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Urban ecological network

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SUMMARY

Protected Areas (PAs) have been implemented to preserve the remnants of native vegetation, playing a fundamental role in biodiversity conservation. For PAs to be potentially efficient, they must connect to other PAs and/or other remnants in the anthropic landscape, with the matrix permeability being an imperative factor in the dispersion of species, seeds, and pollens. The study's objective was to delineate an ecological network of protected areas inserted in an urban landscape. Geoprocessing and Graph Theory techniques were used to assess functional connectivity between PAs. The focus species used were forest birds, which are endemic to the Atlantic Forest. The information about dispersion capabilities came from the consultation of experts and resulted in a resistance surface. The dispersion model simulation in the landscape resulted in the least-cost path (LCP) and designed the urban ecological network. The LPC was characterized considering the buffer equal to 100m width. The resistance values for each land-use/land-cover, representing endemic bird species of the Atlantic Forest, were equal to one for the native forest located within the PAs. The LCPs were designed by 136 connectors, mostly by native forest (61.3%) and anthropic grasslands (21%). The riparian forests are an essential part of the LCP. The promotion of connectivity between PAs in an anthropic landscape needs the effectiveness of ecological restoration and/or conservation actions and matrix permeability analysis. The connection between PAs by ecological networks must be implemented as a conservation strategy in cities concerning the current era of urban expansion.

KEYWORDS: Protected Areas; Urban planning; Graph Theory.

1 INTRODUCTION

Changes in habitat configuration and matrix composition due to fragmentation and expansion of land-use result in decreased connectivity and a decline in biodiversity (FAHRIG, 2003). The primary strategy used to reduce biodiversity loss involves establishing protected areas (PAs) (WULDER *et al.*, 2018; VIEIRA; PRESSEY; LOYOLA, 2019), mainly in tropical forests such as the Brazilian Atlantic Forest (LAURANCE *et al.*, 2012). However, the PA connectivity with the surrounding landscape and other protected areas is crucial for the persistence of native fauna and flora populations, considering the constant conversion of the natural landscape in anthropogenic environments (SANTINI; SAURA; RONDININI, 2016; SAURA *et al.*, 2018). Therefore, maintaining connectivity among the remaining natural areas in anthropic areas has become increasingly essential to improve the negative effects of habitat loss and fragmentation on biodiversity (HOFMAN *et al.*, 2018).

Rapid urban expansion worldwide has caused the loss, fragmentation, and intense degradation of natural ecosystems (TANNIER *et al.*, 2016). Cities grow, expand, and spread due to population growth and the ensuing and inevitable infrastructural developments (ESPINDOLA; CARNEIRO; FAÇANHA, 2017; WOLFF *et al.*, 2017). The negative results of urban expansion on ecosystems, which affect ecological connectivity, ecosystem services, biodiversity, and the quality of life of the population living in cities, have drawn attention in recent decades (MCDONALD; KAREIVA; FORMAN, 2008; VIMAL *et al.*, 2012 DUPRAS *et al.*, 2016; DUPRAS; PARCERISAS; BRENNER, 2016; KONDO *et al.*, 2018). There is growing concern about the impact of urban areas on natural ecosystems in the Atlantic Forest, as the country's largest cities are concentrated in this biome, such as São Paulo and Rio de Janeiro, and where more than 65% of the population lives (SOS MATA ATLÂNTICA, 2019; ISSII *et al.*, 2020).

PAs generally contribute to protecting endangered species and habitats from extinction, carbon storage, and ecosystem services provision, among other functions (MARGULES; PRESSEY, 2000). Urban PAs are also distinguished because they promote health and wellbeing, strengthen cities' resilience to climate change, contribute to green infrastructure in cities, and contribute to the local economy with income from tourism

(TRZYNA, 2014). Still, conservation of the natural areas in the urban environment depends on their protection and connection with the landscape (LOVEJOY; WILSON, 2015).

Studies on the connectivity of the PAs in urban environments have been globally gaining prominence especially in 2020, when the theme "biodiversity" stands out (RUTZ *et al.*, 2020). The global pandemic of COVID brought decades of biodiversity loss to the center of discussions, making the world rethink more sustainable ways that support the triad of developments: social, economic, and environmental (MCELWEE *et al.*, 2020).

Thus, the connections between PAs through ecological corridors and permeability matrix levels have been established as environmental planning strategies in cities (XUN *et al.*, 2014; HUANG *et al.*, 2018; WHEELER *et al.*, 2020; WOOD; GILBERT; LACHER, 2020). Ecological corridors are an effective means of achieving connectivity in the landscape by creating connections between PAs (WOOD; GILBERT; LACHER, 2020). Well-designed and connected PAs protect biodiversity and ecosystems, promote ecological flows and functions, movement of animals, seeds, and pollens, in addition to providing essential ecosystem services to humans (TAYLOR *et al.*, 1993; CDB, 2010; WATSON *et al.*, 2014; DE LA FUENTE *et al.*, 2018).

Methodologies based on species dispersion paths have been used to support the definition and delineation of ecological corridors (SAURA *et al.*, 2017; THOMPSON; GONZALEZ, 2017). These dispersion paths identified as least-cost paths (LCP) result from a species movement model, weighted by resistance values to the landscape (PINTO; KEITT, 2009). The resistance values are attributed to the different land use/land cover (LULC) and consist of the difficulties or facilities imposed by focus-species when they move through the anthropic landscape (LOMOLINO; PERAULT, 2001; PINTO; KEITT, 2009).

Frequently, the basis for functional connectivity models is the Graph Theory, including for LCP theory (URBAN; KEITT, 2001). Graph Theory provides a spatial view of the matrix through its mathematical algorithm and allows the inclusion of biological data in spatial modeling (URBAN; KEITT, 2001; SAURA; TORNÉ, 2009). The visualization of ecological networks in spatial maps is an essential tool in the technical-scientific investigation of landscape connectivity (POCOCK *et al.*, 2016).

The way we plan and build our cities defines our quality of life, the quality of our public spaces, our transport systems, and most importantly, the air we breathe and the water we drink, among other essential services for life (UN-HABITAT AND WORLD HEALTH ORGANIZATION, 2020). Thus, currently, thinking about urban planning is thinking about an agenda that prioritizes the relationship between urban soil, natural resources, and human health, making cities more resilient (KONDO *et al.*, 2018; UN-HABITAT AND WORLD HEALTH ORGANIZATION, 2020), in contrast to the view of the past that the city is an isolated environment, dissociated from the environment and the surrounding landscape.

Studies of UC connectivity in urban landscapes, with prioritization of green spaces, the planning of ecological corridors, the conservation of urban forest fragments, the restoration of areas and remnants, and actions to increase the permeability of the matrix are essential to the perpetuation of species, including human beings (DALLIMER *et al.*, 2012; TAMBOSI *et al.*, 2014; SALVATI *et al.*, 2017; MÜLLER *et al.*, 2018). Life on Earth thrives when ecosystems are healthy and ecologically connected (HILTY *et al.*, 2020).

2 OBJECTIVES

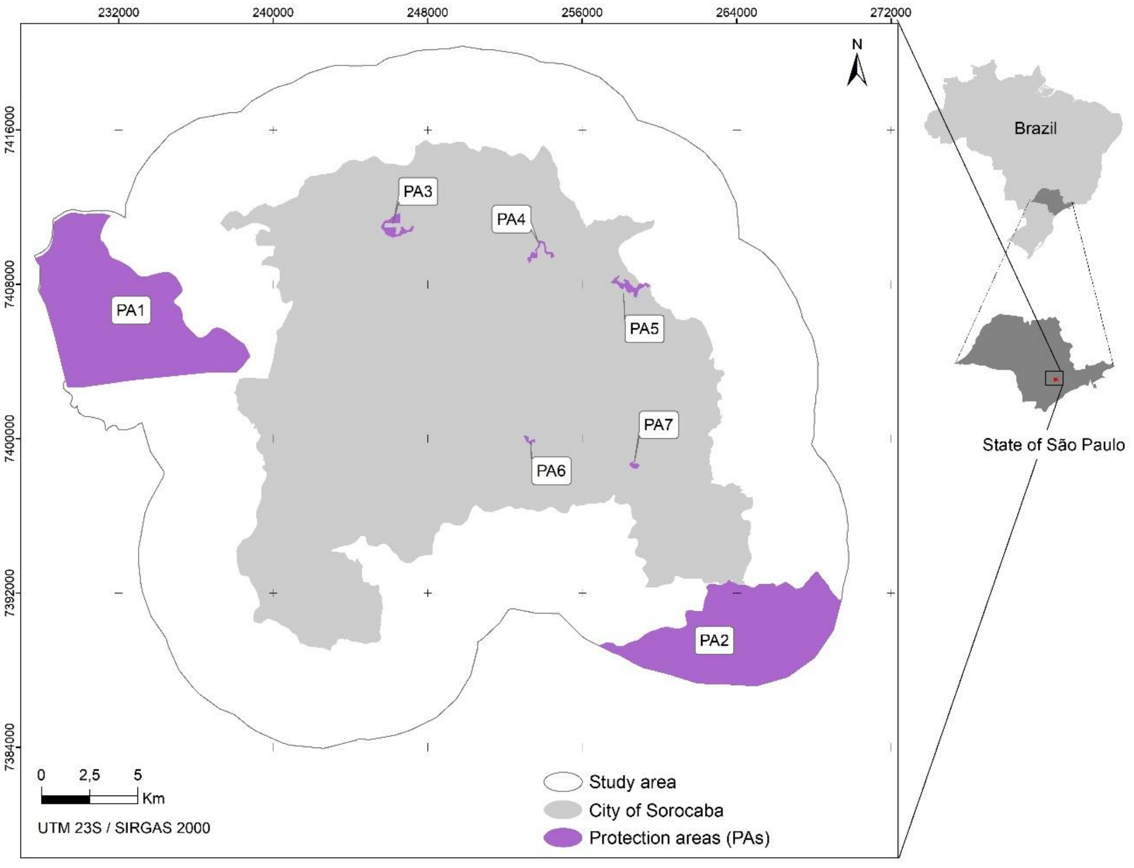
The main objective was to delineate an ecological network of protected areas inserted in an urban landscape. The specific objectives were (1) to assess the matrix permeability in a predominantly urban landscape, (2) to identify the possible connection paths between the protected areas, (3) to evaluate the patterns of land use and coverage of the connection paths between the protected areas, contributing to the establishment of an efficient and representative ecological network in the urban environment.

3 METHODOLOGY

3.1 STUDY AREA

The study area was Sorocaba and its surroundings (5 Km-buffered), located on the Atlantic Forest Biome in Southeast Brazil and comprising 109.560 ha (Figure 1). The remaining forest cover is highly fragmented, with small and isolated forest fragments (MELLO; TOPPA; CARDOSO-LEITE, 2016; RIBEIRO; MELLO; VALENTE, 2020).

Figure 1: Sorocaba and its surroundings in the São Paulo state (SP), Brazil, and its Protected areas.



Source: The authors.

The study area has two PAs protected at federal and state levels, Ipanema National Forest (PA1 - 5.069,73 ha) (INSTITUTO CHICO MENDES DE CONSERVAÇÃO DA BIODIVERSIDADE, 2010) and in the Southeast is the Itupararanga Environmental Preservation

Area (EPA) (PA2 – 93,357 ha) (SÃO PAULO, 2003). The EPA has 93,357 ha, but only 4,170 ha are in the study area. Both PAs are for sustainable use.

The city of Sorocaba has five PAs that are indexed on the Brazilian National Protected Areas Register (https://www.mma.gov.br/areas-protegidas/cadastro-nacional-de-ucs) as strict protection. There are: Municipal Natural Park of Biodiversity Corridor (PA3 - 62.5 ha), Municipal Ecological Station of Pirajibu (PA4 - 45 ha), Governador Mário Covas Ecological Station (PA5 - 50 ha), Bráulio Guedes da Silva Ecological Station (PA6 - 8.9 ha), Brigadeiro Tobias Municipal Natural Park (PA7 - 11.7 ha).

3.2 SPATIAL DATA

The LULC map was provided by Ribeiro, Mello, and Valente (2020). This map was produced by image classification techniques, such as maximum likelihood (MAXVER), and finalized in the System Information Geographic (SIG). For this, CBERS-4 satellite images (10m-spatial resolution; spectral bands: green, red, and near-infrared, year: 2016) supplied free by the INPE, was used. The global accuracy was 93.23%.

The watercourse was supplied from the Environmental Company of the State of São Paulo (Cetesb – http://cetesb.sp.gov.br), from the Department of Water and Electricity (DAEE) project. The main transportation infrastructures (highways and railroad lines) were supplied from the National Department of Transport Infrastructure (DNIT – http://dnit.gov.br). These data were at a 1:50.000 scale and were freely available.

The PAs boundaries were obtained free from the National Register of Conservation Units (https://www.mma.gov.br/areas-protegidas/cadastro-nacional-de-ucs) on a scale of 1: 50,000.

All vector files were later converted to Datum Sirgas 2000, UTM projection and standardized to execute the proposed methodology.

3.3 PERMEABILITY OF THE MATRIX

The movement of species across the landscape only happens if their biological characteristics make it possible to move through different landscape elements, tolerating different types of LULC (RIBEIRO *et al.*, 2017). The perception of the landscape by the focal species, in functional connectivity assessments, are often represented by resistance surface values attributed to the different LULC (METZGER, 2006).

In this study, the matrix's permeability was evaluated based on a resistance surface generated for each land-use to a given focal species' movement. The resistance surface was built from the perspective of endemic forest birds in the Atlantic Forest, a species defined as an umbrella, with greater environmental demands (METZGER, 2006), such as P.leucoptera (Thamnophillidae), Thamnophilus caerulecens (Thamnophilidae) and Basileuterus culicivorus (Parulidae), such as P.leucoptera (Thamnophillidae), Thamnophilus caerulecens (Thamnophilidae) and Basileuterus culicivorus (Parulidae) (AWADE; METZGER, 2008; CORNELIUS *et al.*, 2017).

We consulted eight experts on the focal species (Atlantic Forest birds). They did similar work and knew the study area. They set values assigned to a range between one (1) and 100 for each LULC class, which characterize resistance: the perceived ecological costs by focal specie of traversing an anthropic landscape. The resistance values were computed through average weight and outliers were discarded.

3.4 LEAST-COST PATH AMONG PROTECTED AREAS

The LCP is the model movement result assuming dispersing organisms are more likely to use the least resistance when moving between two points (PINTO; KEITT, 2009). Graph theory provided the LCP modelling between PAs, and we did not limit the distance to a relevant maximum for the focal-species profile (i.e., Atlantic Forest birds). The LCP was established when the most efficient path was found between two forest remnants (PINTO; KEITT, 2009; URBAN *et al.*, 2009; FOLTÊTE; CLAUZEL; VUIDEL, 2012).

The LPCs between PAs were arbitrarily defined as forested areas with 100 m width that linked two fragments for the quantitatively analyzed, 50m on each side about the paths' axes. We used 100 m because Brazilian environmental agencies commonly propose this value as a corridor of sufficient width (BRASIL, 1996).

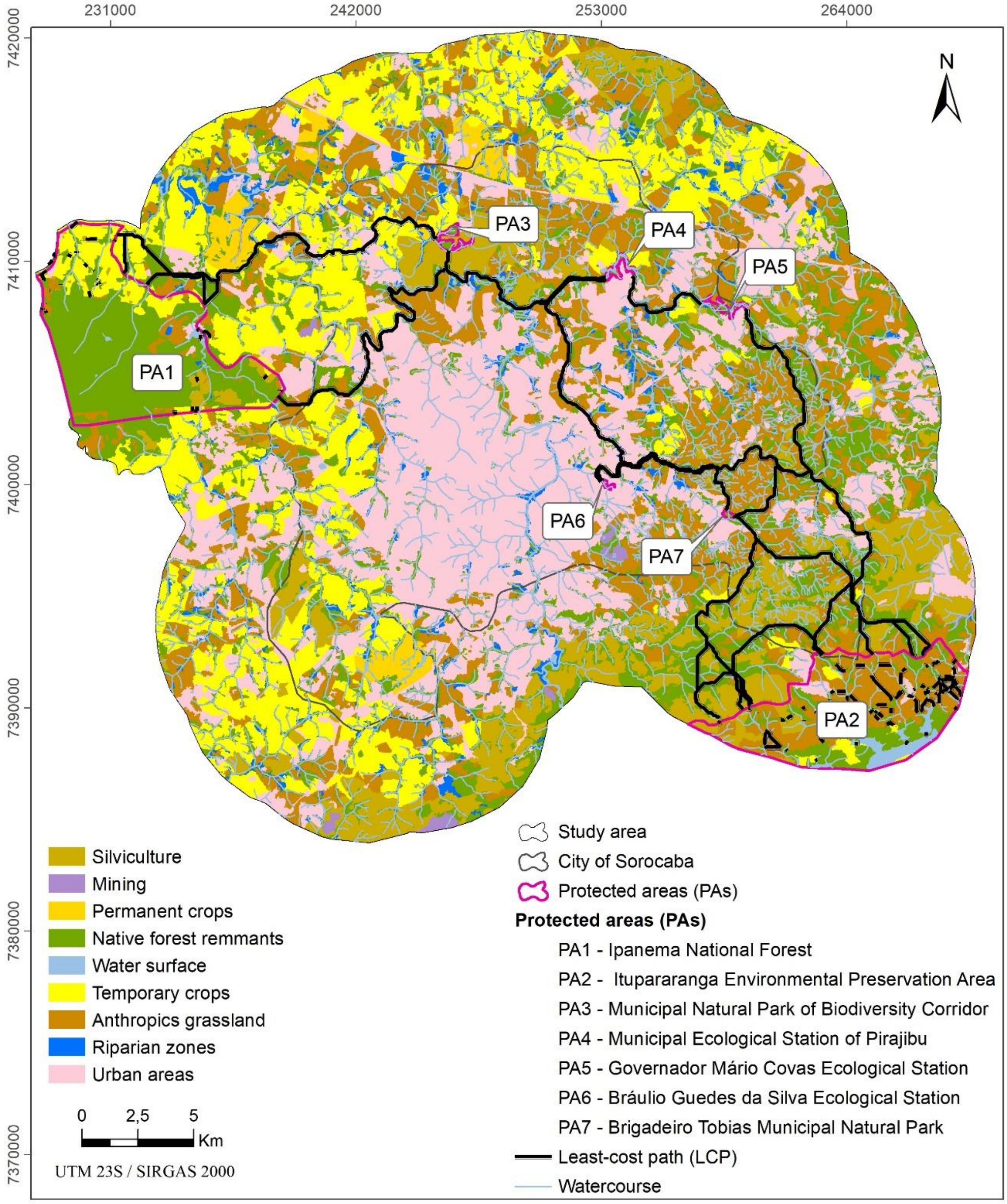
4 RESULTS AND CONCLUSION

The resistance surface values were adjusted for the focal specie (Atlantic Forest birds). The native forest located in PAs were had the minimum resistance value equal to one, and the values have were increased when the movement had to occur outside the considered habitat, up to a value of 100 for urban areas and mining (representing existing barriers for focal species within our study area) (GOULART *et al.*, 2015; RIBEIRO *et al.*, 2017; DE LA FUENTE *et al.*, 2018; HOFMAN *et al.*, 2018). The resistance values for each LULC type to endemic bird species of the Atlantic Forest were (1) the native forest located within PAs, (2) native forest remnants, (65) silviculture, (70) temporary crops, (30) anthropic grassland, (50) permanent crops, (10) riparian zones, (100) urban areas, (100) mining, (70) Water surface, (50) Watercourse, (90) highways and railroad.

In this study, species dispersion scenarios allowed the identification of priority ecological corridors for effective connectivity between PAs. It is understood that the best way to model functional connectivity for a given species in an anthropized landscape is considering the various types of land use in the landscape and the ability of species to transpose these environments. A significant advantage of Graph Theory is the few biological data requirements (ETHERINGTON, 2016) and the mathematical algorithms that minimize the models' subjectivities (HOFMAN *et al.*, 2018).

The ecological network outlined between the PAs of the landscape, which considered the resistance matrix for the species of forest birds previously selected (i.e., endemic birds of the Atlantic Forest), is shown in Figure 1. The result is 136 optimal connections were identified, which are responsible for the interconnection between the fragments present within the PAs with the surrounding landscape, thus outlining our proposal for an urban ecological network for the study area. All PAs were connected because the links between PAs do not weigh the distance limit for the dispersion of species, thus forcing the connection between them.

Figure 1: The least-cost paths interconnecting native forest remnants within protected areas overlapping land-use and land-cover of Sorocaba and its surroundings, State of São Paulo, Brazil, for 2019.



Source: Adapted from Ribeiro, Mello, and Valente (2020).

It is observed that PA1 (FLONA) and PA2 (APA) are the largest PA in the landscape and bring together varied paths on their surrounding taken by the focal species to the protected forest reserves. The Sorocaba city's PAs are essentially urban and cannot have enough areas for species maintenance (areas vary between 9 ha and 62.5 ha). Thus, establishing effective ecological networks between these protected areas is a solution to increase natural flows in the landscape (CROUZEILLES; LORINI; GRELLE, 2011). Ecological networks promote the connection between different forest areas and contribute to animals' displacement, the dispersion of seeds, and increased native vegetation (BRASIL, 2002; GUZMÁN WOLFHARD; RAEDIG, 2019).

Forested areas comprise 61.3% of the LCP and represent 22.9% of the matrix (RIBEIRO; MELLO; VALENTE, 2020). The spatial distribution of connectors was found along with riparian forests occurring in natural forests with less area than ten (10) ha. With an average of ten (10) ha, this class represents 83% of the total number of remnants on the matrix (RIBEIRO; MELLO; VALENTE, 2020). These remnants were the best alternative for the LCPs designed between PAs, although with these characteristics. Small patches do not uphold species for the long term but are suitable for promoting movement between patches as steppingstones facilitating dispersal among otherwise isolated habitat areas (BAUM *et al.*, 2004; BARBOSA *et al.*, 2017; MARTENSEN; SAURA; FORTIN, 2017).

Our results show that riparian forests, legally called Areas of Permanent Preservation (APP), have outstanding importance in upholding PA's connectivity in the urban ecological network serving as ecological corridors for wildlife. The riparian corridor's importance is highlighted by increasing landscape connectivity, mainly in the tropics, and evidenced by experts such as Sekercioglu (2009), Cruz e Piratelli (2011), and Şekercioğlu et al. (2015). The authors promote that the tropical countryside riparian corridors provide critical habitat and connectivity for forest birds in a fragmented landscape.

Restoration actions for riparian networks and floodplains of rivers in Sorocaba city are essential management strategies for the region (RIBEIRO; MELLO; VALENTE, 2020). These actions can improve water quality and enhance the connectivity between municipal PAs and other PAs, increasing the region's biodiversity, as such as riparian zones are natural ecological corridors in the landscape (VALENTE; PETEAN; VETTORAZZI, 2017; MELLO et al., 2018).

On the LCP, the second class of more excellent representation was anthropic grasslands (21.0%), frequent in the study area, presenting 20.4% on the landscape (RIBEIRO; MELLO; VALENTE, 2020). Habitats' broken connectivity promotes forest birds venture out into the open habitats, such as the anthropic grasslands, and are exposed to predation risks and physical stress (BÉLISLE, 2005). Thus, these open areas can be barriers to forest bird movement or alternate routes within fragmented and urbanized areas, such as the study area. Ecological restoration projects can promote native vegetation in these areas and potentialize the connectivity between patches in the landscape (LATAWIEC *et al*., 2015). In addition to native forest remnants (61.3%) and anthropic grassland (21.0%), CLOs used areas with higher resistance values for the route, such as temporary crops (3.9%), riparian zones (3.6%), silviculture (3.4%), urban areas (3.3%) and permanent crops (0.28%) that make up the landscape of the study area.

Urbanization has one of its most significant consequences, the fragmentation of natural habitats and the loss of biodiversity (GRIMM *et al.*, 2008). In this study, the landscape is dominated by urban areas and anthropic grasslands, which surround small forest fragments on the vast majority, belong to private properties (approximately 80%), and the rest are PA (RIBEIRO; MELLO; VALENTE, 2020). Thus, actions to encourage the conservation of native vegetation on private properties are necessary to ensure the maintenance of urban forests (GUZMÁN WOLFHARD; RAEDIG, 2019).

Actions that increase the matrix's permeability are also essential management strategies in highly modified landscapes such as the study area (UMETSU; PAUL METZGER; PARDINI, 2008; METZGER *et al.*, 2009). Since the urbanization process is a strong driver of LULC changes (GRIMM *et al.*, 2008; SALVATI *et al.*, 2018), the transformation of non-urbanized areas, inserted in the urban context, into built environments and waterproofed surfaces (LA ROSA *et al.*, 2014), modify and compromise landscape connectivity and biodiversity maintenance (LA ROSA *et al.*, 2014; SAURA *et al.*, 2018).

Efforts to connect PAs in tropical regions such as the study area are nature-based solutions for promoting biodiversity, ecosystem services, climate mitigation, and cities' resilience and are direct and indirect beneficial public health strategies (LAURANCE *et al.*, 2012; UN-HABITAT AND WORLD HEALTH ORGANIZATION, 2020). Thus, territorial planning is a facilitator for the promotion the health and wellbeing of populations in cities (DWEVEDI; KRISHNA; KUMAR, 2018). The urban ecological network proposed in this study is a solution based on nature that can provide in the short term the increase of natural flows in the urban landscape, the mitigation of air pollution and heat islands and effectively collaborate with improvements in water quality, in addition to providing better outdoor experiences for the urban population (METZGER, 2006; RICHARDS; EDWARDS, 2017; MELLO *et al.*, 2020; WHEELER *et al.*, 2020; XIE; BULKELEY, 2020).

5 CONCLUSION

The ecological network proposed for Sorocaba and the surrounding area was delineated by 136 least-cost paths, providing the connection of all PAs present in the landscape. The forest remnants were the primary class used on the ecological network based on their low resistance to forest bird dispersion. The riparian zones are the connectivity backbone of natural forest and an essential green infrastructure safeguarding the connectivity. Anthropic grasslands, the second class with a significant representative on the landscape, evidenced the potential restoration projects to reorder and potentiate the PA's connection.

In regard of the current era of urban expansion, the connection between protected areas through ecological networks promote the maintenance of biodiversity by ensuring the persistence of the species in the landscape and thus the effectiveness of PAs and providing city dwellers ecosystem services, air pollution mitigation, and heat islands and improvements in water quality, directly and indirectly affecting the health of the urban population.

With the identification of a significant ecological network for PAs connectivity is possible to direct efforts to the development of landscape management actions, such as the conservation and/or restoration of forest remnants, conservation incentives to forest fragments located on private property, the restoration or enrichment of anthropic grasslands, abundantly present in the study area, or even conservation actions and/or restoration of riparian zones and actions to promote increased permeability of the matrix.

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