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How can forest fragments support protected areas connectivity in an urban landscape in Brazil?

Marina Pannunzio Ribeiro [a,*], Kaline de Mello [b], Roberta Averna Valente [c]

[a] The Program in Planning and Use of Renewable Resource, Federal University of São Carlos, Sorocaba Campus, João Leme dos Santos Road (SP-264), km 110, Sorocaba, SP, Brazil
[b] Department of Ecology, Institute of Biosciences, University of São Paulo, R. do Matão, 321, São Paulo, SP, Brazil
[c] Department of Environmental Science, Federal University of São Carlos, Sorocaba Campus, João Leme dos Santos Road (SP-264), km 110, Sorocaba, SP, Brazil

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ABSTRACT

Cities continue to grow worldwide, and the highly modified urban landscape becomes an inhospitable environment for many species because the natural vegetation cover is commonly fragmented, and the remnants are often isolated. Protected Areas (PAs) located surrounding or within urban areas may not achieve their goal of protecting local or regional biodiversity. Thus, an urban ecological network is essential to support their PAs. Thus, this study aimed at assessing the PAs connectivity in an urban landscape in Brazil and understanding whether urban forest fragments can support an urban ecological network. Besides spatial models based on functional connectivity and graph theory, we used participatory techniques to design the resistance surface and the least-cost paths (LCPs) for Atlantic Forest birds. The results showed critical paths (LCPs), important areas for restoration programs for improving PAs connectivity, and essential forest fragments for conservation and restoration. Although the landscape has a forest structure with 1873 forest fragments and 516 links through which the LCPs were structured, most forest fragments and LCPs cannot provide the necessary support for the PAs connectivity. The current ecological network is dependent on forest fragments neighboring (outside PAs) and the flux dispersions occurred mainly in the peri-urban areas. Riparian zones and anthropic grasslands also showed importance for the PAs connectivity. We identified only 28 forest fragments spatially connected, presenting several sizes, and located near large forest areas, relevant PAs, and riparian zones. Six of these forest fragments, smaller than ten hectares and strategically located in the urban matrix, were indicated for restoration actions. The current low connectivity among PAs brings the importance of native vegetation restoration in the riparian zone and anthropic grassland and the importance of the periurban areas to promote biodiversity connectivity in the urban landscape.

1. Introduction

The population is growing, and its continuous demand for space and infrastructure causes pressure on natural areas due to urban sprawl (Tannier et al., 2016; Habitat UN, 2021). Urbanization leads to forest loss and fragmentation, converting natural ecosystems into small fragments with complex shapes and isolated from other forest fragments scattered in an inhospitable matrix for native species (Haddad et al., 2015; Liu et al., 2017). It affects landscape connectivity, i.e., species movement and flow of the natural process landscape (CMS, 2020), causing biodiversity losses (Hernández et al., 2015). As cities continue to grow, the pressures of urbanization cannot lead to neglect for the protection of natural areas within the urban landscape (Trzyna, 2014).

The creation of Protected Areas (PAs) has been used as a global biodiversity conservation strategy to mitigate these losses (Wulder et al., 2018; Vieira et al., 2019) and as the primary strategy to protect these latest forest fragments in urban and peri-urban landscapes (Jenkins and Joppa, 2009; Leberger et al., 2019). If these areas are isolated from other forest fragments in the landscape, however, their ability to meet the conservation goal is hampered (Laurance et al., 2012; Saura et al., 2017; Hilty et al., 2020). This is the situation for many PAs in urban areas worldwide (Saura et al., 2017). Therefore, it is essential to ensure that

Abbreviations: PAs, Protected Areas; LCPs, Least-cost paths; LULC, Land-use and land-cover; OECMs, Other Effective Area-based Conservation Measures; PC, Probability of connectivity.

* Corresponding author.
E-mail addresses: marinapr@estudante.ufscar.br (M.P. Ribeiro), kaline.mello@usp.br (K. de Mello), roavalen@ufscar.br (R.A. Valente).

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these areas are connected to the landscape.

The connectivity between PAs and other forest remnants in anthropic landscapes has become essential to minimize the adverse effects of habitat fragmentation on biodiversity, ensuring the persistence of species on the landscape through the animals, seeds, and pollens dispersion (Saura et al., 2014; de la Fuente et al., 2018). Connecting these PAs with other natural elements in the urban and peri-urban landscapes, such as riparian corridors, small forest fragments, and green spaces, is crucial to the PAs' ecological integrity (Trzyna, 2014).

In the tropical regions such as the Atlantic Forest in Brazil, some PAs located in urban landscapes protect native vegetation fragments that often represent the last forest fragments in metropolitan regions (Laurance et al., 2012; La Rosa and Privitera, 2013). These fragments are recognized as unique ecosystems, with the potential for biodiversity conservation and ecosystem service provision essential to urban populations (Tannier et al., 2012; Zhang and Muñoz Ramírez, 2019). The Atlantic Forest is one of the most biodiverse biomes and one of the most threatened tropical ecosystems in the world (Laurance et al., 2014; Myers et al., 2000), considered a global biodiversity hotspot (Laurance, 2009). It covers approximately 15% of the entire Brazilian territory (SOS Mata Atlântica, 2016), and recent studies indicate that only 28% of its original coverage remains (Rezende et al., 2018). For five centuries, urbanization, industrialization, and agricultural expansion were the drivers of intense changes in land use in this biome (Tabarelli et al., 2005; Joly et al., 2014). Currently, 60% of the Brazilian population lives in this biome's domain (Scarano and Ceotto, 2015), where most of the country's largest cities are located, including São Paulo, Rio de Janeiro, and Salvador. Therefore, it is crucial to discuss forest conservation in urban landscapes in the Atlantic Forest Biome and analyze if the PAs in these landscapes are connected.

Studies worldwide have focused on understanding and improving PAs connectivity as a global strategy for biodiversity conservation (Saura et al., 2017, 2018, 2019). Ecological corridors, stepping-stones, and permeable matrices are used as strategies to improve landscape connectivity (de la Fuente et al., 2018; Huang et al., 2018). Together, these natural landscape elements build an ecological network that will support species permanence and dispersion (Huang et al., 2021). In Brazil, even though most of the Brazilian population (over 85%) lives in the cities (IBGE, 2010), there is a significant gap in research on PAs connectivity in urban landscapes. PAs connectivity studies are mainly conducted in the Atlantic Forest Biome; however, they are focused on the conservation of terrestrial mammal species in forested areas (Crouzeilles et al., 2011; Castilho et al., 2015; Diniz et al., 2017), and studies in agricultural landscapes (Moraes et al., 2017) or at a state level (Saraiva et al., 2018).

It is critical to identify priority urban forest fragments and other natural elements (i.e., semi-natural green spaces) that promote urban ecological network among PAs. The PA connectivity can ensure the landscape's critical ecological functions, promoting conditions to support biodiversity and the provision of ecosystem services in urban areas. This urban ecological network is composed by paths that connect ecological sources (natural and semi-natural), such as UCs, green areas (public or private), riparian zones, parks, squares, gardens, and cemeteries, among others, that integrate the urban environment (Boulton et al., 2018). Thus, building an urban ecological network to ensure biodiversity conservation while improving ecosystem services provision is one of the current significant challenges for decision-makers in urban planning (Xun et al., 2017; IUCN-WCPA, 2019).

Models based on graph theory, which has been widely applied to assess landscape connectivity in forest and agricultural landscapes (Urban et al., 2009; Foltête and Vuidel, 2017; Sahraoui et al., 2017), can also be applied in studies of urban ecological networks (Urban and Keitt, 2001; LaPoint et al., 2015; Tannier et al., 2016; Huang et al., 2021). Graph theory models can transform the anthropic matrix complexity and biological flows into a vector-based approach (Urban and Keitt, 2001; Etherington and Penelope Holland, 2013), allowing functional connectivity modeling. The least-cost path (LCP) model, based on graph theory, is used to identify paths (i.e., ecological corridors) among PAs where the probability of species movements is higher (or less costly) (Pinto and Keitt, 2009; Etherington and Penelope Holland, 2013). Thus, functional connectivity combined with graph theory have been used to identify priority forest fragments conservation (Crouzeilles et al., 2013; Diniz et al., 2017). Together, these methods can support the design of ecological corridors, setting priority forest fragments, fragments that play the function of stepping-stones, and indicate areas of restoration or management practices to improve matrix permeability (Saura et al., 2017; Thompson and Gonzalez, 2017).

Our study brings a unique application of these methods to an urban landscape in the Atlantic Forest, presenting new and important information about urban forest conservation, restoration, and environmental management in the cities to promote an urban ecological network. This information is essential to making cities more resilient to current and future climate change (Elmqvist et al., 2019). In 2021, the State of São Paulo created the Climate Action Plan (Decree n. 65.881/2021) to achieve the goals of the "Race to Zero" and "Race to Resilience" campaigns of the United Nations. For urban regions, the goal of the Race to Resilience campaign is to promote a healthy, safe, and thriving space that supports resilient livelihoods and allows for green recovery.

In this context, this study aimed to assess the PAs' connectivity in an urban landscape in Brazil and understand whether urban forest fragments can support an urban ecological network, generating important information for biodiversity conservation and urban planning. The specific objectives were to identify: (1) the least-cost paths for endemic forest birds among PAs in the urban landscape; (2) the essential urban forest fragments for landscape connectivity; (3) the forest fragments that work as stepping-stones between PAs, and (4) to identify the necessary actions to improve the urban ecological network. For this purpose, we used functional connectivity based on graph theory and least-cost paths (LCPs).

This research supported the design of the Sorocaba ecological corridor, which will soon become a municipal Decree (Municipal Process No. 2020/013463–3). With this study, we can create ecological corridors and set priority areas for conservation and restoration in the urban matrix to support the decision-making in Sorocaba. As the method can be applied to other urban areas, this study is also important to other cities in the Atlantic Forest biome and tropical urban landscapes worldwide.

2. Material and methods

2.1. Study area

The study area is the Sorocaba city and its surroundings (a five km-buffer), representing a typical urban landscape in the Atlantic Forest context, wherein the major challenge is the maintenance of functional connectivity among its PAs (Fig. 1). The five km-buffer was used to include the riparian vegetation along the rivers in the municipality boundary and critical forest fragments, such as the Ipanema National Forest, located in the town of Iperó, and the Itupararanga Environmental Preservation area in the south (Fig. 1). The Ipanema National Forest is the largest forest fragment of Seasonally Dry Tropical Forest in the region, with species of Atlantic Forest and Cerrado (ICMBio - http://www.icmbio.gov.br). The Itupararanga Environmental Preservation Area was created to protect the important dam in the region that supplies seven cities, including Sorocaba (Smith and Petrere Jr, 2000). Thus, we used the buffer to consider the total forest fragments in our analysis, including these essential regional protected areas, which are larger and older than municipal Sorocaba PAs (Supplementary Material - Table S1).

The remaining forest cover is highly fragmented, with small forest fragments, characterized by transitional vegetation between Atlantic Forest and Cerrado, with a predominance of Seasonally Dry Tropical Forest (Mello et al., 2016).

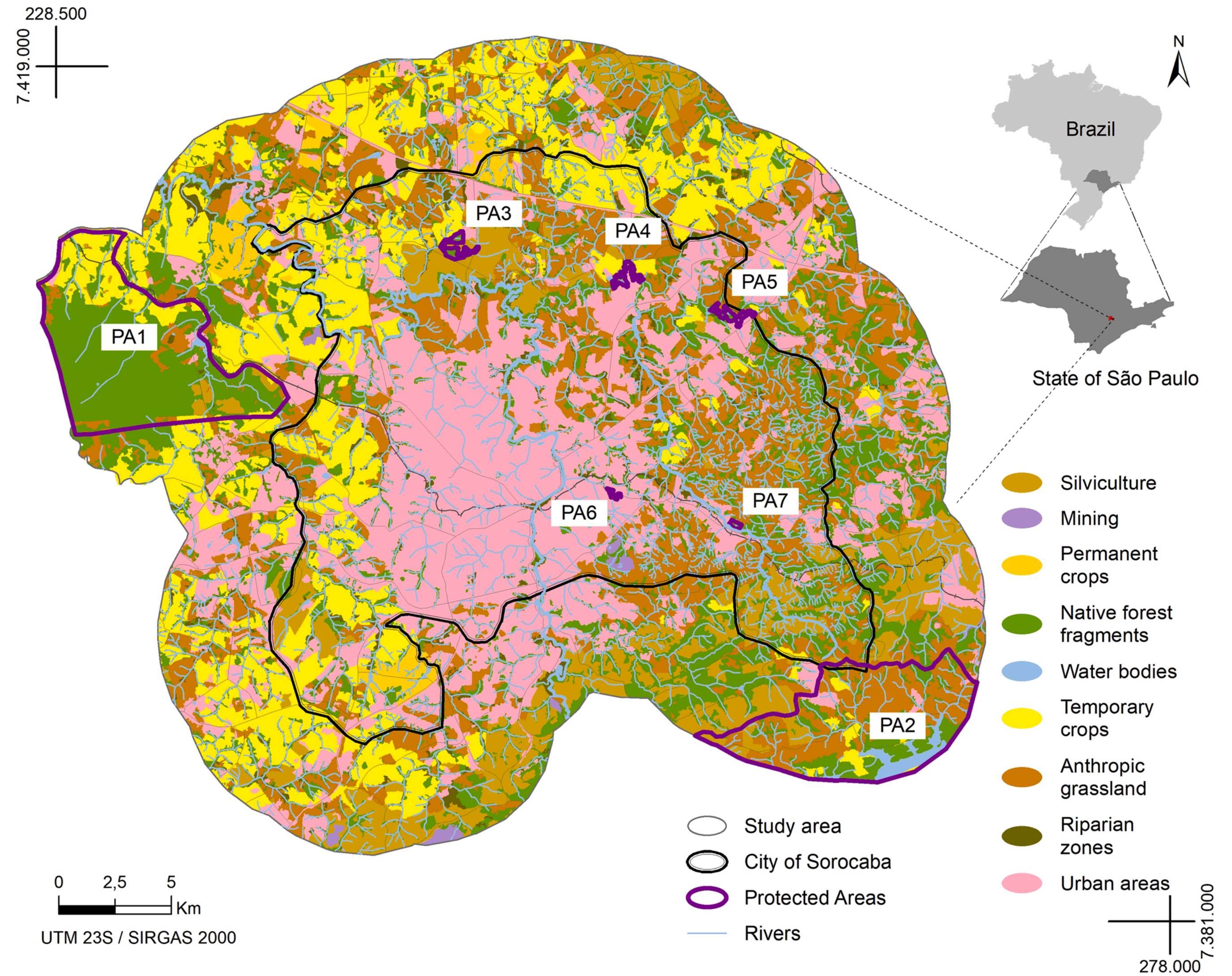

Fig. 1. Sorocaba and its surroundings, in the São Paulo state (SP), Brazil: location and its Protected Areas (PA1–7) and the land-use/land-cover. Source: Adapted from Ribeiro et al. (2020).

Some forest fragments belong to these two largest PAs (administered by the federal and state governments, respectively) and are classified as sustainable use (IUCN categories V to VI). The West contains the Ipanema National Forest (PA1 – Fig. 1) with 5400 ha, and the Southeast the Itupararanga Environmental Preservation Area (PA2 – Fig. 1). PA3 to PA7 (Fig. 1) are smaller and administered by the municipal government in Sorocaba and registered in the Brazilian National Protected Areas Register as strict protection (corresponding to the IUCN categories I to IV) (https://www.gov.br/mma/pt-br). The size of these areas varies from 9 ha to 63 ha (Supplementary Material - Table S1).

2.2. Spatial data

We used a land-use and land-cover (LULC) map produced during the same research project (Ribeiro et al., 2020), having 93.23% global accuracy and 88.46% for the native forest class. It was generated based on supervised digital classification of CBERS-4 satellite images (10 m-spatial resolution; spectral bands: green, red, and near-infrared, year: 2016), freely accessed in the National Institute for Space Research (INPE - https://www.gov.br/inpe/pt-br).

The study area (Fig. 1) presents native forest fragments (22,9%), silviculture (9%), temporary crops (17%), anthropic grasslands (20,4%), permanent crops (1,4%), riparian zones (2,9%), urban areas (24,9%), mining (0,3%), and water bodies/rivers (1,2%). Native forest fragments represent areas covered by forest types of Atlantic Forest and Cerrado, and urban areas include residential, commercial, and industrial areas. The anthropic grasslands comprise exotic or modified natural grasslands without or low grazing activity or abandoned pastures in the initial succession stages of natural vegetation.

The forest fragments of the study area (25,066.50 ha) have an average size of 13.52 ha (standard deviation = 132.27 ha) (Ribeiro et al., 2020). Most of them (about 83%) have less than 10 ha, and only three have an area greater than 500 ha. The landscape's largest and most significant forest remnant is located inside the Ipanema National Forest (PA1-NF), with 4600 ha.

We obtained PAs boundaries from the Brazilian National Protected Areas Register (https://www.mma.gov.br/areas-protegidas/cadastro-nacional-de-ucs). The river network was obtained from the Environmental Company of the State of São Paulo (Cetesb — http://cetesb.sp.gov.br). We used a transportation network (highways and railway lines) from the National Department of Transport Infrastructure (DNIT – http://dnit.gov.br). All data are at a 1:50.000-scale.

2.3. Resistance surface

The resistance surface represents the degree to which some landscape feature (or LULC type) hinders or facilitates some movement process as the focal species movement (Wade et al., 2015). The focal species selected for this study were Atlantic Forest birds such as *P.leucoptera* (Thamnophillidae) (Papa-taoca-do-sul), *Thamnophilus caerulecens* (Thamnophilidae) (Choca-da-mata), and *Basileuterus culicivorus* (Parulidae) (Pula-pula) (Awade and Metzger, 2008; Cornelius et al., 2017). Forest birds are considered umbrella species, defined as species with greater environmental demands compared to other species; thus, providing ideal habitats for them will benefit other species (Metzger, 2006; Goulart et al., 2015).

The resistance matrix requires information about the relationship between species and the LULC as the movement capacity considering the different LULC types in the anthropic matrix, habitat preferences, and dispersion-distance information (Ribeiro et al., 2017). Following authors such as Gurrutxaga et al. (2010) and Etherington (2013), we based on the knowledge of experts to obtain this information. Thus, we invited 20 experts on Atlantic Forest birds' dispersion who also knew the study area to fill out an electronic form related to this information. They received information about our study area, such as a LULC map and the focal species used in this study. A group of eight experts accepted the invitation. We invited them to assign values, from one (1) to 100, for each LULC type, identifying the most and the least permeable areas, i.e., the LULC types that impede or facilitate the focal species movement within the study area.

The final LULC weights that integrated the resistance matrix represented the mean values from experts' answers. These resistance surface weights for Atlantic Forest birds were used in the next stage to build the least-cost paths (LCPs).

2.4. Least-cost path modeling

We identified the LCPs for endemic forest birds among PAs in the urban landscape based on Graph Theory, which is the common method for most functional connectivity models (Beier and Noss, 1998; Hilty et al., 2020). For this, we used the open software Graphab (https://sourcesup.renater.fr/www/graphab/en/home.html), which requires the following inputs: (i) identification of the ideal habitats for focal species, (ii) resistance surface values for the LULC, and (iii) gap crossing ability for forest species (i.e., Atlantic Forest birds).

The experts indicated the ideal habitats for forest species when defining the resistance surface values. Relating to species' ability to gap crossing, we fixed the value of 100 m, considering empirical research with Atlantic Forest birds that indicated values varying from 50 to 150 m (Awade and Metzger, 2008; Cornelius et al., 2017; Hatfield et al., 2018).

To assess LULC in the LCPs, we produced a 100 m-buffer along the path's axes, based on the Brazilian resolution about ecological corridors (CONAMA Resolution N°. 09, October 24, 1996). According to this resolution, a corridor's width should be ten percent of its total length, and its minimum width must be 100 m (Brasil, 1996).

2.5. Landscape connectivity modeling

Graph Theory considers the ideal habitat for focal species as nodes, and the LCP as links, to create a spatial vector representing a landscape and its biological fluxes (Saura and Pascual-Hortal, 2007). This way, the nodes and the links (i.e., the LCPs) were interpreted by the probability of connectivity (PC) index (Saura and Pascual-Hortal, 2007) through Graphab software.

The PC index is a global metric given by the following Eq. (1):

$$PC = \frac{\sum_{i=1}^{n} \cdot \sum_{J=1}^{n} \cdot a_i \cdot a_j \cdot p_{ij}^{*}}{A_L^2} \quad (1)$$

where p_{ij}^{*} is the maximum probability of movement between the parcels i and j (i.e., corresponding to the minimum cost); a_i a_j are the areas of the parcels i and j; A_L is the total area of the study zone, and n is the number of parcels.

The probability p_{ij}^{*} is obtained by transforming the distance d_{ij}, between parcels i and j by an exponential function such that:

$$p_{ij}^{*} = e^{-\alpha d_{ij}}$$

Where d_{ij} is the least-cost distance between i and j, and α expresses the intensity of decreasing probability of dispersion p resulting from the exponential function. The value α was determined by $p_{ij}^{*}= 0.5$ when d corresponds to the median dispersal distance (for birds) (Sahraoui et al., 2017; Saura and Pascual-Hortal, 2007). Thus, the PC metric was set up at a distance (d) of 100 m, covering 50% of the dispersal events of the focal study species (i.e., Atlantic Forest birds).

The values derived from this metric can be partitioned into three fractions: dPCintra, dPCflux, and dPCconnector, which quantify the different ways nodes and links can promote habitat connectivity (Saura and Rubio, 2010).

This study quantified the local contribution of each node and link to the landscape connectivity through the nodes' removal methodology (Saura and Rubio, 2010) using the dPCflux and dPCconnector fractions. The first fraction considers the area of the removed element and its location on the matrix, and the second considers only its location (Saura and Rubio, 2010). The dPCflux fraction was chosen to measure how well a forest fragment is connected to other forest fragments in the study area (Saura and Rubio, 2010). The dPCconnector fraction supports measuring the forest fragments' importance to the landscape connectivity only based on their location. Thus, this fraction was used in this study because, if evaluated separately, it can highlight essential forest fragments for landscape connectivity in this study area (Gurrutxaga et al., 2010).

The fractions were calculated from 0 to 1 (Saura and Rubio, 2010), and the results were multiplied by 100 to interpret the percentage. The Natural Breaks algorithm was used to classify dPCflux and dPCconnector into very-high, high, medium, low, and very low levels on the Geographic Information System (GIS). Comparing the maps resulting from the fractions dPCflux and dPCconnector, we could classify the forest fragments (nodes) based on their relative importance for functional connectivity. The forest fragments with low connectivity levels or higher values of these fractions and with active links (i.e., essential urban forest fragments for landscape connectivity) were considered effective urban ecological networks connecting PAs. To check the forest fragments that work as stepping-stones between PAs we analyzed the nodes that presented high values only by the dPCconnector fraction.

The paths, supported by active links, indicate a high frequency of species dispersion and consequently the critical paths to PAs connectivity. Oppositely, paths with low frequency or without links show the demand for improved connectivity (Hofman et al., 2018). The potential active links were clustered into five frequency levels using the Natural Breaks algorithm (very-high, high, medium, low, and very-low).

3. Results

3.1. The resistance surface and the least-cost paths for Atlantic Forest birds in an urban matrix

The resistance surface of the Sorocaba city and its surroundings showed a minimum resistance value (equal to one) for the ideal forest bird habitat, i.e., the native forest within PAs. Conversely, when the birds' movements occurred outside the ideal habitat, we observed an increase in the values (Supplementary Material, Table S2).

The maximum value observed for the resistance surface was 100 for urbanized and mining areas, representing barriers to species movement. Temporary and permanent crops (agricultural areas) presented values ranging from 50 to 70, respectively. Anthropic grasslands value 30, and finally, riparian zones 10 (Supplementary Material, Table S2).

The LCPs for endemic forest birds indicated that our study area has a forest structure in the landscape with 516 links among 1873 forest fragments (Supplementary Material, Fig S1). These paths have a mean distance of 53.8 m (standard deviation was 24.36 m), and the native forest fragments class as the principal land use (38.56%). They are predominantly located in the peri-urban area, especially in the southwest, north, northeast, and east (Supplementary Material, Fig S1). Riparian zones (27.61%) and anthropic grasslands (18.29%) also showed a relevant area in the LCPs. Other LULC types showed lower values: temporary crops (5.97%), urban areas (5.18%), water bodies (2.34%), silviculture (1.69%), and permanent crops and mining (0.35%).

3.2. *Essential forest fragments for urban connectivity*

The dPCflux fraction indicated that most forest fragments in the landscape (98.88%) have very-low connectivity among them (dPCflux < 0.06%) (Fig. 2A). They have an average size of 7.42 ha (standard deviation = 19.23 ha) and represent most of the forest cover in this landscape (more than 55% of the total). These dPCflux values indicated that most forest fragments could not provide the necessary support for PA connectivity.

We found only 21 important urban forest fragments for PAs' connectivity considering only the dPCflux (dPCflux > 0.07%), representing 43.86% of the native forest fragments area (Fig. 2A). Two of them belong to the Ipanema National Forest, presenting the highest connectivity values (dPCflux varying from 8.23% to 9.13%). In the southeast, near PA7, two forest fragments (outside PAs) showed high connectivity values (dPCflux ranging from 2.12% to 2.81%) (Fig. 2A). The results also showed important forest fragments to landscape connectivity along the main rivers in the study area (Fig. 2A and B).

The dPCconnector fraction identified 17 forest fragments (range between 0% and 0.57%) that work as stepping-stones between PAs

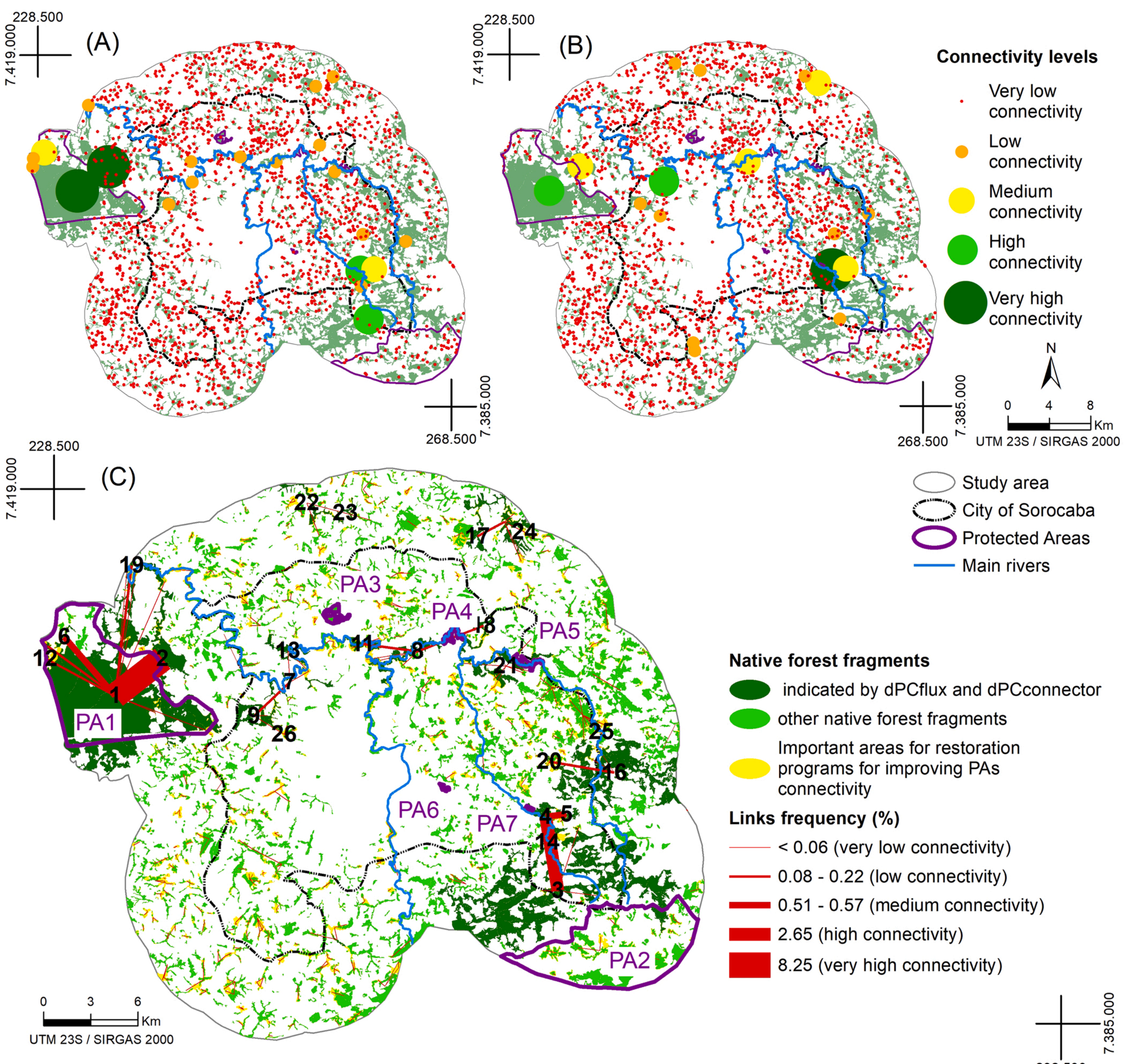

Fig. 2. Essential forest fragments for Sorocaba and its surroundings in São Paulo state (SP), Brazil: with highlighted nodes from (A) dPCflux; (B) dPCconnector; and (C) with 28 forest fragments indicated by both fractions.

(Fig. 2B). One of them showed the best location in the landscape, with a very-high dPCconnector value (0.57%). These 17 forest fragments cover 9171 ha of the native area (35.59% of the total). Most forest fragments in the landscape (98.56%) presented very-low connectivity (dPCconnector < 0.003%) though.

Comparing the 21 forest fragments indicated by the dPCflux fraction with the 17 identified by the dPCconnector fraction, we obtained 28 essential urban forest fragments that can support an ecological network among PAs (Fig. 2C, Supplementary Material, Table S3). These forest fragments have the best connectivity potential with the highest values for the fractions dPCflux or dPCconnector. Of these 28 forest fragments, ten (10) were indicated by both fractions (dPCflux and dPCconnector), representing 81.06% of the total essential forest fragments, seven (7) exclusively by the dPCconnector fraction (1.29%), and eleven (11) exclusively by the dPCflux fraction (17.65%). They vary in size, ranging from 0.83 ha to 4600 ha, representing 44.43% of the forest fragments in the landscape or 11,136.61 ha.

Forest fragments near PA1 and PA7 are the most significant fragments that support landscape connectivity, presenting the highest dPCflux or dPCconnector. The group formed by forest fragments #1, #2, #6, #10, #12, and #19 (near PA1), represent 20.04% of the forest area (Fig. 2C). Moreover, they are connected by many links with high frequency, indicating much dispersion by species and consequently critical urban forest fragments for landscape connectivity. The group formed by forest fragments #3, #4, #5, #14 #16, #20, and #25 (near PA7) has a good dispersion of species, with high-connectivity links.

Furthermore, the links are concentrated in the west (near PA1) and southeast (near PA7) of Sorocaba, indicating these PAs (PA1 and PA7) related to other essential forest fragments in this urban landscape in the Atlantic Forest.

Our results revealed critical dispersion paths among forest fragments following the study area's main rivers (Fig. 2C), such as forest fragments #8, #11, #18, and #21. These forest fragments are in strategic positions and can promote the link between PA4 and PA5.

The results showed that PA1, PA7, PA4, and PA5 have connections to other forest fragments. PA3 and PA6, on the other hand, were isolated in the landscape. PA3 lies between other essential fragments, such as #13 and #11 (Supplementary Material, Table S3), but with no links and, consequently, with no potential for species dispersal. The PA6 is in a highly-density urbanized area (Fig. 1), hampering species dispersal. Thus, we identified significant gaps in connectivity between PAs, such as the isolated areas between PA3 and PA6; PA5 and PA7; and PA7 and PA2 (Fig. 2C). However, we identified that PA7, PA4, and PA5 - even small compared to PA1 - are surrounded by riparian areas. Because of that, their strategic localization near main rivers favored their connectivity with other forest fragments. Furthermore, the PA7 is near an essential forest fragment in the southeast region, which improves its connectivity.

4. Discussion

Graph theory and functional connectivity models supported the analysis of PAs connectivity for Sorocaba and its surroundings. We identified essential paths for bird dispersal in the urban matrix, such as forest fragments, riparian zones, and anthropic grasslands composing an urban ecological network. Furthermore, we found significant connectivity gaps among PAs in this urban landscape. Our study in Sorocaba brings a new view of urban forests that can compose an urban ecological network. The ecological network included the paths and essential forest fragments for biodiversity conservation and restoration actions through the concept of functional landscape connectivity and graph theory. These critical actions could improve the sustainability and resilience of cities through the many benefits to the people who live in these urban areas with the urban ecological network improvement. Benefits begin with improving ecosystem regulatory services, such as air and water quality, milder temperatures, protecting soil from erosion, and improving human health, to environmental justice for communities living in areas of spatial segregation, among others (Stanturf et al., 2014; Zhang and Muñoz Ramírez, 2019; Habitat UN, 2021).

4.1. The resistance surface and the least-cost paths for Atlantic Forest birds in an urban matrix

The paths that connect forest fragments, i.e., LCPs, showed that flux dispersions occurred mainly in the peri-urban areas (Supplementary Material, Fig S1). The LCPs used mainly forest fragments, riparian zones, and anthropic grasslands. Other LULC types tended to be avoided, such as agriculture areas, urban areas, water bodies, silviculture, and others, as reported by de la Fuente et al. (2018). Thus, these paths have created a spatially explicit model showing some potential urban ecological corridors. Creating LCPs is one of the most important methods for modeling potential connectivity paths for different species in landscape planning studies (LaRue and Nielsen, 2008).

The LCPs showed short distances between forest fragments, with a mean distance less than the predetermined Atlantic Forest birds' dispersion-distance (100 m). Thus, despite the high level of forest fragmentation, Sorocaba and its surroundings presented high values of forest fragments proximity, which may allow the forest birds' dispersion, as mentioned by Hatfield et al. (2018). Therefore, land-use change monitoring in the study area is needed to avoid deforestation, which can increase the distance between the fragments. Martensen et al. (2008) emphasize that close spacing between forest fragments is critical for maintaining biodiversity in anthropic environments.

Riparian zone was the second predominant land cover type in the LCP, following the native vegetation fragments. Besides providing soil erosion protection and flood protection along watercourses, the riparian zones allow animal habitat, and facilitate the movement of organisms among forest fragments (Hilty et al., 2020). In this urban matrix, connectivity improvement largely depends on restoring riparian zones and measures that mitigate the urban expansion intensification in these areas. In the opposite direction to our results, the Brazilian National Congress recently approved an amendment to the New Forest Act (Brasil, 2012) that can end the protection of riparian zones in urban areas (Brasil, 2021). The protection of these areas is now the responsibility of the municipal government, which at the same time represents a weakening of the federal law, and an increase in the role of local governments in the management of urban riparian zones. Thus, riparian zones in the urban landscape could be recognized as an Other Effective Area-based Conservation Measures (OECMs) to promote biodiversity conservation (IUCN-WCPA, 2019). Another LULC important for connectivity was the anthropic grasslands. These areas, such as parks or institutional areas, can also offer areas to contribute to the ecological network. Anthropic grasslands in private lands that showed the importance for the ecological network can be the focus of incentive policies to restore native vegetation in the urban and peri-urban areas (Lemgruber et al., 2021).

4.2. Essential forest fragments for urban connectivity

Although the results showed 516 paths among forest fragments and a short distance (53.8 m) among them, few forest fragments are functionally connected across the landscape (Fig. 2), i.e., most of them cannot provide the necessary support for PAs connectivity. It means that there is a significant gap in landscape connectivity in the urban landscape, consequently harming urban biodiversity conservation. This is a significant issue for biodiversity conservation in the Atlantic Forest, with many small and isolated forest fragments and a few large and well-connected forest fragments (Diniz et al., 2017; Hatfield et al., 2018).

Considering the low connectivity of the urban landscape of Sorocaba and its surroundings, a few forest remnants were considered as spatially connected. They were located near large forest areas, large PAs, and riparian zones (Fig. 2C). A high level of connectivity is observed in the western region (Fig. 2C), led by the Ipanema National Forest, the largest protected forest area in the landscape (4600 ha). Other critical connectivity area in the landscape is the PA7 surroundings (Fig. 2C). However, different from the western region, these large forest fragments are not protected and can suffer LULC changes. Several researchers highlighted the importance of large forest fragments to the Atlantic Forest Biome. According to Ribeiro et al. (2009), these areas "should definitely be a conservation priority." Uezu et al. (2005) demonstrated in an empirical study the importance of large and contiguous forest areas in maintaining bird communities, especially in the fragmented Atlantic Forest Biome. Similarly, a recent report by IUCN-WCPA (2018) recommends that the forest fragments that contribute to conservation due to their role in connecting PAs and have particular importance to biodiversity conservation must be a conservation plan priority. Thus, these essential forest fragments in the study area should be considered in local and regional planning in Sorocaba and its surroundings, such as the municipal Master Plan, watershed plan, and local Atlantic Forest plan, among others.

Even if the large forest fragments are essential for biodiversity, small fragments cannot be neglected (Fahrig, 2019). This study highlighted six essential small forest fragments in PAs surroundings smaller than ten (10) hectares, strategically located in the urban matrix (Fig. 2C, Supplementary Material, Table S3). The small forest fragments should be considered together with the large patches in strategies designed to increase dispersal among fragmented species populations (Baum et al., 2004). Such elements are connectivity enhancers (Saura and Rubio, 2010), working as stepping-stones and helping to compose the landscape's ecological network. Nonetheless, we propose restoration actions for these essential small-sized forest fragments to the ecological corridor. Management actions focused on priority forest fragments enhance the success of forest restoration actions, increasing the potential for dispersal of species and improving essential ecosystem services (Rodrigues et al., 2009; Stanturf et al., 2014; De Matos et al., 2019). These forest fragments restoration could provide a unique opportunity to improve areas for biodiversity and, consequently, take advantage of the potential of these areas to promote a healthy and resilient city (Grimm et al., 2008; Elmqvist et al., 2019).

Environmental planning in cities must go beyond biodiversity protection, considering the social role of urban forests. Thus, riparian restoration of the strategic ecological paths should also consider improving urban water systems (WRI Brasil, 2021). In our study, we observed essential forest fragments for the urban ecological network in riparian zones (Fig. 2C). In addition, this assessment showed that these sites are important for forest birds' dispersal. Empirical research demonstrated that riparian zones are natural corridors and play a fundamental role in dispersing forest birds (Sekercioglu, 2009; Cruz and Piratelli, 2011; Şekercioğlu et al., 2015). Thus, restoring these areas is essential, especially in the urban matrix, where forest fragments are commonly limited to these areas, and their conservation also supports water quality protection (Tromboni and Dodds, 2017; Mello et al., 2020). In this sense, we suggest riparian restoration actions, mainly the forest fragments essential to connectivity nearby main rivers, such as forest fragment #25, which was highlighted with very high connectivity but had less than three hectares (Fig. 2C, Supplementary Material, Table S3). These actions can improve the movement of species in the urban landscape and promote human health (Mello et al., 2018; Valente et al., 2021). Healthy forests, anywhere globally, filter water, reduce sediment pollution, and serve as a buffer against droughts and floods (Ozment et al., 2018; Mello et al., 2020).

Furthermore, the restoration actions could extend to other LULC types, such as anthropic grasslands. These grasslands are abundant in the study area (Fig. 2C) and are located in the riparian zones of the main rivers (Ribeiro et al., 2020). The use of these areas as paths for forest birds highlighted the need to include them in these ecological network projects and the restoration projects. Historically, with the intense urban sprawl, natural forest fragments and especially rural areas in the peri-urban area are frequently converted into anthropic grasslands and urban areas shortly (Joly et al., 2014). Thus, the restoration projects of these urban anthropic grasslands collide with the interests of the real estate market. The restoration projects' viability in these areas depends on the actions of local planners and heavily on the public administration, with command-control and incentive policies (Lemgruber et al., 2021; Mello et al., 2021).

The command-control and incentive policies should be implemented to minimize the significant connectivity gaps among PAs in this urban landscape that occurs among some isolated PAs, such as PA3 and PA6. The scenario of isolation of forest fragments is common for most urban landscapes in the Atlantic Forest biome (Moraes et al., 2017). However, the PAs connectivity is crucial to maintaining ecological integrity (Laurance et al., 2012; Lv et al., 2019), mainly in urban and peri-urban tropical landscapes. Our study showed that the PAs connectivity is impossible without neighboring forest fragments (outside PAs). Although PAs are created to minimize biodiversity losses, they depend on the surrounding areas (Laurance et al., 2012). Furthermore, many forest fragments outside PAs also contribute to the effective conservation of biodiversity and recognizing them is the current concern of the global scientific community, environmental planners, and public administration (IUCN-WCPA, 2019), mainly in rapidly urbanizing landscapes, such as the Brazilian Atlantic Forest (Santini et al., 2016; SOS Mata Atlântica, 2016).

In this sense, this study can significantly contribute to the Sorocaba city, presenting technical criteria and guidelines to the local planners and public administration for designing ecological corridors linking the municipal PAs. The ecological corridor project (Municipal Process nº. 2020/013463–3) is currently approved by the legal department to constitute a Municipal Decree. With the growing concern about ecosystem services improvement and city resilience, it is of great value to the public administration to seek new technical-scientific information for policy design, mainly studies that aim to reduce the ecosystem's vulnerability and people simultaneously (Hilty et al., 2020).

This study presented significant contributions to implementing and improving an urban ecological network connecting PAs. We showed the critical situation in an urban area in Brazil where most PAs currently present low connectivity, which can affect their goal of protecting regional biodiversity. We could identify a potential ecological network among the Ipanema National Forest (PA1), following the main rivers in the landscape and finding considerable forest fragments outside PAs in the East zone. The main challenge now for the environmental agendas, public or private, is implementing these conservation and restoration actions effectively to improve the ecological network. We showed the need for protection and restoration of riparian zones and strategic anthropic grasslands. We also showed the importance of conservation and restoration of small fragments which works as stepping stones, and conserving the largest and most essential fragments for PA's connectivity in Sorocaba and its metropolitan region. However, regional land use management involves different obstacles, such as various actors, cities, cross-border barriers, and many conflicts of interest. The amendment to the Forest Act, reducing and even ending riparian zone protection in urban areas (Brasil, 2021) is an example of a decision that was based on interests other than the biodiversity and ecosystem services conservation. This is a throwback to the worldwide movement to protect these areas in urban environments, and their importance showed in our study. The current UN Decade of Ecosystem Restoration can be an opportunity for the municipal governments to go forward in the opposite direction of federal setbacks, building more sustainable and resilient cities.

5. Conclusion

The multidisciplinary approach applied to an urban landscape in Brazil allowed the understanding of urban PAs connectivity. We identified critical paths (LCPs), important areas for restoration programs for improving PAs connectivity, and essential forest fragments for conservation and restoration through functional landscape connectivity and graph theory.

Our findings suggest significant connectivity gaps among PAs and the current PAs network in Sorocaba and the surrounding forest fragments. Furthermore, the current PAs network is dependent on neighboring forest fragments (outside PAs), followed by riparian zones and anthropic grasslands. These outside PAs forest fragments offer habitat and connectivity for Atlantic Forest birds and potentially for other species as well. However, most of them cannot provide the necessary support for PAs connectivity, indicating a very fragmented landscape with low connectivity. Thus, we cannot confirm that the PAs have the necessary connectivity in this urban matrix. We could identify an ecological network in formation, among the Ipanema National Forest (PA1), following the main rivers in the landscape and finding considerable forest fragments outside PAs in the East.

We identified only 28 forest fragments spatially connected, representing 44.5% of forest fragments on the landscape. They have varying sizes and are near large forest areas, substantial PAs, and riparian zones. Six of them, smaller than ten hectares and strategically located in the urban matrix, were indicated for restoration actions. Furthermore, important areas for restoration programs, such as riparian zones and anthropic grasslands surrounding these 28 essential forest fragments, were considered in the proposal to form a potential urban ecological network. We recommended the conservation of the large forest fragments (outside PAs) and restoring the small-sized forest fragments, riparian zones, and anthropic grasslands. The actions directly aimed at these highlighted forest fragments can improve the movement of species on the urban landscape and help human health by improving essential ecosystem services. Furthermore, we recommend that conservation managers and government agencies pay more attention to these forest fragments when discussing landscape planning to improve the persistence of native species in the existing PAs network.

We emphasize the importance of municipal governments in implementing the urban ecological network to develop more resilient cities, in the opposite direction of the environmental setback that Brazil is going through. This study was applied in an urban matrix in Sorocaba and its surroundings and could be replicated in different locations and Biomes with other focal species. The functional connectivity methodology is highly recommended for establishing ecological corridors among PAs and can bring many ecosystem benefits to city populations if applied to urban planning studies.

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CRediT authorship contribution statement

Marina Pannunzio Ribeiro: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Visualization. **Kaline de Mello:** Conceptualization, Methodology, Validation, Resources, Writing – original draft, Writing – review & editing, Visualization. **Roberta Averna Valente:** Conceptualization, Methodology, Validation, Resources, Writing – original draft, Writing – review & editing, Visualization, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2022.127683.

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