks et al. 2007, Anacleto et al. 2014, Chiarello et al. 2015, Carter et al. 2016, Banhos et al. 2020, Desbiez et al. 2020c). A research that took place across the Cerrado of Mato Grosso do Sul indicates that the remaining habitat for the species is highly fragmented and surrounded by agricultural matrices, with only sixty-nine fragments capable of supporting the home range of a single individual (Ferraz et al. 2021).

Given the loss of habitat due to land use conversion, this armadillo species may take decades to reflect the effects of extinction debt on its population (Tilman et al. 1994, Paese 2012). It means that there is a latency period between habitat loss or fragmentation and population decline or species disappearance. This effect is accentuated due to its slow population growth rate and especially because individuals have a long lifespan (Desbiez et al. 2021). In some regions of the Cerrado, it is possible to currently observe the presence of individuals that will not be able to reproduce, as they are surviving in isolated fragments which is why the Cerrado population in Mato Grosso do Sul could be functionally extinct in the coming generations (Ferraz et al. 2021).

Therefore, in the face of the urgency of devising large-scale strategies for the conservation of big mammals in the Brazilian Cerrado, given the changes and pressures in the biome that do not result from the same variables that determine the species' distribution but rather from human factors, and using *Priodontes maximus* as study case, this research was conducted in two complementary stages. Firstly, we modeled the species' distribution based on environmental and landscape variables to assess environmental suitability and analyze landscape structure throughout its distribution. Then we mapped the socio-economic, agrarian, and governance dimensions in the Cerrado municipalities, seeking to understand the regional-local context which allow as to discuss potential strategies for species conservation.

Methods

Study Area

The focus of this study is the Cerrado biome (IBGE 2019) in Brazil (Figure 1). There are 1434 municipalities and 13 Brazilian states that are fully or partially located within this biome. Approximately 26 million people inhabit the Cerrado, of which only 17% live in rural areas (Embrapa 2017). The diversity in the Cerrado, expressed in its different vegetation types and species numbers, is also reflected among the resident human populations, represented by indigenous people, quilombolas (descendants of escaped African slaves), and other traditional communities such as artisanal fishermen, extractivists, coconut breakers, seasonal floodplain farmers, flower gatherers, among others. In addition to these, more recent populations have become part of the Cerrado's social diversity. This includes urban residents, smallholder farmers, and rural workers that are often from the southern and northeastern regions of Brazil, and overall theses populations are related to the agricultural frontier expansion (ISPN; Embrapa 2017). In the Cerrado, there are currently 44 quilombola territories and 216 indigenous lands belonging to 83 different ethnic groups, with a population of approximately 100,000 indigenous people (Embrapa 2015, Museu do Cerrado). Two hundred and eighty Conservation Units are distributed across this biome, with 120 being Strictly Protected Areas and 158 being Sustainable Use Reserves (SNUC 2000). Nonetheless protected areas across this biome only represents 8% of its total area.

Historically, the Cerrado has been undergoing a continuous process of occupation due to government incentives to fill demographic gaps in the Midwest Brazil and the expansion of the agricultural frontier, resulting in the loss of biodiversity and traditional practices of natural resource use (Embrapa 2017). Currently, 46.1% of the original biome area has been converted into agriculture and urban zones (representing 45.3% and 0.8% of the current territory, respectively). Within the agricultural area, 52% is occupied by pastures, 28% by agriculture, 16% by a mosaic of agriculture and pasture, and 4% by silviculture (Projeto Mapbiomas, coleção 7). Agriculture and livestock farming represent the main economic activities in the region and the estimated annual deforestation rate in

2022 was 10,689 square kilometers in this biome (Projeto Monitoramento Cerrado, INPE). Among the different naturally occurring vegetation types in the Cerrado, open formations have disappeared even more significantly than forested formations (Bonanomi et al. 2019).

Currently, the region with the largest areas of continuous and preserved native vegetation in this biome is also the agricultural frontier expansion area. This region, known as MATOPIBA (Carneiro-Filho & Costa 2016), encompasses the states of Maranhão, Tocantins, Piauí, and Bahia. Due to the low commercial land value and the potential for easy product distribution, this region has become attractive and promising for agribusiness (Belchior et al., 2017). In the last 10 years, most of the annual increase in native vegetation loss (PRODES system, INPE) in the Cerrado has been concentrated in MATOPIBA region.

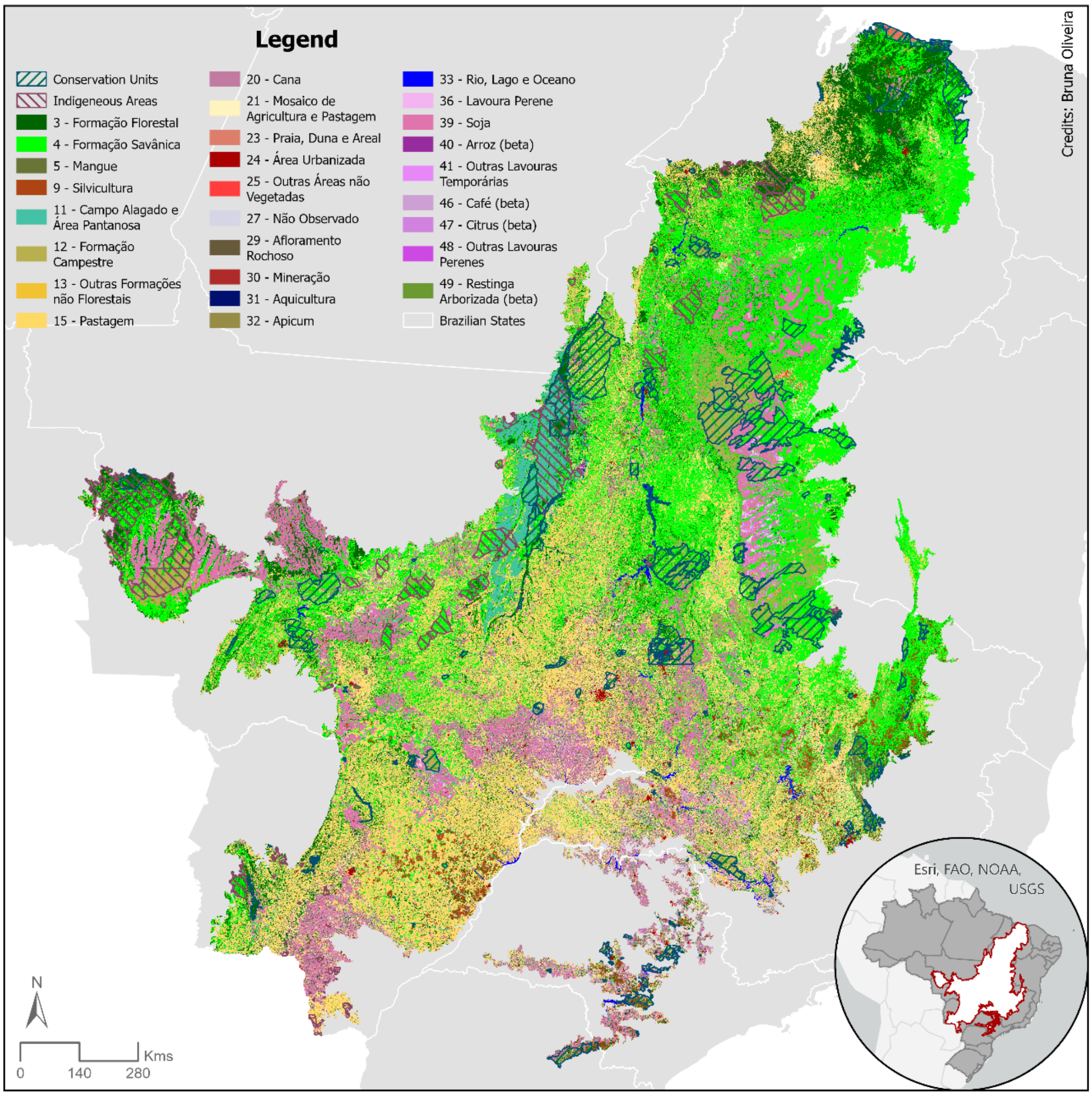

Figure 1. Land Use (Projeto MapBiomas, coleção 7) Conservation Units and Indigenous Areas of Cerrado Biome.

Species Distribution Modeling:

Giant Armadillo Presence Points:

The presence points were obtained through i) communication with researchers who work with mammals in the Cerrado (see acknowledgments), ii) recent literature (last 15 years) including a data paper (Santos et al. 2019), and iii) online databases: Instituto Chico Mendes, specieslink, GBIF, and SiBBr.

The obtained points were screened, and those not meeting the following criteria, in accordance with Dalapicolla's recommendations (2015), were excluded: i) point registration accuracy of 100 meters or less, ii) municipality centroids, iii) at least two decimal places in geographic coordinates, iv) collection dates within the past 15 years, v) verification by species experts to correct potential errors based on their field expertise, vi) points located in urban areas, and vii) duplicated points. The 15-year timeframe was selected to ensure the geographic coordinates remained relevant due to the rapid land use changes in the Cerrado biome.

To mitigate data redundancy in the biotic dataset, a Rarefaction by Environmental Heterogeneity method was applied. This involved utilizing the "Calculate Climate Heterogeneity step 1 and step 2" functionality within the SDMtoolbox package (Brown et al. 2017). An environmental heterogeneity map was generated through Principal Component Analysis (PCA) of the chosen explanatory variables pertinent to the modeling process (see Bioclimatic and Landscape Variables section below). This resulting map was then employed in the "Spatially Rarefy Occurrence Data for SDMs" module within the same toolkit, with a specified 10-kilometer buffer. Points within this buffer were subject to selective inclusion based on their environmental classification. Instances with multiple points within the buffer and belonging to the same environmental class led to the random retention of a single point. In cases where points within the buffer corresponded to distinct environmental classes, all points were preserved. The 10-kilometer buffer distance was chosen considering the species' dispersal capability, as used by Ferraz et al. (2021).

Bioclimatic and Landscape Variables:

Based on prior research (Zimbres et al. 2012, Ferraz et al. 2021), existing database resources, and important ecological traits highlighted by specialists, the following explanatory variables were selected to model the potential distribution of giant armadillo:

I) Altitude from the Global Digital Elevation Model (Gesch et al., 1999);

II) Nineteen Bioclimatic variables from the WorldClim database (Fick & Hijmans, 2017): Bio 1 – Annual Mean Temperature, Bio 2 – Mean Diurnal Range, Bio 3 – Isothermality, Bio 4 – Temperature Seasonality, Bio 5 – Max Temperature Warmest Month, Bio 6 – Max Temperature Coldest Month, Bio 7 – Temperature Annual Range, Bio 8 – Mean Temperature Wettest Quarter, Bio 9 – Mean Temperature Driest Quarter, Bio 10 – Mean Temperature Warmest Quarter, Bio 11 – Mean Temperature Coldest Quarter, Bio 12 – Annual Precipitation, Bio 13 – Precipitation Wettest Month, Bio 14 – Precipitation Driest Month, Bio 15 – Precipitation Seasonality, Bio 16 – Precipitation Wettest Quarter, Bio 17 – Precipitation Driest Quarter, Bio 18 – Precipitation Warmest Quarter, Bio 19 – Precipitation Coldest Quarter;

III) Slope (Jarvis et al., 2008) – the inclination of the terrain surface in relation to the horizontal;

IV) Hand100 – Vertical distance to the nearest drainage. It is indirectly related to groundwater depth, which, in turn, indicates soil water availability. Small values of vertical distance (close to zero) indicate regions where the water table is near the surface, resulting in soil conditions close to saturation. High values of vertical distance identify regions with a deep water table, indicating well-drained areas (Rennó et al. 2008). The algorithm generating this variable considers unidirectional flow to determine the preferential water path to the nearest drainage;

V) Land Use and Land Cover – MapBiomas Project for the year 2021 (Souza et al. 2020, Projeto Mapbiomas, coleção 7), which defined 21 land use and land cover classes in the Cerrado biome at 30-meter resolution using LANDSAT images;

VI) Percent Tree Cover – represents the annual forest canopy cover and is generated from monthly compositions of MODIS sensor bands aboard NASA's Terra satellite, with a resolution of 500 meters (Hansen et al. 2003).

VII) Sand Content (g/kg) – soil composition variable from 30cm to 60cm depth, generated from the Soil Grids initiative (Hengl et al. 2017).

All variables were processed in ArcGIS Pro (version 3.1, Esri 2023), transformed into raster format with a spatial resolution of 30 arc-seconds (~1km), and clipped to the Cerrado region. A correlation table among the variables was generated, and only those with a correlation value of less than 0.70 with another variable were retained for modeling. In cases of correlation exceeding the threshold, the choice of the variable to retain was based on its biological significance for the giant armadillo distribution model in Mato Grosso do Sul (Ferraz et al. 2021).

Modeling:

The Maxent software (version 3.4.1), which employs the principle of maximum entropy based on species presence data and environmental variables (Phillips et al. 2006, Phillips et al. 2008, Phillips et al. 2017a,b), was employed to elucidate the potential distribution of *Priodontes maximus*. Model parameters were configured as follows, in accordance with recommendations by Dalapicolla (2015) and as used by Ferraz et al. (2021): bootstrapping method (n=10) with 30% random points for testing, 10,000 background points, random seed, convergence threshold of 10^{-5}, a maximum of 500 iterations, and Cloglog format for output.

The model was generated utilizing the refined giant armadillo distribution points as previously described, coupled with non-correlated environmental variables. The outcome of the modeling process was the potential species distribution map, with pixel values varying according to the level of environmental suitability for each location.

Assessment of Environmental Suitability within the Landscape Context:

The environmental suitability for the species was categorized into (I) non-suitable, (II) low suitability, (III) moderate suitability, and (IV) high suitability. The value for the first category was determined by the threshold cutoff from the model, while the limits for categories II, III, and IV were established based on the second, third, and fourth quartiles of this variable, respectively. The fusion of categories III and IV was designated as Remnant Habitat (RH) for the species.

To identify recent deforestation expansion within the biome and the areas where it poses threats to the species' remnant habitat, the ten largest RH patches were highlighted and overlaid with the MATOPIBA area (Embrapa 2017) and deforestation polygons identified by the PRODES system (INPE) for 2022.

To assess the conservation potential within protected areas, the quantity and percentage of RH area for the giant armadillo were calculated within Conservation Units (SNUC 2000) as well as Indigenous Lands (Estatuto do Índio 1973).

Municipal Profiles

Agrarian, Socioeconomic, and Governance Variables:

To incorporate socioeconomic and political factors into the strategic planning for the species conservation, municipalities within the Cerrado biome were characterized using the following variables:

I) Human Development Index (HDI): This comprehensive and synthetic measure is used to classify the degree of economic development and quality of life. Comprising gross per capita income, health/longevity, and education, HDI ranges from 0 to 1. The Brazilian Municipal Human Development Index is a methodological adjustment of the global HDI and its data available through the Atlas of Human Development in Brazil (PNUD 2017).

II) Municipal Governance Index (IGM) from the Federal Council of Administration (IGM-CFA): This index encompasses three dimensions—finance, management, and public governance performance—considering areas such as health, education, sanitation, environment, public safety, fiscal management, transparency, human resources, and planning. It evaluates Brazilian municipalities and classifies them on a scale of 0 to 10, where higher values indicate greater municipal government capacity for excellence in execution (IGM-CFA, 2020).

III) Fiscal Module: The fiscal module reflects the average size of properties in the municipality and is used here as a proxy for this purpose. This unit of measurement, in hectares, defined for each municipality by the National Institute for Colonization and Agrarian Reform (INCRA). In Brasil, it varies from 5 to 110 hectares (Instrução Especial nº.5, de 29 de julho de 2022).

IV) Legal Reserve Balance: Derived from the Radiografia do CAR initiative under the Observatory of the Forest Code (Radiografia do CAR 2023). This dataset provides the Legal Reserve balance per property (registered limits in INCRA), and then the values within each municipality are summed to obtain the municipal Legal Reserve Balance. When the value is zero, it means that the municipality has 20% remaining native vegetation within private properties, as mandated by legislation for the biome. A negative value indicates the deficit of remaining native vegetation in Legal Reserves in hectares. Positive values represent remaining native vegetation beyond the legal requirement in hectares.

V) Percentage of Public Lands: This variable was obtained by dividing the area of public lands within each municipality by its total area. Public Lands include Indigenous Lands (Estatuto do Índio 1973) and Conservation Units of both Strict Protection and Sustainable Use (SNUC 2000) whose land ownership is public, not private. Conservation Units on private properties were not considered.

While the first two variables encompass the socioeconomic and governance context of municipalities, the last three characterize the agrarian context. Variables III and V, Fiscal Module and Percentage of Public Lands, enable the identification of key stakeholder profiles involved in municipal-level decision-making.

Although conservation strategies are frequently defined at the state, federal, or international levels, the municipal level was chosen as the sampling unit due to its role as the smallest political-administrative division of public governance. Moreover, actions from larger spheres significantly impact municipalities. This classification can also be applied at the state level by summing the values.

The five variables were paired, and Spearman analyses were conducted to assess the amount of correlation among them.

Municipal Classification

A cluster analysis was performed to group municipalities according to the values of the 5 agrarian, socioeconomic, and political variables. Using the Grouping Analysis tool within ArcGIS Pro, we categorized the 1434 municipalities into 3 groups. Municipalities exhibiting similarities among themselves are categorized into the same group. The objective of this analysis was to find a solution that maximizes the similarity of all features within each group while maximizing the dissimilarity between the groups themselves. It was selected No Spatial Constraint parameter, so a K Means algorithm was used for grouping (Esri 2023).

The K Means algorithm works by first identifying seed features used to grow each group. Consequently, the number of seeds always match the Number of Groups. The first seed is selected randomly. Selection of remaining seeds, however, while still employing a random component, applies a weighting that favors selection of subsequent seeds farthest in data space from the existing set of seed features (Esri 2023).

Once the seed features are identified, all features are assigned to the closest seed feature (closest in data space). For each cluster of features, a mean data center is computed, and each feature is reassigned to the closest center. The process of computing a mean data center for each group and then reassigning features to the closest center continues until group membership stabilizes, up to a maximum number of 100 iterations (Esri 2023).

The R2 value reflects how much of the variation in the original Test Scores data was retained after the grouping process, so the larger the R2 value is for a particular variable, the better that variable is at discriminating among features (Esri 2023).

Incorporating Environmental Suitability Data into Municipal Profiles:

The mean of environmental suitability value was estimated by extracting and averaging the suitability values from all pixels within the boundaries of each municipality, resulting in the municipal environmental suitability value. These values were subsequently categorized into two distinct groups: "high suitability" based on the values within the first two quartiles, and "low suitability" corresponding to values within the last two quartiles.

As a result, each municipality was classified based on its profile and the environmental suitability for the species, generating six subgroups of municipalities: group 1 - high and low suitability, group 2 - high and low suitability, group 3 - high and low suitability. The methods are illustrated in the figure bellow (Figure 2).

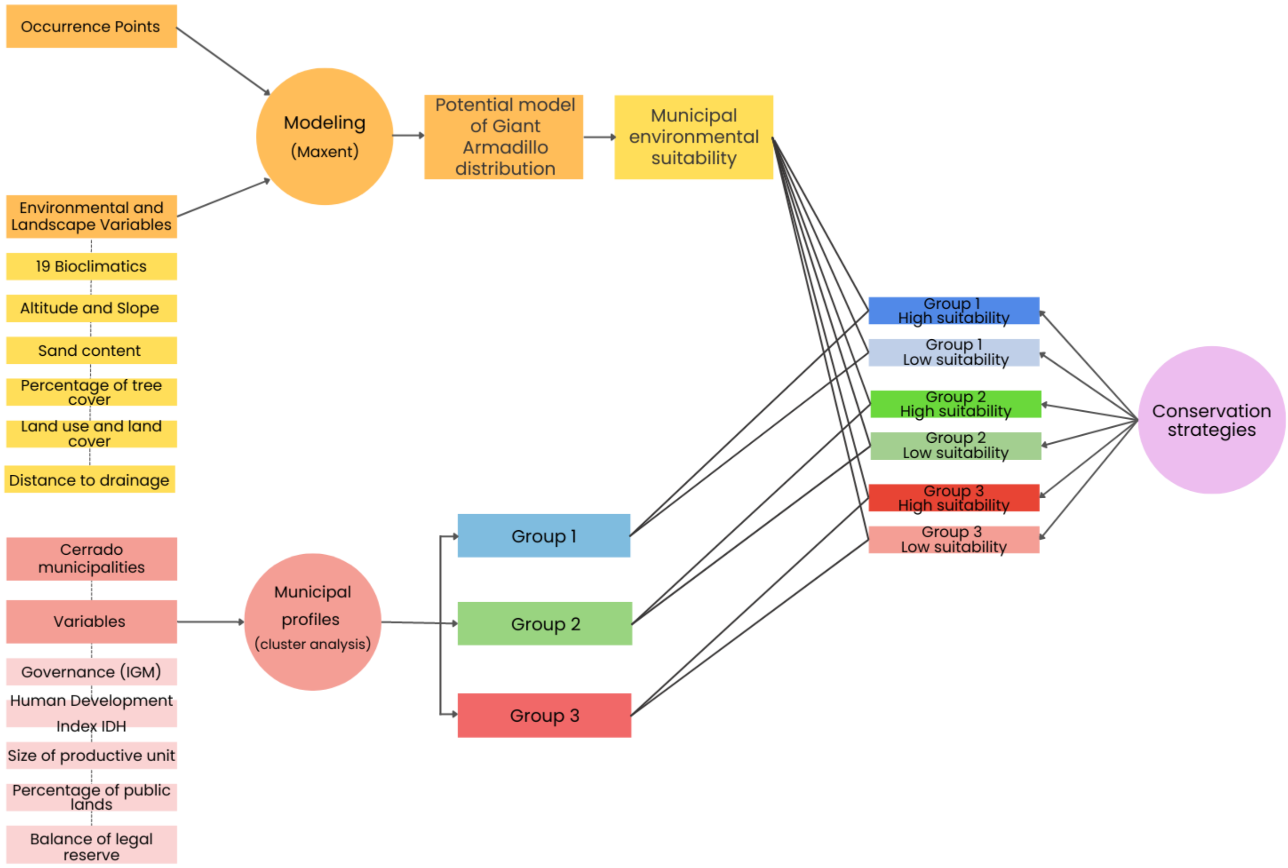

Figure 2. Flowchart depicting the stages and analyses conducted. The species distribution modeling stages are represented in yellow and orange, while the municipality classification into three groups/profiles is shown in pink. The groups derived from the classification of municipalities based on municipal profile and environmental suitability are represented in blue, green, and red. Finally, the proposition of conservation strategies for the six subgroups is indicated in purple.

Conservation Strategies:

To propose customized conservation strategies for each of the municipal subgroups and to achieve the goals of preserving the remaining habitat and enhancing environmental suitability in degraded areas, we considered the following conservation strategies, which were adapted from Strassburg et al. (2017).

I) Protected Areas - establishment of new Conservation Units or Indigenous Lands or provide support for the improved implementation of existing ones;

II) Government Incentives, such as lowering taxes or revenue sharing mechanisms (e.g., Ecological ICMS tax);

III) Compliance with the Native Vegetation Protection Law (NVPL; Lei 12.651, de 25 de maio de 2012, that replaced the Forest Code), which addresses protected areas within private properties and stipulates that in the Cerrado biome, 20% of the total area of private properties must be maintained with native vegetation as Legal Reserves;

IV) Payment for Environmental Services - an economic instrument that follows the "protector-receiver" principle, rewarding and encouraging those who provide environmental services, thereby improving the profitability of protective and sustainable use activities of natural resources;

V) Bioeconomy - ecotourism, extractivism, development of value chains for natural products, and other initiatives generating income from conserved environments;

VI) Climate Initiatives, such as REDD+ and Carbon Credits, which need to be expanded and enhanced in the Cerrado;

VII) International Agreements or Policies Ensuring Supply Chain Traceability and Blocking Products with Origins in Recent Deforestation - extending successful actions from the Amazon biome to the Cerrado, such as the soy moratorium or the European Union policy to reduce imports of products that incentivize deforestation;

VIII) Enhancing productivity and reducing degradation in areas that have already been converted - requires the use of technologies like pasture management, suitable soil and water conservation techniques and intercropping, while also adhering to the biome's carrying capacity;

IX) Restoration - a process aiding in the reestablishment of a degraded, damaged, or destroyed ecosystem;

X) Improving Enforcement Mechanisms and Law Application;

XI) Land Use and Occupation Planning and National Action Plans;

XII) Integrated Fire Management - prevention and control measures against forest fires, which pose a threat to the biome;

XIII) Environmental Education;

XIV) Research and Monitoring.

The last two conservation strategies (XIII, and XIV) were not individually pointed for each group of municipalities, as they should be present in all cases with a focus shift in each situation. Furthermore, the intention of this study did not involve discussing these strategies, as they cannot be quantified through landscape analysis.

Results

Presence Points:

A total of 1,387 points were obtained in the data collection phase, and after filtering, 486 presence points of the species were retained and used for modeling.

Modeling:

The final model for the potential distribution of the giant armadillo in the Brazilian Cerrado exhibited strong performance (AUC = 0.8565 ± 0.0438, 22% omission rate, $p \leq 0$). The most influential explanatory variables in deciphering species distribution were Land Use and Cover (27.3% prediction), vertical distance to water - Hand100 (16.2% prediction), and altitude (9.1% prediction).

Environmental suitability ranged from 0 to 0.99. The model was cut at the highest level (0.39), thus values between 0 and 0.39 were considered unsuitable for species occurrence, and any value below 0.39 was treated as zero. Figure 3 illustrates the model of the potential distribution of the giant armadillo. Upon extracting the mean environmental suitability per municipality, the range varied from 0 to 0.7067.

The suitable area for the species encompassed 695,366.60 km2, representing 33% of the sampled area (Cerrado biome), out of a total of 2,124,105.10 km2.

The ten larger patches of remnant habitat, in descending order, are located 1) In the north and northeast of Mato Grosso do Sul, southeast of Mato Grosso, and southwest of Goiás, bordering the Pantanal biome to the west. This region comprises protected areas (35,909km^2); 2) In the eastern part of the state of Mato Grosso, bordering the Amazon biome. There are Indigenous Territories in this portion (18,600km^2); 3) In the western part of the state of Mato Grosso, bordering the Amazon biome, with Indigenous Territories present (13,692km^2); 4) In the western part of the state of Minas Gerais (12,368km^2); 5) In MATOPIBA region with protected areas (12,368km^2); 6) In the central-western part of the state of Minas Gerais, including a protected area (4,707km^2); 7) In the central part of the state of Mato Grosso, with Indigenous Territories present (4,083km^2); 8) In the western region of Bahia, in MATOPIBA region (4,079km^2); 9) In the south of Tocantins, also in MATOPIBA region (2,638km^2); 10) At the border of the states of Mato Grosso and Rondônia, bordering the Amazon biome (1,945km^2). These patches are represented in Figure 4.

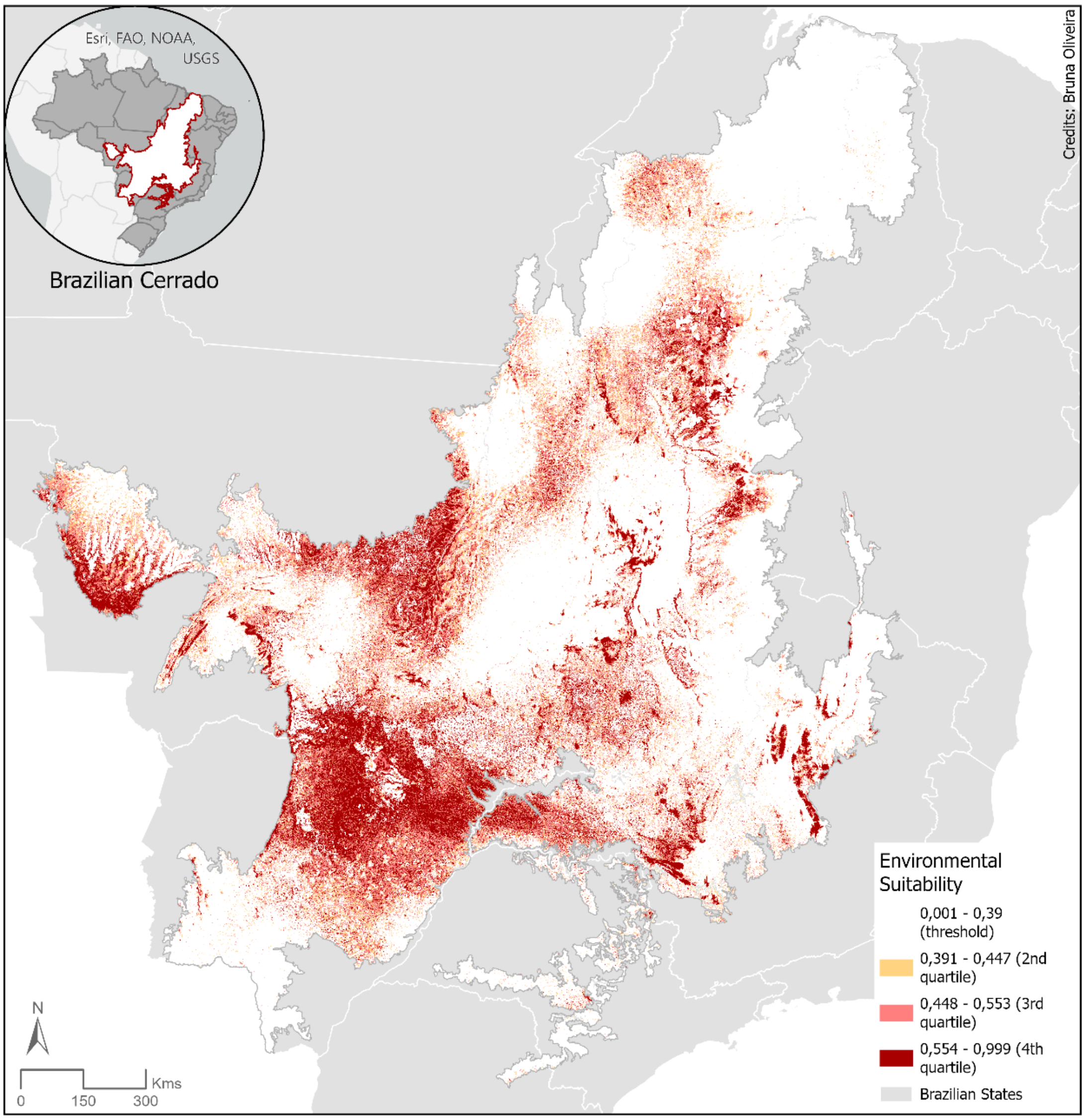

Figure 3. Giant Armadillo Distribution Model in Brazilian Cerrado.

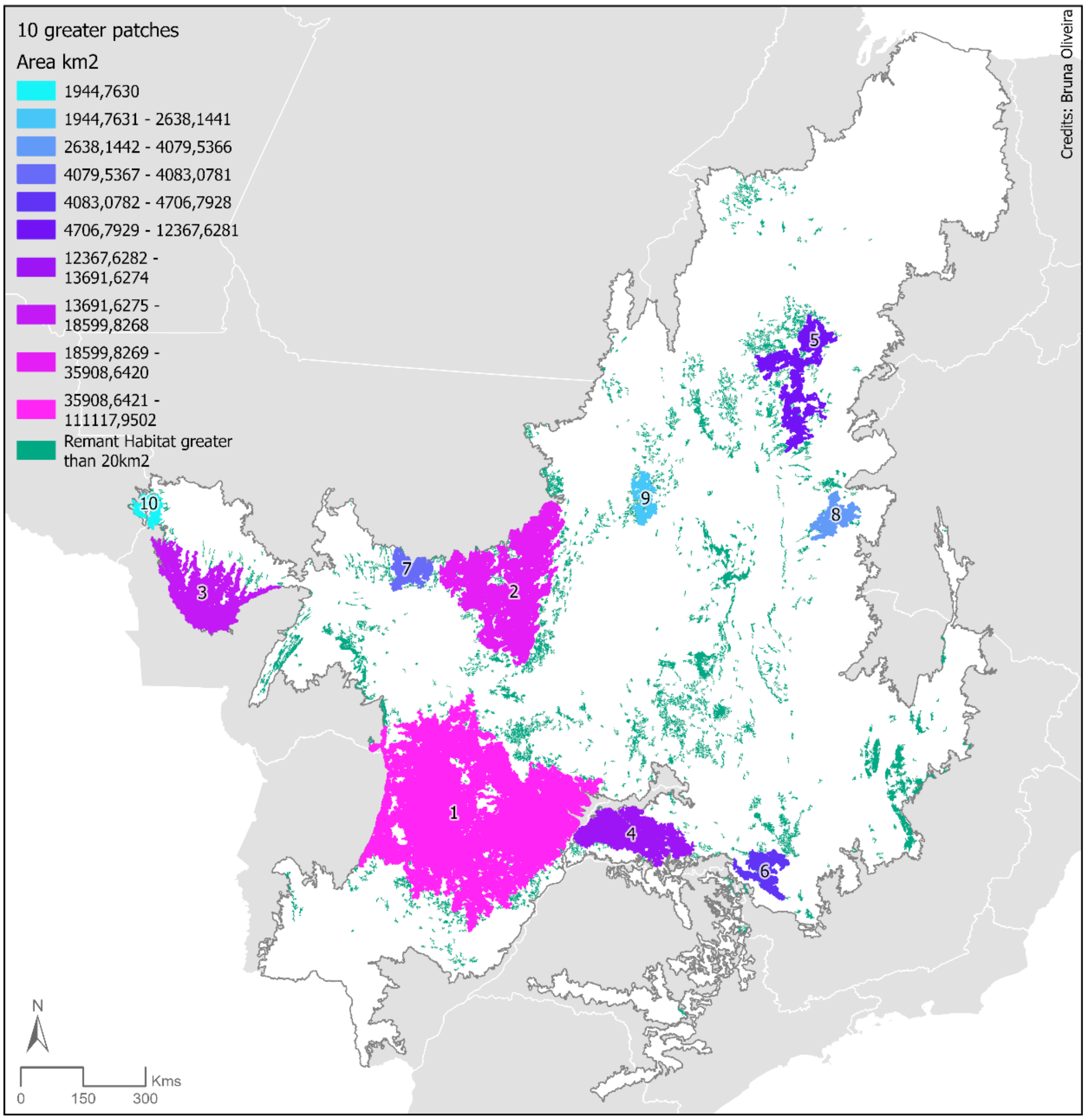

Figure 4. Largest patches of remnant habitat for Giant Armadillo in Cerrado Biome.

Landscape Structure and Composition

A total of 29,553.4 km2 is within protected areas (4.25% of the RH), and 23,330.27 km2 is within Indigenous Lands (3.35% of the RH), totaling 52,883.67 km2 of public lands, equivalent to 7.6% of the RH (Figure 5).

The overlay with deforestation polygons indeed reveals that the patches in MATOPIBA are the most susceptible to deforestation expansion due to the higher proportion of polygons in this area. Meanwhile, the overlay with land use-derived layers indicates that some patches, as the largest one, are situated in regions where a significant portion of the natural habitat has already been replaced and is anthropogenically altered.

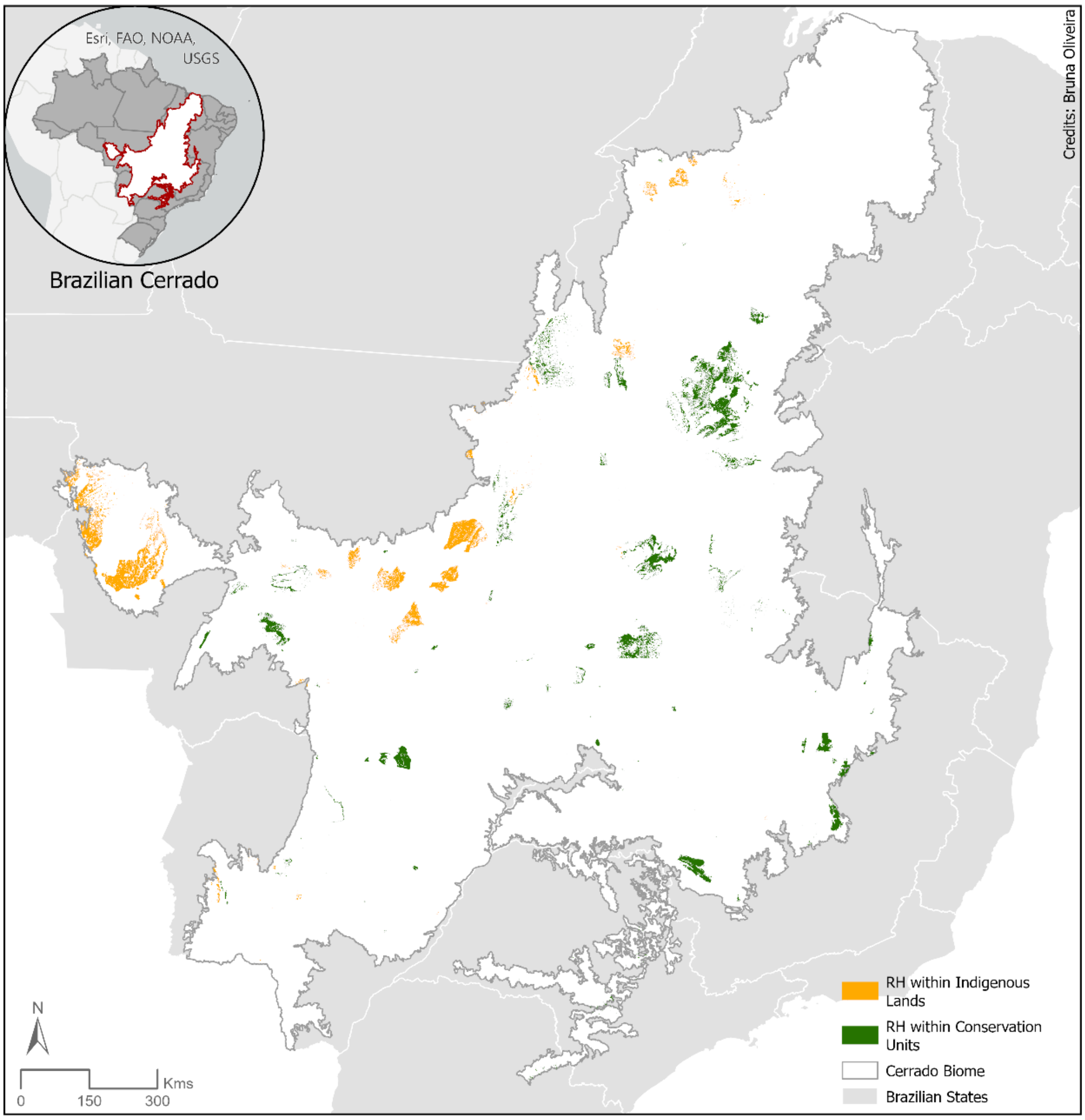

Figure 5. Remnant Habitat (RH) for Giant Armadillo within Indigenous Lands (yellow) and Conservation Units (green).

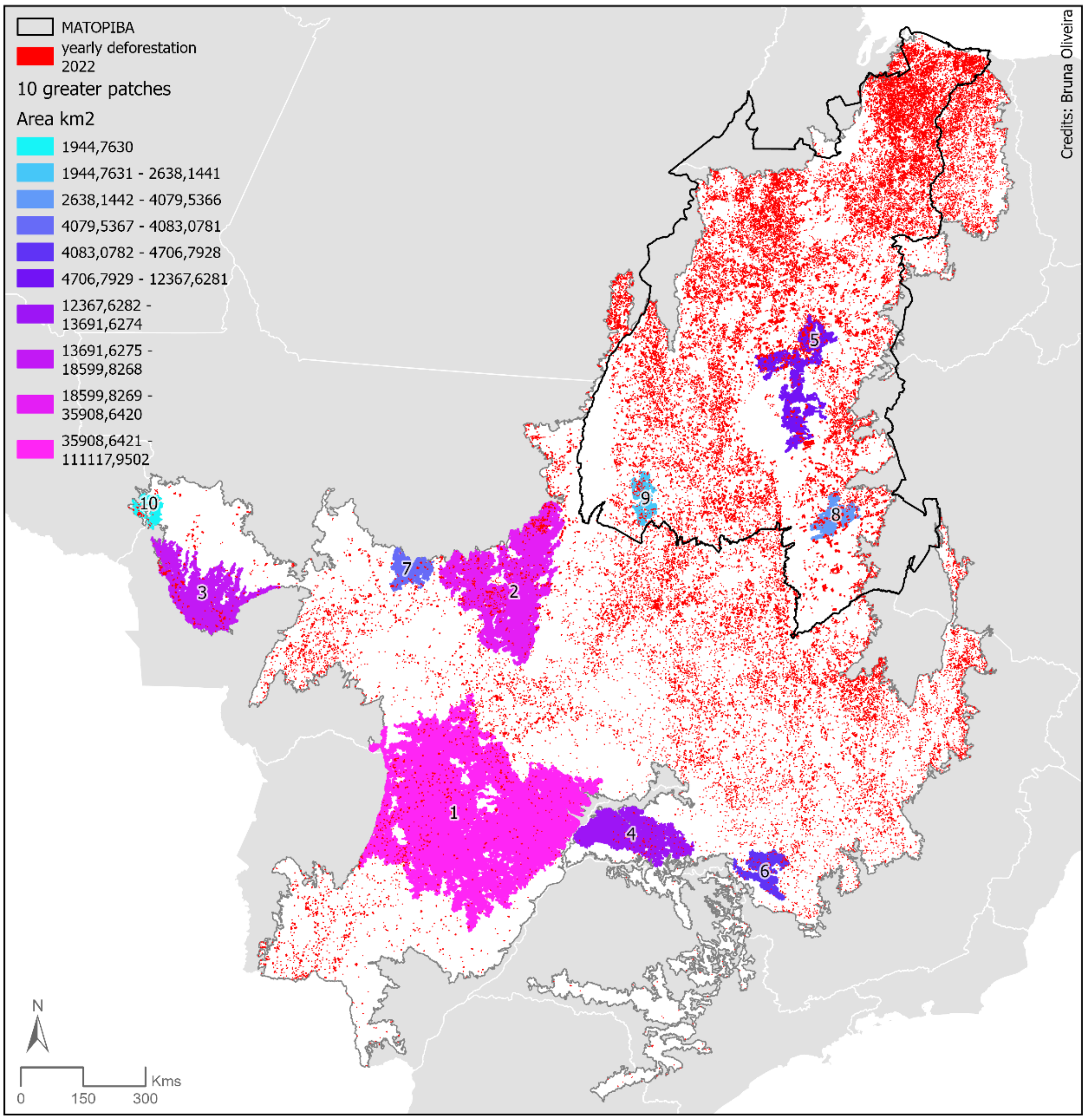

Figure 6. The larger patches Giant Armadillo habitat remnants are overlaid with the annual increment in native vegetation suppression for the year 2022, as documented by the PRODES system of the National Institute for Space Research (INPE), highlighted in red. This visualization delineates the areas of greatest concern with respect to deforestation threats to the species. Deforestation activity is currently predominant within the MATOPIBA region (demarcated by a black polygon).

Municipal Grouping

The five socio-economic, political, and agricultural variables were assigned values for each municipality in accordance with the representation depicted in Figure 7.

Municipal Cluster Analysis

The cluster analysis resulted in three groups of municipal profiles, based on the socio-economic, agricultural, and political characteristics of each municipality. The variables that most influenced the formation of these groups were the percentage of public lands ($R2=0.7118$) and fiscal modules ($R2=0.5690$).

Group 1, represented in figures 8 and 9 by the blue color, comprises 617 municipalities and stands out for having the lowest averages of governance and HDI, larger fiscal modules, low percentage of public lands, and low surplus of legal reserves. Similarly, Group 2, represented by the green color, also exhibits low percentage of public lands and low surplus of legal reserves. However, it has the smallest average fiscal module size and the highest averages of governance and HDI. This group consists of 743 municipalities, mainly distributed in the southern region of the midwest and southeast of the country. On the other hand, Group 3, represented in the figures by the red color, includes municipalities where the averages of percentage of public lands and the balance of legal reserves are the highest compared to the others. This group has the greatest amount of remaining native habitat, both in protected lands and private properties. It also has larger fiscal modules and moderate values of governance and HDI. This group is composed of the fewest municipalities, totaling 74 units.

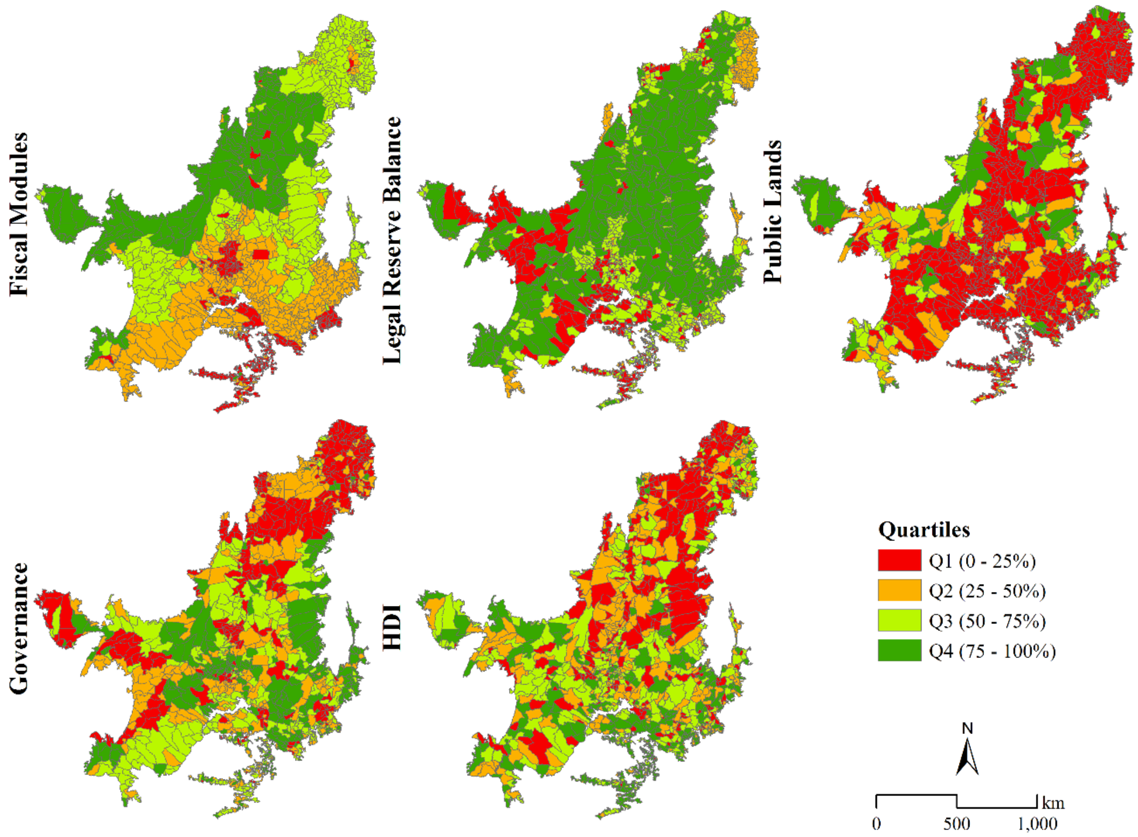

Figure 7. Spatially distributed socio-economic and agrarian variables at municipal level. Polygons represent municipality boundaries. The color red represents the lowest quartile of values, orange the second quartile, light green the third quartile, and dark green the fourth and top quartile of values for each variable. Fiscal Modules (MF) ranged from 5 to 110 hectares; Balance of Legal Reserves from -152,984 to 2,577,982 hectares; Public Lands from 0 to 0.9951; Municipal Governance Index (IGM) from 0.86 to 6.61; and Human Development Index (HDI) from 0.497 to 0.854.

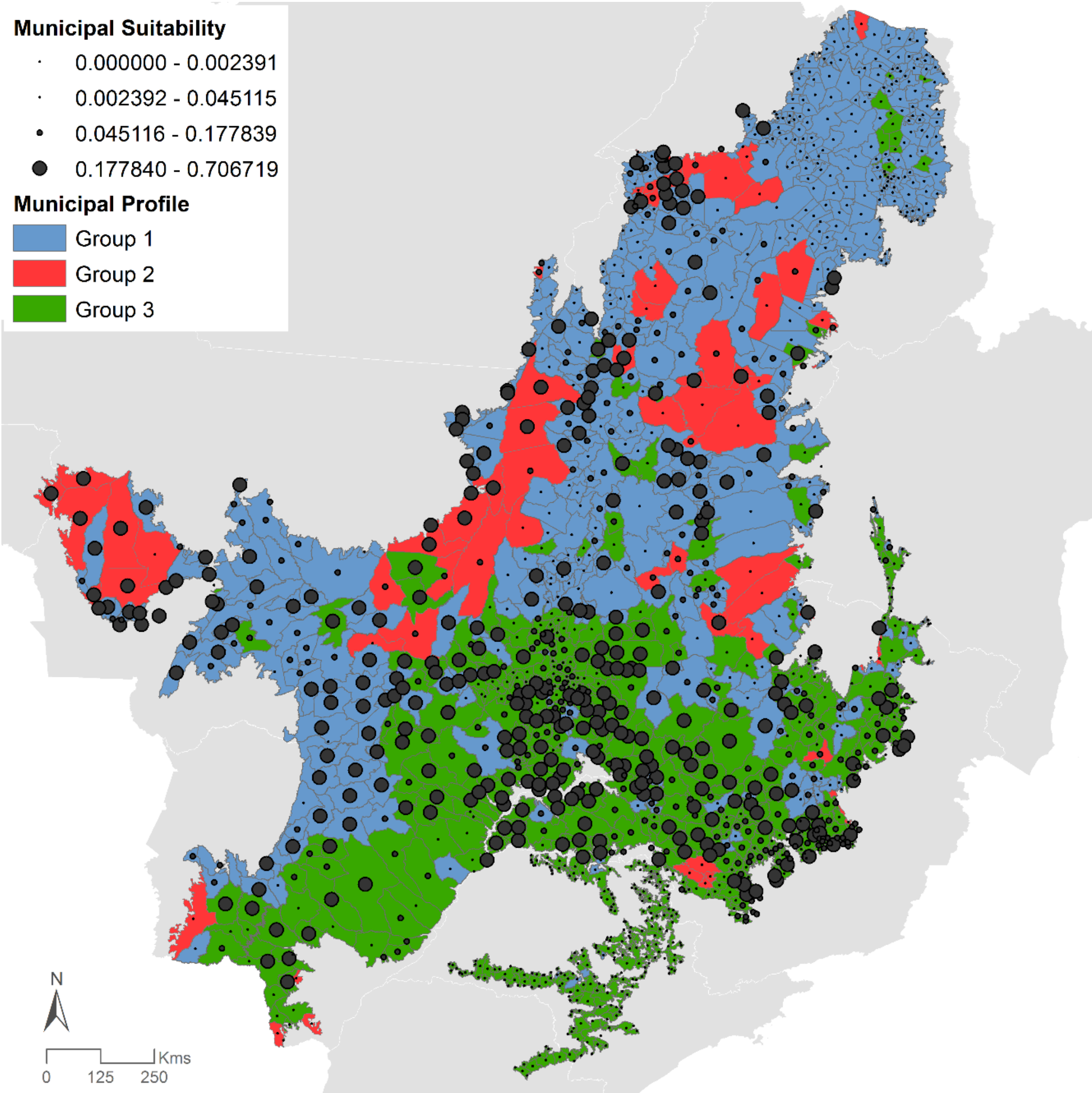

Figure 8. Cerrado municipalities classified into three groups with distinct colors based on their socioeconomic, governance, and agrarian profiles, and further categorized according to environmental suitability for the Giant Armadillo. Black circles are used to represent areas with either high or low environmental suitability, with circle size corresponding to the degree of suitabilityl. Regions with denser clusters of circles indicate areas with smaller municipalities and a higher concentration of political subdivisions, but not necessarily greater environmental suitability for the species.

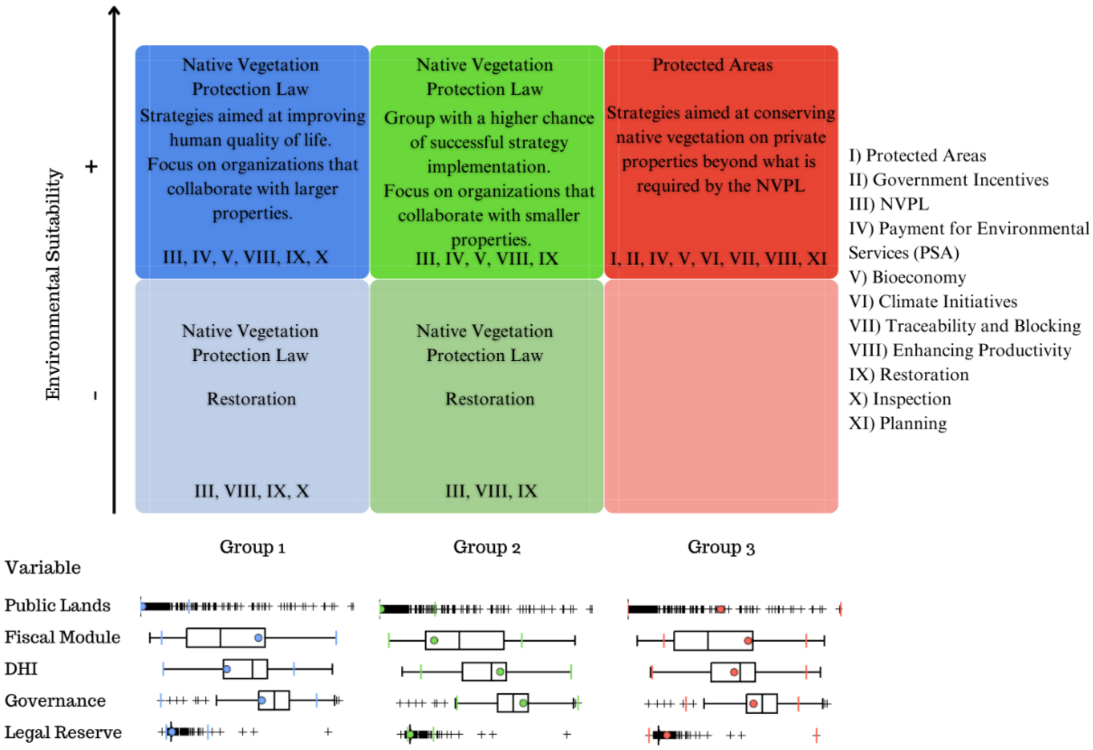

Figure 9. Framework representing each subgroup established based on the municipal profile and environmental suitability. Within this framework, conservation guidelines have been outlined for each subgroup, and conservation strategies have been enumerated, taking into account the agrarian, socioeconomic, governance, and species suitability realities of each location. These strategies are not mutually exclusive and were designed for a local-regional scale. Below of it, there are boxplots illustrating the behavior of each variable within each group.

Incorporating Environmental Suitability and Proposing Conservation Strategies

The value of municipal environmental suitability was classified as low when it ranged from 0 to 0.045, and as high when it ranged from above 0.045 to the maximum value of 0.707. Both the classification into municipal profiles and environmental suitability classes were spatially mapped and depicted in Figure 8. Conservation strategies were then proposed for each subgroup, as presented in Figure 9, taking into consideration their specific characteristics.

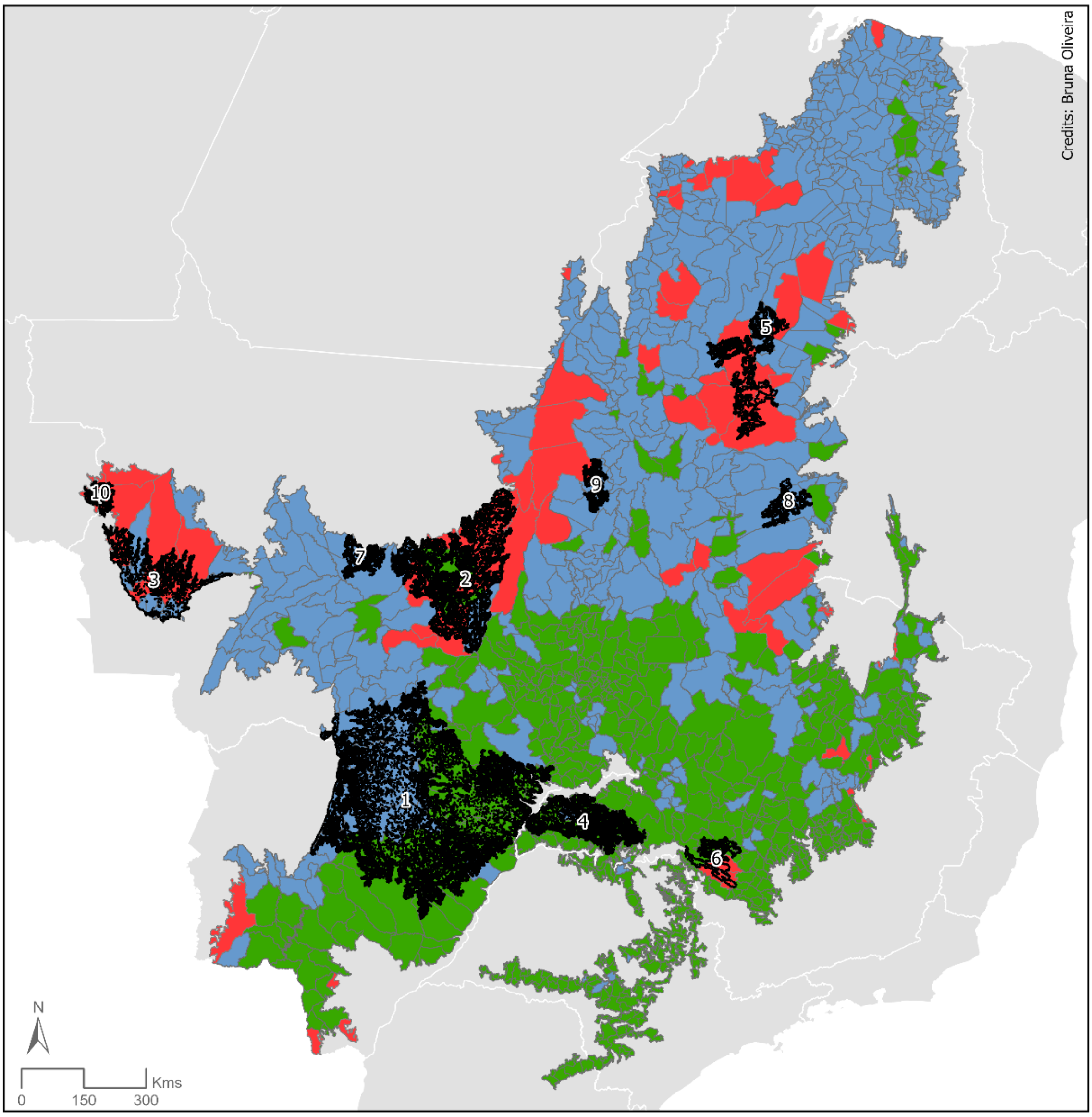

Figure 10. Incorporating the 10 largest patches overlaid onto categorized municipalities. This figure illustrates the municipality groups within the largest patches, facilitating the planning of conservation strategies for these significant suitable areas.

Discussion

Numerous strategies must be considered to conserve biodiversity, ranging from ethical and moral arguments (Jepson & Canney 2003, Robinson 2011) to economic perspectives (Tisdell 1994, Balmford et al. 2002, Duarte et al. Under Review). In the Cerrado, many of these strategies have already been proposed, including enhancing the restoration and protection of key habitats, allowing agricultural expansion with clear land-use planning criteria, promoting agricultural expansion without deforestation, increasing pasture productivity, fostering economic mechanisms within the bioeconomy (e.g., carbon markets, local products based on native species, etc.), and extending the Soy Moratorium to cover the Cerrado for sugarcane and beef (Strassburg et al. 2017, Soterroni et al. 2018, Brock et al. 2021, Flach et al. 2021, Colman et al. 2021, De Marco et al. 2023). These strategies should be seen as a range of possibilities whose operationality and successful implementation depend on socio-cultural, political, and economic contexts (O'Connor et al., 2003; Bode et al. 2008; Knight et al. 2010, Smith et al. 2010, Bennett et al. 2017). As our study demonstrates, these contexts can be spatialized and considered since the first steps for conservation planning and implementation.

The categorization of geopolitical locations into large groups and their overlay with environmental suitability for the species reveal significant social, agrarian, and economic differences, crucial for establishing conservation strategies. This approach aligns with global studies showing that conservation of mammals in different regions can benefit from tailored strategies. The identified municipal profiles highlight opportunities and challenges for conservation efforts in each group.

Among the three identified municipal profiles, Group 3 stands out. It is characterized by a significant quantity of remaining habitat, within both protected areas and in surplus on private properties. When prioritizing efforts within a context of limited resources, this group emerges as a promising focus. It concentrates extensive blocks of native habitat, that are repeatedly emphasized as important for conservation (MacArthur & Wilson 1967, Ferraz et al. 2007) within Conservation Units or other conservation strategies that benefit wildlife within private properties (Soares-Filho et al. 2014, De Marco et al. 2023). Furthermore, it comprises only a few municipalities, what makes it easier to implement strategies.

Group 2 stands out as the municipal profile with the highest capacity for conservation actions' implementation. Boasting elevated levels of governance and HDI, it encompasses municipalities more capable of both administrative and financial implementations. According to Oliveira et al. (2011), these dimensions are indicators of better implementation of conservation actions. Furthermore, high levels of human development have been correlated with reduced deforestation (Jha & Bawa 2006). However, this group presents an average balance of legal reserves and a percentage of public lands close to zero, indicating limited opportunities for actions related to the protection of large habitat fragments beyond what is already guaranteed by current legislation. Therefore, to enhance their effectiveness, conservation efforts in this group should focus on preserving and enhancing the remaining habitat, as well as restoration. Additionally, this group comprises municipalities with a relatively small average fiscal module size, generally representing smaller properties. Thus, conservation strategies for this group may need to prioritize finding on few big properties that represents key role in connecting, restoring or protecting bigger amounts of land, as Stefanes at. al (2018) finds to be more effective.

Group 2 stands out as having the highest potential for implementing conservation actions at the municipal level. It distinguishes itself by exhibiting elevated levels of governance and Human Development Index (HDI), which collectively make these municipalities more adept at executing both administrative and financial aspects of conservation initiatives. As highlighted by de Oliveira et al. (2011), these dimensions serve as indicators of better implementation of conservation actions. Furthermore, there exists a positive correlation between high levels of human development and reduced deforestation, as demonstrated by Jha and Bawa (2006).

Nevertheless, this group presents an average balance of legal reserves and a percentage of public lands close to zero, suggesting limited opportunities for actions aimed at protecting substantial habitat fragments beyond what is already mandated by existing legislation (Lei 12.651, de 25 de maio de 2012). Additionally, this group encompasses municipalities characterized by a relatively modest average fiscal module size, typically indicative of smaller properties. Consequently, conservation strategies for this group may need to prioritize identifying a few larger properties that play a pivotal role in connecting, restoring, or safeguarding more extensive tracts of land, as Stefanes et al. (2018) have found to be a more effective approach

With the lowest averages of HDI and governance, conservation strategies for Group 1 may be the most challenging to implement. Improving people's quality of life and income-generating initiatives are important for valuing the remaining native vegetation in these municipalities. Studies highlight that, in the Cerrado, large properties tend to comply more with the Native Vegetation Protection Law (Stefanes et al. 2018). Given that these municipalities typically consist of larger properties, it is advisable to prioritize collaboration with key large landowners and organizations dealing with this landowner profile working closly with private sector associated to cattle ranching or soy maize production.

Conservation strategies for giant armadillo

Numerous strategies have been discussed and some of them have been implemented for the conservation of large mammals in the Cerrado. Several of these strategies focus on species conservation to increase public interest and empathy, and reduce human-wildlife conflicts (e.g.). Others target landscape and territorial policies to ensure habitat and connectivity (Carvalho et al. 2009, De Marco et al. 2018,) and Species Distribution Models are essential for these (Margules & Austin 1994, Ferraz et al. 2012). Big mammals needing large areas that have low population growth rates need conservation strategies at a landscape level (Purvis et al. 2000) and National Action Plans for Species Conservation (PANs) have proven to be effective tools proposing actions for both levels of conservation (Vercillo et al. 2023).

For the giant armadillo, a rare, fossorial, and cryptic species, which is one of the last large mammal species to be studied for these reasons (Silveira et al. 2009), scientific research has primarily focused on understanding the animal's biology (Meritt, 2006; Silveira et al. 2009; Desbiez & Kluyber 2013; Desbiez et al. 2020a, 2020b, 2021). There has been less emphasis on the landscape scale (Srbek-Araujo 2009, Superina & Abba 2014, Chiarello et al. 2015, Lemos et al. 2018, Ferraz et al. 2021). Consequently, based on the existing knowledge of the species, most of the conservation strategies currently proposed are also more focused on the animal itself, such as environmental education and conflict reduction (Desbiez et al. 2020c), rather than on its habitat (e.g. Pombo Park and Cisalpina study areas). It is important to consider both the biology of this species, but also the socioeconomic contexts where the species tend to occur as the basis for a cost effective intervention on the territory.

Our study advances the giant armadillo distribution modeling with a larger and more comprehensive dataset compared to previous analyses, such as Anacleto et al. (2014) and Ferraz et al. (2021). The modeling reveals that areas of high suitability for the species are not equally distributed across the Cerrado. Considering that agriculture is the main driver of change in this biome (Dobrovolski et al. 2011, De Marco et al.2018), and large areas are expected to be converted in the coming years, especially in MATOPIBA (Carneiro-Filho & Costa 2016), some of the conservation opportunities overlap with these expanding agricultural regions. This is of great concern and calls for immediate conservation actions, including reactive strategies (Dobrovolski et al. 2011) and action plan implementation. On the other hand, there are vital areas for the species beyond the agricultural expansion frontier, where conservation opportunities face less pressure, and proactive conservation strategies can be devised (Dobrovolski et al. 2011).

In this context, our framework can be useful in the process of defining prioritization strategies for the implementation of projects and programs for giant armadillo conservation, as it explicitly considers key socio-ecological and governance aspects for public policies, particularly those that take into account federal, state, and municipal geopolitical divisions.

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