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Mapping ecological corridors in the Upper Paraguay River Basin, Brazil: Applications for sustainability, public policy and decision-making

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Abstract

The Upper Paraguay Basin (BAP) is one of the largest river basins in South America, covering three countries: Brazil, Bolivia and Paraguay. In Brazil, one of the main risks to BAP conservation is the loss of native vegetation. In the floodplain region of the BAP, more than 13% of native vegetation was converted, while in the surrounding highlands the loss of native vegetation reached over 61% of the area. These values tend to increase, highlighting the importance of territorial planning for sustainable development in the region. In this sense, we mapped the ecological corridors in the Upper Paraguay Basin, in Brazil, to support conservation strategies focused on maintaining connectivity on a regional scale. To achieve this, we use the Least Cost Path and Circuitscape methods, based on a multispecies approach. As a result, we identified 303 fragments of native vegetation or conservation units that can be considered nodes and 859 ecological corridors. Of all the ecological corridors identified, around 288 were lost in just 3 years, due to the conversion of native vegetation. In general, our results were an extensive network of corridors, which can be applied in UPRB territorial planning, aiming to reduce the impacts of loss of connectivity in the region. Our results highlight the importance of territorial planning and quick and effective decision-making to mitigate the effects of native vegetation loss for biodiversity conservation in the UPRB.

KEYWORDS

circuitscape, connectivity, environmental corridors, least cost path, natural corridors, pantanal, wetlands

1 | INTRODUCTION

The main threat to biodiversity is habitat and connectivity loss (Newbold et al., 2015). Currently, it is estimated that 44% of the Earth's land surface is under high human impact, generating fragmentation of habitats and loss of connectivity across most terrestrial biomes (Edelsparre et al., 2018; Madadi et al., 2017). The loss of connectivity in natural areas can affect the long-term viability of populations of wild species (Haddad et al., 2015; Rudnick et al., 2012), lead to reproductive isolation, loss of genetic variability, and even local species extinction (Haddad et al., 2015; Holderegger & Di Giulio, 2010). An essential element in mitigating the impacts of fragmentation is the use of ecological corridors. According to the IUCN, ecological corridors can be defined as areas of the natural environment that are governed and managed over the long term to maintain or restore effective ecological connectivity (Hilty et al., 2020). Habitat patches that are connected can be considered conservation targets, and a set of targets and ecological corridors can be defined as an Ecological Network for conservation (Hilty et al., 2020). Ecological networks ensure the functioning of systems and guarantees the maintenance and connection between populations, even in the face of climate change (Hilty et al., 2020). Due to their importance for conservation, ecological corridors and ecological networks should be considered in territorial planning, especially in developing regions. These tools can work for conservation in both multifunctional landscapes, which are composed of a mosaic of land cover types, and fragmented landscapes due to intensive land use (Parrott et al., 2019; Parrott & Meyer, 2012).

The Upper Paraguay River Basin (UPRB) is one of the largest river basins in South America, covering three countries: Brazil, Bolivia, and Paraguay (Tomas et al., 2019). In Brazil, the UPRB consists of lowland and highland regions. The lowland area is characterized by the Pantanal biome, a floodplain, while the highland region is predominantly composed of the Cerrado and Amazon biomes (SOS-Pantanal, 2015, 2017). The loss of native vegetation in the UPRB varies according to the region (Guerra, de Oliveira Roque, et al., 2020b; Oliveira et al., 2021). In the lowlands, where more than 13% of the native vegetation has been converted, the loss primarily occurs in the “Arc of Deforestation,” located in the transition zone between lowlands and highlands (Guerra, de Oliveira Roque, et al., 2020b). Additionally, areas with low flooding frequency tend to experience higher rates of conversion compared to areas with high flooding frequency (Oliveira et al., 2021). The highland region has experienced the greatest loss of native vegetation, with over 61% of the area affected (SOS-Pantanal, 2015, 2017). Projections for the next 50 years indicate a 10% increase in the loss of native vegetation in the UPRB (Guerra, de Oliveira Roque, et al., 2020b). This situation could worsen, as in 2022, the Pantanal and Cerrado biomes within the UPRB showed a 4.4% and 31% increase, respectively, in the rate of native vegetation loss (MapBiomas, 2023).

These increasing rates of conversion of native vegetation, along with spatial pattern variations and a lack of public policies, can lead to high levels of habitat fragmentation and loss of connectivity in the UPRB. This emphasizes the need for up-to-date information to support territorial planning in the region. In this study, we identified and mapped the Ecological Network of corridors and Connectivity targets for the UPRB at the landscape scale to generate information that can inform planning and decision-making processes. Furthermore, we discuss how the information generated in this study can be applied to territorial planning, the development of public policies, and decision-making processes, with the aim of mitigating the impacts of habitat fragmentation throughout the UPRB.

We utilized a structural connectivity modeling method that considers habitat permeability based on physical characteristics and the arrangement of habitat patches (Hilty et al., 2019, 2020; Keeley et al., 2021). This approach is particularly useful when there is limited knowledge about species movement patterns and can be applied to multiple species (Hilty et al., 2019, 2020; Keeley et al., 2021). Thus, to address existing information gaps in the UPRB, such as species occurrence and habitat preferences, we adopted an approach that incorporates structural connectivity and the concept of umbrella species.

2 | MATERIALS AND METHODS

2.1 | Study area

The UPRB is located in the center of South America and has approximately 600,000 km^2 shared by Brazil, Bolivia and Paraguay (Tomas et al., 2019; Figure 1). The UPRB in Brazil comprises approximately 372 mil km^2, accounting for nearly 61% of all UPRB (SOS-Pantanal, 2015, 2017). In Brazil, the UPRB can be divided into lowlands, with approximately 150,000 km^2 or 41% of Brazilian UPRB, and surrounding highlands, with approximately 211,000 km^2 or 59% of Brazilian UPRB (Guerra, de Oliveira Roque, et al., 2020b; Tomas et al., 2019). The lowland (floodplains) correspond to the Pantanal biome, one of the largest inland wetlands in the world, a biodiversity-rich natural heritage recognized by UNESCO (Junk et al., 2014; Tomas et al., 2019).

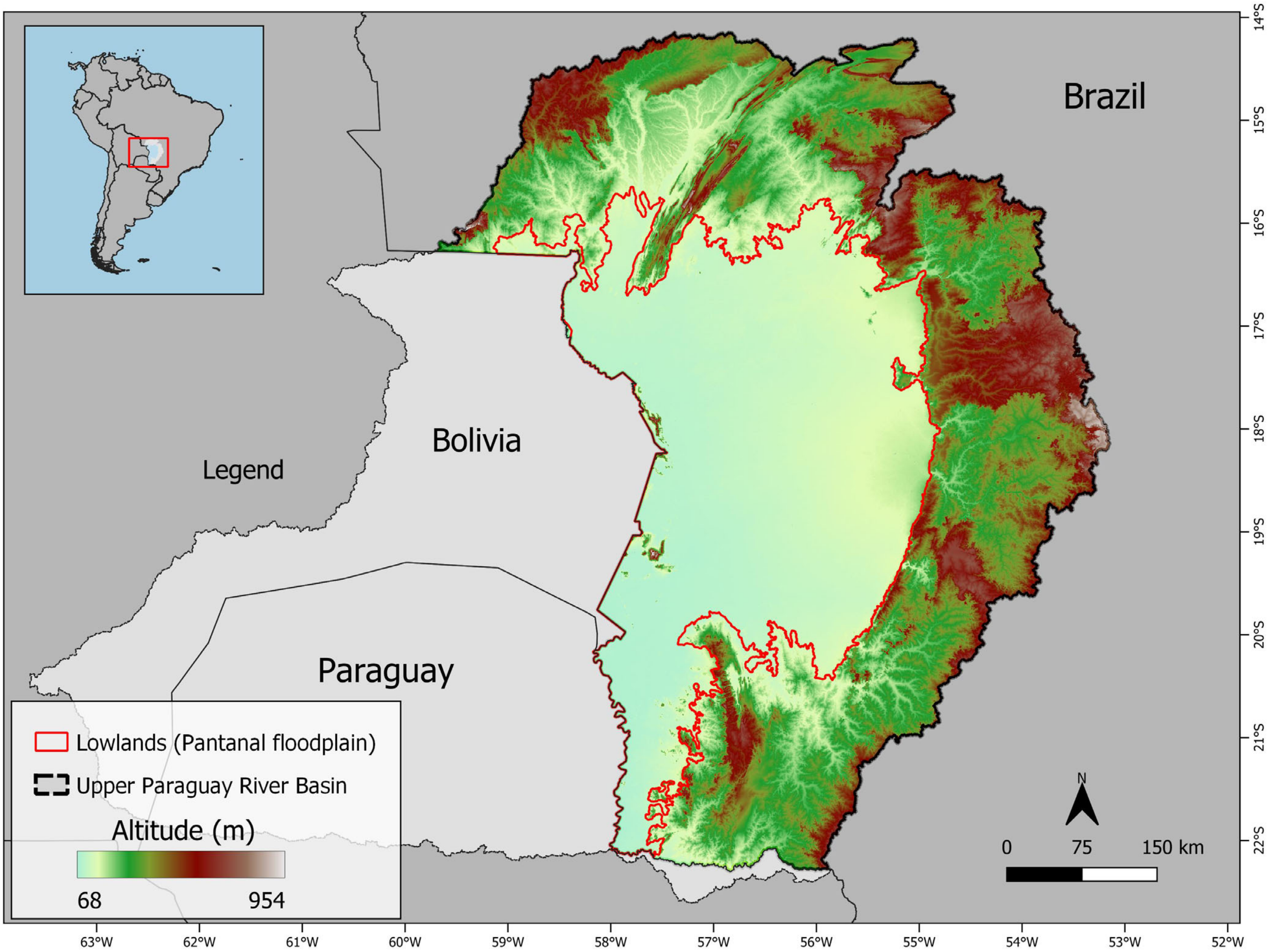

FIGURE 1 Upper Paraguay River Basin in Brazil, including the Pantanal floodplain (blue) and the surrounding highlands (light gray).

In the highlands, the dominant ecosystems are the Cerrado and Amazonia biomes, both considered hotspots of global biodiversity (Junk et al., 2014; Tomas et al., 2019). In the surrounding highlands, most of the native vegetation corresponds to open woodland savannas, grasslands, forested savannas and seasonal and riparian forests (Pott et al., 2014). In contrast, the lowland, Pantanal floodplain, is characterized by a high environmental heterogeneity and a seasonal flood pulse (Junk et al., 1989; Junk et al., 2014; Junk & Wantzen, 2004), with mosaics of open woodland savannas, grasslands, deciduous and semi-deciduous forests, monodominant woodlands, and floodable forests (Pott & Pott, 2009; Tomas et al., 2019).

The floodplain and the surrounding highlands are treated differently by the Brazilian Native Vegetation Protection Law (NVPL). The main difference is that the Pantanal biome is considered as a restricted use region, where only ecologically sustainable land use is allowed (Brasil 2012). On the other hand, these regions receive similar rules in some aspects of the NVPL: the legislation requires that at least 20 and 35% of private properties are to be designated as Legal Reserve (LR), destined for sustainable use and conservation of biodiversity; similarly, the NVPL determines specific, variable metrics for riparian zones along river, stream, ponds, lakes and other drainage systems, which are considered as Permanent Preservation Areas (PPA).

2.2 | General aspects and concepts of modeling

The UPRB has a large knowledge gap in all aspects of biodiversity, such as occurrence, habitat suitability, movement patterns, as well as other information needed for modeling species-specific ecological corridors. (Fernández-Arellano et al., 2021; Junk et al., 2006; Schulz et al., 2019). However, there are ways of modeling that consider these gaps, such as using the concept of

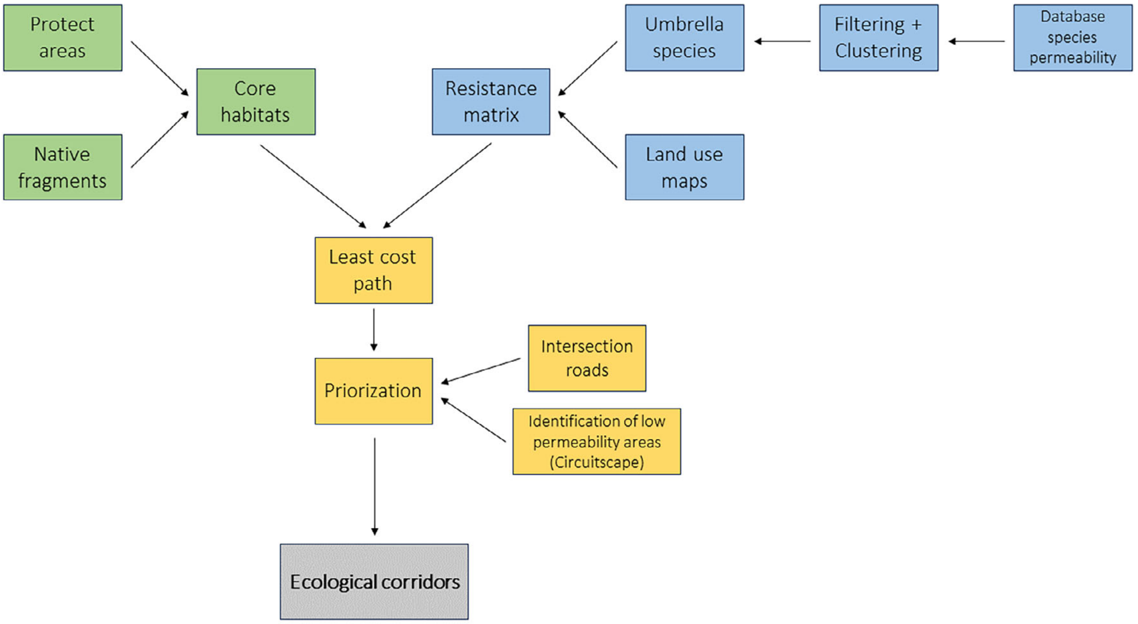

FIGURE 2 Flowchart with ecological corridor modeling process used for corridor mapping in the UPRB.

structural connectivity and umbrella species (Hilty et al., 2019; Hilty et al., 2020; Keeley et al., 2021). Structural connectivity is a measure of connectivity that considers habitat permeability, based on the physical characteristics and arrangements of habitat patches (Hilty et al., 2019; Keeley et al., 2021). Modeling methods that use the concept of structural connectivity, that is, the permeability of the environment, can be applied in multispecies approaches (Hilty et al., 2019; Keeley et al., 2021). The umbrella species has been used in conservation planning with differing goals (Branton & Richardson, 2011). This concept defines that conservation planning elaborated for one species can benefit co-occurring species or species that have lower environmental requirements when compared to the umbrella species (Branton & Richardson, 2011). We considered these two concepts for the modeling process to reduce the effect that knowledge gaps may create.

The process of modeling ecological corridors can vary depending on the method used. We used the Least Cost Path (LCP), a widely used method for modeling structural connectivity. This method requires two inputs, a resistance matrix and connectivity targets. We adopted the term “connectivity targets” instead of “core habitat” as suggested by IUCN, to avoid the disputed meaning of this term (e.g., Hall et al., 1997; Kirk et al., 2018), as habitat is conceptually linked to specific species (Morrison et al., 1992). In our study, the connectivity targets are composed of protected areas and fragments of unprotected native vegetation, as well as large natural patches of native vegetation. The resistance matrix is composed of different land use classes to which a permeability value is assigned, based on the physical structure of the environment and considering the set of focal species. We used the concept of umbrella species to define the focal species. For this, we selected groups of species for which the land use classes presented similar permeability patterns. After preparing the inputs, we ran the model. For the LCP results, we performed a prioritization of the mapped ecological corridors. The prioritization was conducted by checking regions of intersection with roads and railroads and areas of low permeability. To identify the areas of low permeability in the mapped corridors we used the Circuitscape method, which identifies connectivity, considering the concept of random walkers moving on a resistance surface (McRae, 2006, McRae et al., 2008; Figure 2).

2.2.1 | Focal species

We used the permeability value for different types of vegetation and anthropic use to select the species used in the modeling, under a structural connectivity perspective. Permeability can be considered as the ability of species to move in a given type of vegetation, based on the physical structure of the vegetation. The permeability values of the different land use classes for the species were obtained from the database of the Ecological Economic Zoning of the Mato Grosso do Sul state of Brazil (Estado de Mato Grosso do Sul, 2015), where most of the UPRB is located. This database contains a list of 152 species from different taxonomic groups and their respective permeability values, ranging from 1 to 10, in different types of land use, as forests, planted forests, open woodland savannas, grasslands, cultivated grasslands, agriculture and urban areas (Estado de Mato Grosso do Sul, 2015). This database was created using an expert-based approach, involving experts from different taxonomic groups (for more details see, Estado de Mato Grosso do Sul, 2015).

The permeability data was filtered considering three factors: complete data on permeability; terrestrial species, and occurrence recorded in the UPRB. Firstly, we removed from the list those species that did not present permeability data for all land use classes. Subsequently, we removed from the list species linked to aquatic and semi-aquatic habitats, such as amphibians, otters, and caimans. This approach was taken because the work's goal was to map terrestrial corridors, and the reliance of these species on aquatic habitats would require the mapping of aquatic corridors. Finally, we removed the species with no records in the URPB. The filtering reduced the list to 56 species of mammals and birds.

Despite reducing the list to 56 species, this is still a large number of species representing a wide diversity of permeability patterns in different land use classes (see Data S1). This large number can make it difficult to select a single representative species that may function as an umbrella species. Thus, to facilitate this decision, we grouped these 56 species according to their permeability patterns. To form these species groups we performed a cluster analysis. We calculated a similarity index, based on Euclidean distance and performed a cluster analysis using the unweighted arithmetic average clustering method (UPGMA; Legendre & Legendre, 1998). Subsequently, to verify if the groups have different permeability, patterns we performed a post-hoc pairwise Adonis test, using the Vegan and pairwise.adonis packages of the R software (Arbizu, 2019; Oksanen et al., 2020).

The clustering divided the 56 species into 10 groups with different permeability patterns, facilitating the choice of a representative group (see Data S1). Considering the umbrella species concept, we selected the group with the highest environmental requirements, in other words, the group with the highest permeability values in its habitat, but the lowest permeability values in other land cover types. Thus, modeling this group as a focal species ensures connectivity across other species groups. However, the analysis showed two antagonistic permeability patterns (groups 1 and 4 in Table S1), with one group preferring savanna environments and the other preferring forest habitats. For the forest environment group, the forests have high permeability and the savanna and grassland environments have low permeability. On the other hand, for the savanna group the forests were the environments with the lowest permeability values. Therefore, we decided to generate models separately for these two groups, thus ensuring a greater representation of biodiversity in the UPRB. For this, the entire process detailed in the previous topic was carried out for each group.

2.2.2 | Modeling

Connectivity targets

Two layers of information were needed for the modeling: the connectivity targets, formed by the unprotected target areas and the boundaries of protected areas, and the resistance matrix. To identify target areas and to construct the resistance matrix we adopted the land cover map obtained from MapBiomas (Projeto MapBiomas, 2020), corresponding to 2018, considering the land classes, as forests, planted forests, open woodland savannas, grasslands, cultivated grasslands, agriculture and urban areas. The same land cover map was used to identify the fragments and the natural patches of native vegetation to be considered as targets (separately for forests and savanna land cover types). The boundaries of the protected areas were obtained from the Protect Planet website (www.protectedplanet.net) and the national database of protected areas, available at the Chico Mendes Institute for Biodiversity Conservation (ICMBIO—www.gov.br/icmbio). We considered protected connectivity targets all public and private protected areas, as well as Indigenous Lands. However, we excluded protected areas that were smaller than 500 hectares. Although small areas may have important roles in conservation, they may maintain smaller numbers of species or fail to maintain viable populations (Godefroid & Koedam, 2003; Volenec & Dobson, 2020).

The selection of unprotected target areas was conducted using two criteria: patch size and core area size. The use of core area size was adopted to reduce the uncertainty about the habitat integrity of the small fragments of native vegetation as well as the border effect. Border effects are known to be deleterious to several species due to biotic and abiotic changes that occur in the transition zones (Murcia, 1995; Revilla et al., 2001). Furthermore, we assumed as a threshold values that we considered high core area size to select unprotected target areas. In this way, we hope to avoid the uncertainties generated by the lack of information about species-habitat relationships, the conservation status of native vegetation remnants and the long-term effects of land change.

We assumed a different selection size of core area for the lowlands and surrounding highlands. This approach

TABLE 1 Criteria for selecting unprotected connectivity targets to be connected by ecological corridors in Upper Paraguay River Basin, in the Brazil.

	Highlands		Lowlands	
	Forest	**Savannas**	**Forest**	**Savannas**
Fragments smaller than 100 km^2	250 meter of edge Core area above 10 km^2	250 meter of edge Core area above 10 km^2	No border area Core area above 10 km^2	No border area Core area above 10 km^2
Fragments larger than 100 km^2 hectare	500 meter of edge Core area above 10 km^2	500 meter of edge Core area above 10 km^2	500 meter of edge Core area above 10 km^2	500 meter of edge Core area above 10 km^2

was necessary because the highlands are highly modified due to the removal of native vegetation, while in the lowlands most of the landscape is still conserved (Tomas et al., 2019) and it is characterized by a complex mosaic of different native land cover types. In the highlands, we use filters based on the size of the core area of remnants of the native vegetation. We assume as unprotected target areas all remnants presenting core areas larger than 10 km^2 (Table 1). To calculate the core area we defined 500 meters of edge for patches larger than 100 km^2 and 250 m for patches under 100 km^2. In the lowlands for patches larger than 100 km^2, we assumed the edge of 500 m and calculated the core area (Table 1). For patches smaller than 100, we did not use the core areas to define the targets for connectivity modeling, instead selected all patches larger than 10 km^2 (Table 1). These criteria were used because in the Pantanal the forest and savanna patches are usually narrow and irregular, presenting a linearity often arranged in intricate patterns. Thus, the application of criteria similar to those adopted for the surrounding highlands would lead to the exclusion of almost all patches of native vegetation.

Resistance matrix

To construct the resistance layer, we considered as resistance value the inverse of the permeability values for each land cover type for species. For example, considering a permeability scale that goes from 0 (non-permeable environments) to 1 (maximum permeable environments), forest environments have high permeability (values close to 1) and low resistance (values close to 0) for forest-dependent species. On the other hand, grassland environments have low permeability (values close to 0) and high resistance (values close to 1) for forest-dependent species. We applied the resistance values (calculated from permeability values) of the focal species groups to each of the land cover classes from the MapBiomas database (Projeto MapBiomas, 2020). Since we selected two species groups for modeling (species from savanna environments and forest environments), it was necessary to create two resistance matrices separately for these two groups.

In addition, we defined as barrier areas those areas presenting very low permeability, such as urban areas, mining areas, large rural settlements, and areas with steeper slopes. The layers used as barriers were obtained from different databases. The urban and mining areas were obtained by manual vectorization with the help of Google Earth and the Institute of Geography and Statistics (IBGE—www.ibge.gov.br). The rural settlement areas (settlements) were obtained from state and federal agencies' databases, such as the Brazilian Institute of Geography and Statistics (IBGE—www.ibge.gov.br) and the National Spatial Data Infrastructure Bank (NSDI—www.inde.gov.br). For the steeper slope regions, we used the Topographic Radar Shuttle Mission (SRTM) images, available on the United States Geological Survey (USGS—www.usgs.gov) website. We calculated the slopes using QGIS v.3.10 (QGIS Development Team, 2022), adopting 45° as the limit, so that areas with greater slopes were included as areas of relatively high resistance to species.

Least cost modeling

The LCP method identifies the least resistance paths for the species to move between two patches of habitat. To do this, we initially converted the resistance matrix layer (described in the previous topic) into a transition matrix, using the values of neighboring pixels in eight possible directions. After this conversion, a geographic correction was performed using "geoCorrection." All these steps were performed using R's gdistance package (van Etten, 2017). Next, a nearest neighbor matrix was built using the connectivity target areas layer as a basis (unprotected remnants and natural native vegetation patches, and protected areas). This matrix defines which connectivity targets will be connected during the modeling procedure, based on the distance between them and the user-predetermined number of connections. We

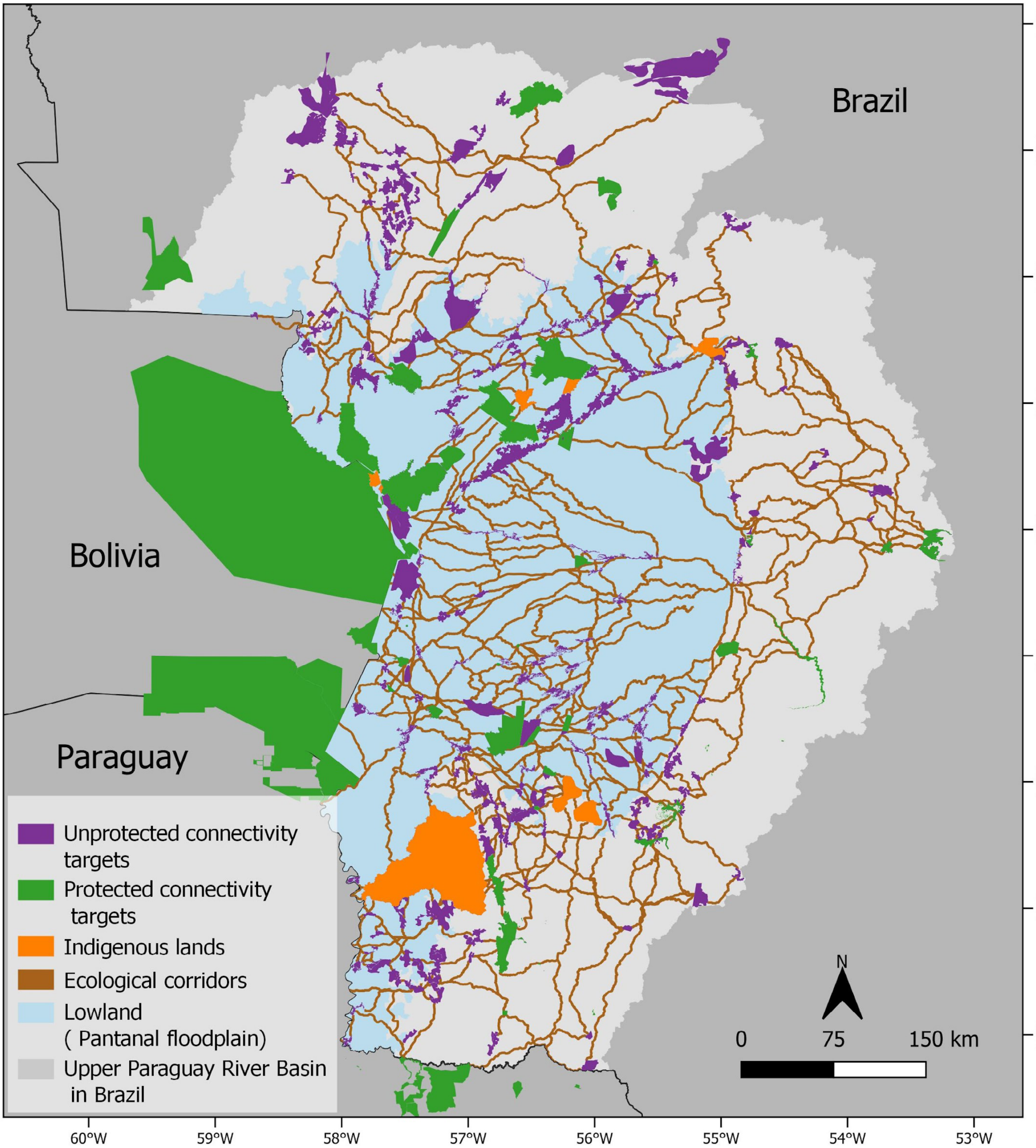

FIGURE 3 Results of the Least Cost Model, showing the connectivity targets of native vegetation and protected areas, and the ecological corridors in the Upper Paraguay River Basin, Brazil.

defined four connections for each target and used the "cost matrix" command from the leastcostpath package (Lewis, 2020) to create the matrix. Finally, we used the "create_lcp_network" command from the leastcostpath package (Lewis, 2020) to calculate the least-cost corridors among the connectivity targets. This entire process was performed independently for savanna and forest species.

Finally, we examined the corridors and connectivity targets to assess the eventual loss due to the removal of the native vegetation after 2018. In cases where the native vegetation were quickly and extensively converted to anthropogenic land use classes such as pasture or agriculture, the affected ecological corridors and the target areas were disregarded in the final map. This type of correction was done manually by comparing the maps used in the modeling, the map of the Ecological Network of corridors obtained in the modeling, the current land use maps and satellite images.

Permeability of the corridors

We used a modeling procedure based on Electric Circuit Theory as a complementary approach to identify corridors or parts of corridors with different resistances to the dispersion of focal species. We applied a 1-km buffer on both sides along the LCPs in which the resistance was modeled using the software Circuitscape v4.0.5 (McRae et al., 2008; McRae et al., 2013; Shah & McRae, 2008), configured to analyze eight neighboring cells. The Circuitscape modeling was performed separately for savanna and forest environments, considering their respective resistance matrix and connectivity targets. Additionally, we identified the points of intersection between ecological corridors with transportation infrastructure (roads and railways). We used the database of the Ministry of Planning Budget and Management available in the National Spatial Data Infrastructure website (INDE—www.inde.gov.br), which was manually corrected for precision using Google Earth.

3 | RESULTS

We identified 313 unprotected native vegetation patches considered as connectivity targets based on our selection criteria, 123 of savanna and 180 of forest (Figure 3). The average size of these targets was 103.8 km^2 for savanna and 43.5 km^2 for forests, and only three targets were larger than 1000 km^2. Protected area targets consisted of 94 protected areas and 25 Indigenous lands. The most numerous category was Private Reserves of the Natural Heritage (RPPN, from the Portuguese Reserva Particular do Patrimônio Natural) with 42 units. RPPN is a category of private protected area present in the Brazilian System of Conservation Units (SNUC, from Sistema Nacional de Unidades de Conservação). It is a sustainable use category similar to IUCN categories I, II or III. However, when the area is considered, the federally protected units present the largest areas, with an average of 1478.6 km^2, while the RPPNs present an average of 109 km^2. The public protected areas of sustainable use presented an average area far above the other categories of protected areas. This fact occurred due to the Bolivian San Matías protected area, included in the study as a connectivity target because it is located on the border between Brazil and Bolivia, and covers over 30,000 km^2.

The LCP identified 859 path corridors in the UPRB, of which 288 were removed due to the loss of native vegetation between 2018 and 2022. Considering the 570 corridors remaining, we obtained 85 ecological corridors for the savanna environment, with an average length of 69.1 km between connectivity targets (Figure 3). Modeling for forest environments resulted in 486 ecological corridors with an average length of 42.6 km between connectivity targets. A set of 217 corridors presented points of intersection with the transportation infrastructure, of which 154 are intersected only by roads, seven by railways and 28 are intersected by railways and roads (Figure 4). In addition, most corridors presented few connections, while a reduced number of corridors presented a large number of connections (Figure 5). The average cumulative current flow presented by the corridors was 4.36, with some corridors presenting a maximum value of 27.8. The savanna environments had an average cumulative current flow value of 6.2, with a maximum of 22.8, while the corridors for forest environments had an average value of 4.02 and a maximum of 27.8 (Figure 6).

4 | DISCUSSION

Connectivity is a major issue in conservation planning and reconciliation among conflicting land use objectives (Bennet et al., 2006; Dettman, 2006; Hilty et al., 2012; Keeley et al., 2018). Corridors are relevant tools in fragmented landscapes because they are able to reduce the effects of habitat fragmentation by reducing isolation and allowing the maintaining of viable populations (Noss & Daly, 2006). In our study, savanna environments had a lower number of corridors compared to forest remnants in the UPRB. In addition, savanna corridors tended to be longer when compared to forest corridors. These results may be associated with the spatial pattern of native vegetation patches. In some regions, savanna environments can be highly fragmented, especially in an agricultural matrix (e.g., Ferraz et al., 2021). Furthermore, as Brazilian legislation protects riparian forests, most of these areas can function as corridors for forest environments. On the other hand, the corridors of savanna environments showed a higher cumulative current flow, that is, a lower resistance to dispersal, when compared to the ecological corridors of forest environments. This lower resistance in corridors probably is due to the higher permeability for savanna species presented by some land use classes, such as cultivated pasture and agriculture (Estado de Mato Grosso do Sul, 2015).

The identification of connectivity targets and ecological corridors may constitute a basis for the development of strategies that seek to ensure large-scale conservation outcomes, including the prioritization targets for

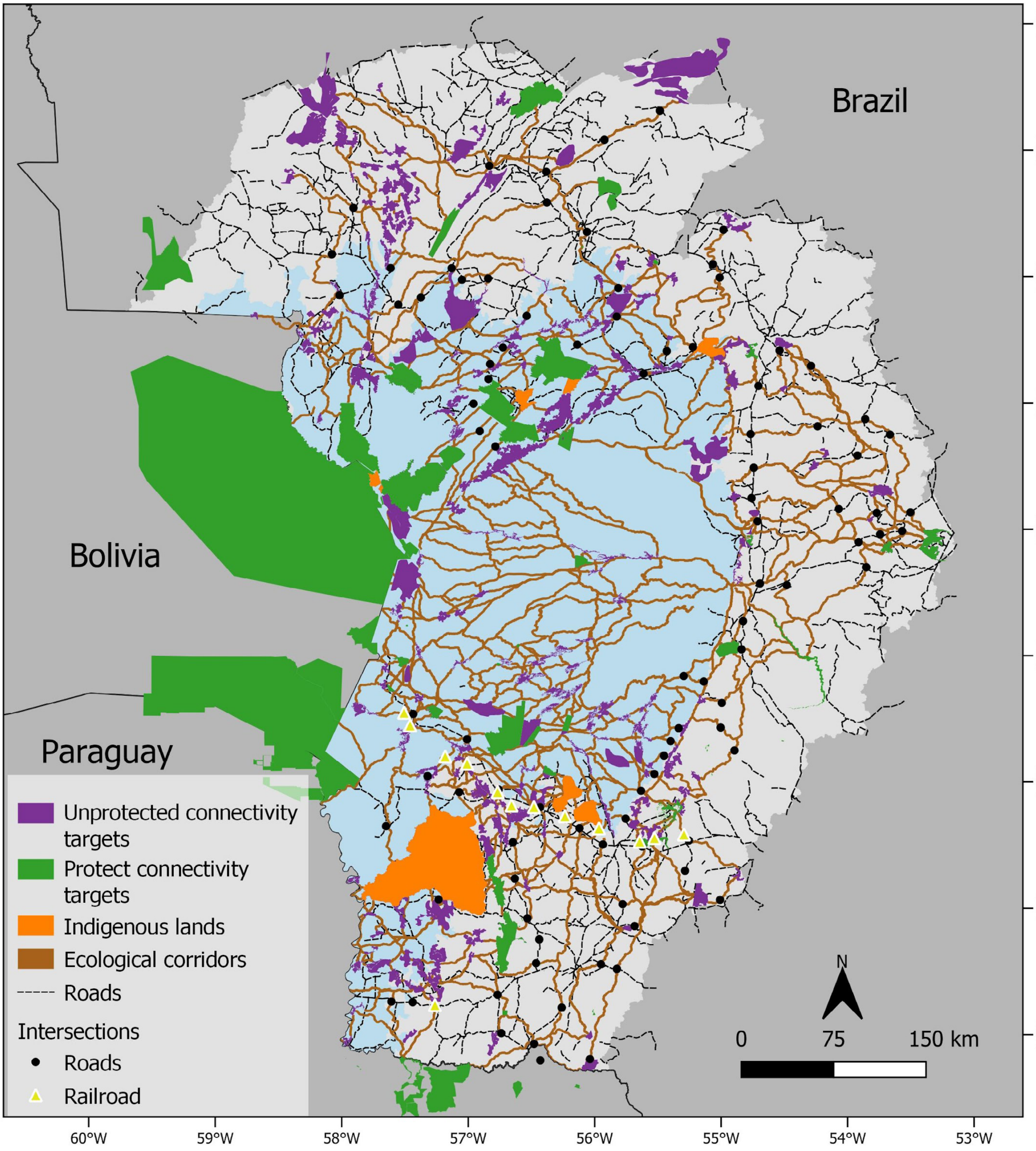

FIGURE 4 Intersection points between the mapped ecological corridors and the main roads and railways in the Upper Paraguay River Basin, Brazil.

restoration. The connectivity targets that do not correspond to the current formally protected areas system may be considered priority areas for biodiversity conservation in the UPRB. As priority areas for conservation, they should be the focus of public policies to encourage protection, not necessarily for the establishment of new public protected areas. Ecological corridors can be implemented through, in the establishment of new protected areas, to implement programs aiming to incentive the landowner engagement in conservation and sustainable land use, as well as to provide inputs as certification criteria for rural properties and/or its products.

Other public policies can also help in the implementation of ecological corridors, as their inclusion in the

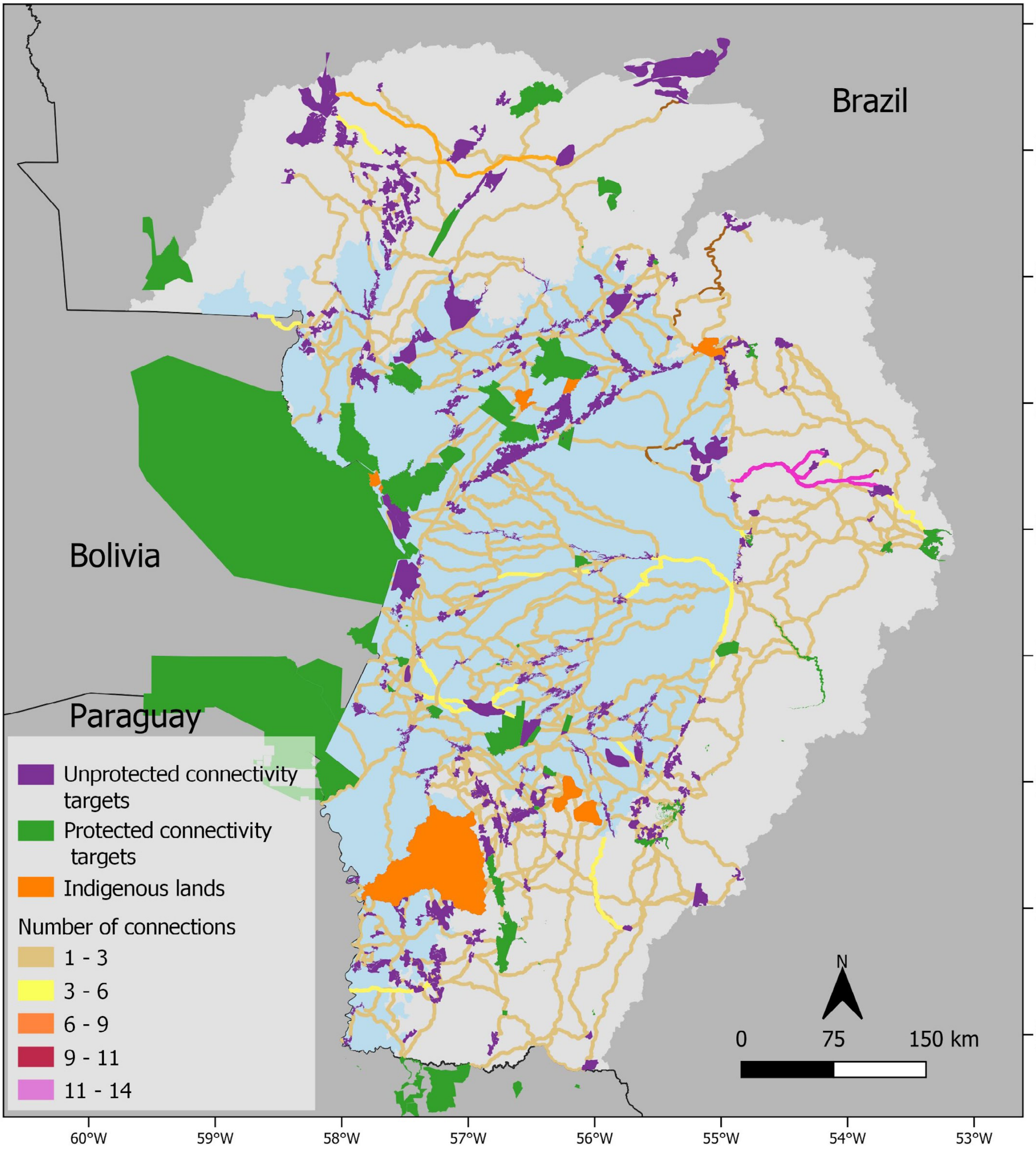

FIGURE 5 Number of connections made by the corridors at the Upper Paraguay River Basin, Brazil.

prioritization of the location of Legal Reserve Areas (LR). The LR is the area ranging from 20% to 35% of private properties where the native vegetation must be conserved. The LR are important conservation areas in the UPRB (Guerra, de Oliveira, et al., 2020a), and if located in the areas of the corridors can improve the connectivity throughout the region. In addition, they can also be adopted as additional information layers for licensing processes, helping the selection of the best options for interventions in the rural landscape. The native vegetation connectivity targets and corridors can be used as parameters to define ecological value in environmental compensation and biodiversity offsetting approaches, either through Environmental Reserve Quotas (CRA) or leasing, as defined by the Brazilian law (May et al., 2015; Silva & Ranieri, 2014). In landscapes already modified by

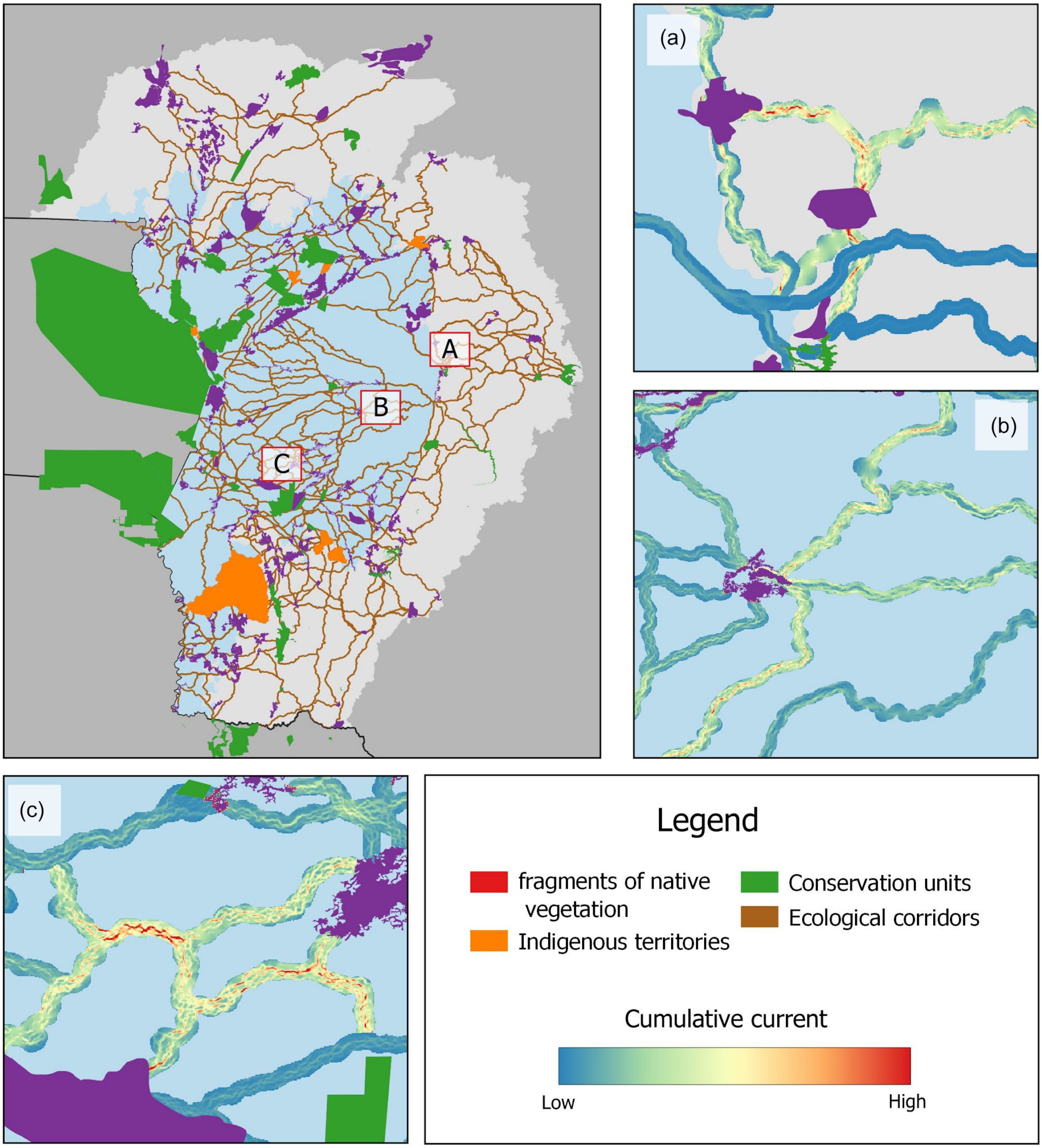

FIGURE 6 Circuitscape result of the ecological corridors at the Upper Paraguay River Basin, Brazil. The box A, B and C—shows in detail the variation in permeability in different corridors, produced as a result of Circuitscape.

anthropogenic activities, the corridors may serve as a basis for prioritizing areas for ecological restoration.

The identification of corridor intersections with the regional transportation infrastructure indicates the potential impact of roadkill over wildlife populations at a larger geographic scale. This is a relevant issue for wildlife conservation in the UPRB as roadkill is known to be affecting a large number of species, including several endangered ones such as lowland tapir (*Tapirus terrestris*), jaguar (*Panthera onca*), maned wolf (*Chrysocyon brachyurus*), bush dog (*Speothos venaticus*), march deer (*Blastocerus dichotomus*), and giant anteater (*Myrmecophaga tridactyla*), among other species (Abra et al., 2020; Ascenção et al., 2017; Ascenção & Desbiez, 2022; Pinto et al., 2021). Rodkill rates for the UPRB can reach 0.05 individuals/km/day (Ascenção et al., 2017; Ascenção &

Desbiez, 2022; Pinto et al., 2021). This high mortality rate can reduce the viability of populations surrounding the roads (Ascenção & Desbiez, 2022; Fischer et al., 2018). The modeling of corridors to identify the points of interest is a strategy capable of supporting the decision-making process, especially in planning the implementation of structures to mitigate and avoid roadkill impacts (e.g., Zeller et al., 2020; Zhang et al., 2021).

The corridor network for conservation developed by our study corresponds to a detailed connectivity planning tied in a landscape scale but reaching a regional scale, which includes protected and unprotected areas as connectivity targets for two Brazilian states. As such, it will require federal and state-level strategies to be implemented in practice at such a large-scale perspective. To address this challenge, effective public policies and the inclusion of corridors and connectivity targets in the decision-making processes should be among other conservation approaches, such as the increase of the protected area network, environmental restoration initiatives, conservation incentive programs, and sustainable land use.

Our results showed that in a short period, only 3 years (2018–2022), approximately one third of the initially mapped ecological corridors were lost due to native vegetation conversion. These values may be higher in the coming years if we consider the increasing deforestation rates and the projections of native vegetation conversion for the UPRB (Guerra, de Oliveira Roque, et al., 2020b; MapBiomas, 2023). These facts highlight the importance of corridor mapping as well as the need for rapid decision making especially in landscapes with high rates of change. Thus, quick and effective decision-making is essential to reduce the effects of loss of native vegetation and connectivity of the UPRB.

The knowledge gap on the different elements of biodiversity in the UPRB can be a limiting issue in modeling. This lack of information may limit the application of more robust methods, as well as the selection of criteria that may not be biologically real. Thus, the implementation of ecological corridors may not be as efficient as expected in reducing the negative effects of habitat fragmentation. However, this fact does not overshadow or diminish the importance of this study. We believe that increasing knowledge, especially on animal movement, home range and habitat preference, can improve the results of connectivity models and thus increase the efficiency of ecological corridors.

5 | CONCLUSION

The corridors identified in this study result in an extensive ecological network of connectors and connectivity targets covering the UPRB in Brazil. The ecological network at a regional scale is a useful basis to support the definition and implementation of public policies in the UPRB, considering the specificities of both lowlands and the surrounding highland regions. As such, the corridor network and the native vegetation remnants and natural patches used as connectivity targets should be part of the decision-making processes related with land use planning in the UPRB, including the implementation of public and private protected areas. In addition, our results highlight the importance of territorial planning and rapid and effective decision-making to mitigate the effects of native vegetation loss for biodiversity conservation in the UPRB.

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Additional supporting information can be found online in the Supporting Information section at the end of this article.

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