How urban forest can support Protected Areas connectivity?

Marina Pannunzio Ribeiro (marinapr@estudante.ufscar.br)
UFSCar https://orcid.org/0000-0002-9343-331X
Kaline de Mello
USP https://orcid.org/0000-0001-7873-3042
Roberta Averna Valente
UFSCAR https://orcid.org/0000-0001-7273-7042

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Abstract

The highly modified urban matrix becomes an inhospitable environment for many species because the natural vegetation fragments are highly fragmented and often isolated in the landscape. Protected Areas (PAs) located closer or within urban areas may not achieve their goal of protecting local or regional biodiversity. Thus, the proposition of ecological corridors aims to connect the PAs, providing the dispersion of species in anthropogenic landscapes. In this context, this study aimed to evaluate the PAs connectivity in an urban landscape and understand if urban forest fragments can support their connectivity, generating important information for biodiversity conservation and urban planning. For this, we used models based on Graph Theory to assess the functional connectivity among PAs. The focal species used were Atlantic Forest birds. We used the participatory technique to assess their dispersal capabilities, and this information was used to create a resistance surface map. The focal species movement in the landscape was modeled through Graph Theory. This model evaluated the functional connectivity and extracted the least-cost paths between PAs and other forest fragments that designed the urban ecological network. We identified that few PAs are connected in the urban landscape of Sorocaba city and its surroundings and 28 forest fragments that are important to support the connectivity among PAs. Among these, only four fragments are located within a PA. The other 24 forest fragments located outside PAs should be the center of attention for forest conservation and restoration actions, as they can improve the connectivity between the PAs. Our results show that PAs connectivity in urban landscapes depends on incentives for native vegetation conservation on private lands once most of the important forest fragments for the PAs connectivity are located in these areas. In addition, the restoration of riparian zones is important because they compose a great ecological corridor in the urban landscape. Strategies that increase the permeability of the matrix (e.g., increasing green spaces and gardens) and restoring target fragments are also important. Finally, land-use planning, focusing on natural ecosystem conservation and combating urban sprawl, is necessary to promote PAs connectivity in urban landscapes.

1. Introduction

The population is growing, and its continuous demand for space and infrastructure generate pressure on natural areas due to urban sprawl (Habitat UN, 2021; Tannier et al., 2016). Urbanization leads to forest loss and fragmentation, converting natural ecosystems into small fragments with complex shapes and isolated from other forest fragments, that are scattered in an inhospitable matrix for native species (Haddad et al., 2015; Liu et al., 2017, 2014). It affects landscape connectivity, i.e., species movement and flow of the natural process landscape (CMS, 2020), causing biodiversity losses (Hanski, 2011; Hernández et al., 2015; Tannier et al., 2016).

Protected Areas (PAs) have been created as a global biodiversity conservation strategy to mitigate these losses (Vieira et al., 2019; Wulder et al., 2018) 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). However, if these areas are isolated from other forest fragments in the landscape, their ability to meet the conservation goal is hampered (Hilty et al., 2020; Laurance et al., 2012; Saura et al., 2017). Worldwide this is the situation of many PAs in urban areas (Johnson and Klemens, 2005). Therefore, it is essential to ensure that these areas are connected in the landscape.

The connectivity between PAs and the remaining forest areas 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 (de la Fuente et al., 2018; Saura et al., 2014). Connecting these protected areas with other natural elements in the urban and periurban landscapes, such as riparian corridors, small forest fragments, and green spaces, is crucial to the PAs' ecological integrity (IUCN, 2016; Trzyna, 2014).

In the tropical regions such as the Atlantic Forest in Brazil, some of these PAs located in urban landscapes are protecting 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 (Pickett and Grove, 2009; 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 is remaining (Rezende et al., 2018). For five centuries, urbanization, industrialization, and agricultural expansion were the drivers of intense land-use change in this biome (da Fonseca, 1985; Joly et al., 2014; Tabarelli et al., 2005). 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.

The importance of PA' connectivity is one of the global biodiversity targets, signed by Brazil and other 192 countries and the European Union through the Convention on Biological Diversity (CBD) (CDB, 2010). The CBD defined 20 Aichi Biodiversity Targets for a strategic plan for biodiversity conservation, with actions planned between 2011 and 2020 (CDB, 2010). The 11th target specifies that 17% of the terrestrial environment, especially areas of particular importance for biodiversity and ecosystem services, must be protected through PAs systems that are effectively managed, ecologically representative, and well connected (CDB, 2010). In Brazil, policies have been created to minimize the impacts of forest degradation in Atlantic Forest and to connect the forest fragments, such as the Law of Atlantic Forest Protection at the national level (BRASIL, 2006) and a recent state resolution that defines the technical criteria and guidelines for the establishment of ecological corridors between PAs in the State of São Paulo - Sima Resolution nº 17/2020 (São Paulo, 2020). It is important to understand how the PAs are connected and where landscape connectivity can be improved to support these agreements and policies and achieve the conservation targets.

Studies worldwide have focused on understanding and improving PAs connectivity as a global strategy for biodiversity conservation (Belote et al., 2020; Saura et al., 2019, 2018, 2017). Ecological corridors, stepping-stones, and permeable matrix are used as strategies to improve the landscape connectivity (DeFries et al., 2007; de la Fuente et al., 2018; Hansen and DeFries, 2007; Hofman et al., 2018; Huang et al., 2018; Liang et al., 2018). In Brazil, the studies are conducted mainly in the Atlantic Forest Biome (Crouzeilles et al., 2011; RENATO Crouzeilles et al., 2013; Diniz et al., 2017; Moraes et al., 2017; Santos et al., 2018). However, PAs connectivity in urban landscapes is still poorly studied. Some studies highlighted the importance of introducing the focal species on the urban studies (Lv et al., 2019), the urban forest fragments around PAs (Xun et al., 2017), and the adequate management of the landscape matrix to achieve sustainability of the ecological flows and ecosystem services (Rubio et al., 2012). It is critical to identify priority urban forest fragments and other natural elements that promote ecological corridors between PAs and ensure the landscape's critical ecological functions, promoting conditions to support biodiversity conservation and provide essential ecosystem services in urban areas. Ensuring biodiversity conservation while minimizing urban development restrictions is one of the current significant challenges for decision-makers in urban planning (DeFries et al., 2007; IUCN, 2019; Xun et al., 2017).

Models based on graph theory that has been widely applied to assess landscape connectivity in agricultural landscape (Foltête and Vuidel, 2017; Martensen et al., 2017; Sahraoui et al., 2017; Saura et al., 2017; Serret et al., 2014; Tambosi et al., 2014; Urban et al., 2009) can also be applied in studies of urban forest connectivity (LaPoint et al., 2015; Pietsch, 2017; Tannier et al., 2016; Urban and Keitt, 2001). Recent studies such as Xun et al. (2017) identified priority habitat fragments for conservation located outside PAs in an urban landscape, using graph theory and least-cost path (LCP). Graph Theory models transform the anthropic matrix complexity and biological flows into a vector-based approach (Etherington and Penelope Holland, 2013; Saura and Torné, 2009; Urban and Keitt, 2001), allowing modeling of functional connectivity. The LCPs model is based on graph theory and is used to identify paths (i.e., ecological corridors) between PAs where the probability of species movements is higher (or less costly) (Etherington and Penelope Holland, 2013; Lomolino and Perault, 2001; Pinto and Keitt, 2009). These methods can support the design of ecological corridors, setting priority urban 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).

In this context, this study aimed at evaluating the PAs connectivity in an urban landscape and understanding if urban forest fragments can support their connectivity, 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 important urban forest fragments for landscape connectivity; and (3) the forest fragments that work as stepping-stones between PAs. For this, we used functional connectivity based on graph theory and least-cost paths (LCPs).

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

Some forest fragments belong to two large PAs (administered by the federal and state governments, respectively) classified as sustainable use (IUCN categories V to VI). In the West is the Ipanema National Forest (PA1 – Figure 1) with 109.560 ha, and in the Southeast (representing just around 5% of the total area) is the Itupararanga Environmental Preservation Area (EPA) (PA2 – Figure 1). The PA3 to PA7 (Figure 1) are smaller and administered by the municipal government in Sorocaba city and are registered in the Brazilian National Protected Areas Register (https://www.mma.gov.br/areas-protegidas/cadastro-nacional-de-ucs) as strict protection (corresponding to the IUCN categories I to IV) (SNUC/Brasil, 2000). The size of these areas varies between 9 ha and 63 ha.

2.2. Conceptual model

The conceptual model includes the land-use/land-cover (LULC) types and PAs boundaries within the study area. The construction of the resistance surface map was based on expert knowledge about the bird's species dispersion through the participatory technique. We used the Graph Theory approach to design the least-cost paths (LCPs) for the focal species and the landscape connectivity modeling (Fig. 2).

2.3. Spatial data

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

The study area presents native forest fragments (22,9%), silviculture (9%), temporary crops (17%), anthropic fields (20,4%), permanent crops (1,4%), riparian zones (2,9%), urban areas (24,9%), mining (0,3%), water bodies, and rivers (1,2%). In this study, temporary crops represent fast-growing vegetables, e.g., onions, potatoes, pumpkins, strawberries, and lettuces. The urban areas represent residential, commercial, and industrial areas. The anthropic fields comprise exotic or modified natural grasslands without grazing activity or old pastures in the initial succession stages. The permanent crops represent plantations such as citrus, and native forest fragments represent areas covered by forest types of Atlantic Forest and Cerrado.

The forest fragments of the study area have an average area of 13.52 ha (standard deviation = 132.27 ha; coefficient of variation = 978.29%) (Ribeiro et al., 2020). Most forest fragments (about 83% of the total) have less than 10 ha, and only three forest fragments have an area greater than 500 ha. The landscape's largest and most significant forest remnant is in FLONA Ipanema (PA1-NF), with 4600 ha. In addition, most of the forest fragments (54% of the total) have at least one remnant with minimum proximity of 50 m away from another.

The river shapefile was provided by the Environmental Company of the State of São Paulo (Cetesb — http://cetesb.sp.gov.br). We used transportation infrastructures (highways and railway lines) from the National Department of Transport Infrastructure (DNIT – http://dnit.gov.br). These data have a 1:50.000 scale and are freely available.

The PAs boundaries were obtained from the Brazilian National Protected Areas Register (https://www.mma.gov.br/areas-protegidas/cadastro-nacional-de-ucs). These data are at a 1:50.000 scale and are also freely available.

2.4. Resistance surface

In this study, we produced the resistance surface considering the focal species capacity in dispersion across the LULC of the study area (Lomolino and Perault, 2001; Pinto and Keitt, 2009). The focal species used here are Atlantic Forest birds 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).

The main challenge in least-cost modeling is to assign a resistance surface for ecological applications (Etherington, 2016). This way, ecological least-cost modeling has often been conducted based on expert opinion (Etherington, 2016; Gurrutxaga et al., 2010). InThistudy consulted eight experts in Atlantic Forest birds dispersion (through electronic forms), who know the study area. We invited them to assign values, between one (1) and 100, for each LULC type. These values represent the ecological costs by focal species to move across an anthropic matrix. The weights attributed to the LULC types to build the resistance surface are the arithmetic mean of the values attributed by the experts, with the outlier values discarded. These resistance surface values were used in the next stage to build the least-cost paths (LCPs).

2.5. Least-cost path modeling

We designed the LCPs among PAs based on Graph Theory, which provides the basis for most landscape connectivity models, including LCPs modeling (Beier and Noss, 1998; Hilty et al., 2020). This way, we modeled dispersal routes for the endemic forest birds between pairs of PAs of the study area (Bunn et al., 2000; Saura and Torné, 2009).

The software used was the Graphab, which required: (i) identification of the ideal habitats, (ii) the resistance surface values for the LULC types, and (iii) the focal species dispersal capacity.

The method used considers nodes and links to create a spatial vector basis in the landscape (Saura and Pascual-Hortal, 2007). These vectors or spatial graphs are spatial explicit elements used for landscape studies of ecological, genetic, and epidemiological phenomena (Dale and Fortin, 2010). The nodes represent the ideal habitats to the focal species in the vector graphs, and the links represent the LCPs between the nodes. The focal species (i.e., Atlantic Forest birds) dispersion capacity values were extracted from empirical researches with Atlantic Forest birds, such as Awade and Metzger (2008); Boscolo et al. (2008); Cornelius et al. (2017); Hatfield et al. (2018). The ideal habitats (nodes) were defined as the native forest fragments within PAs. The dispersion capacity to cross the anthropogenic matrix was fixed at 100 m (the dispersion distance values ranged between 50 m and 150 m in the empirical studies consulted).

Once the LCPs are built, the landscape connectivity analysis is the next step.

2.6. Landscape Connectivity modeling

We evaluated the PAs connectivity in the urban landscape through graph theory using the metric Probability of Connectivity index (PC), developed by Saura & Pascual-Hortal (2007). This metric was used to evaluate the PAs connectivity, stepping-stones, and understanding which urban forest fragments can support the PAs connectivity (Saura and de la Fuente, 2017; Saura and Pascual-Hortal, 2007).

The forest fragments (defined as nodes) and the links among these fragments (i.e., the LCPs) were interpreted by the PC index through Graphab software.

The PC index is a global metric given by the following Equation 1:

$$PC = \sum_{i=1}^{n} . \sum_{j=1}^{n} . a_i . a_j . p_{ij}^* \Big/ A_L^2 \qquad \text{(Equation 1)}$$

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 study focal species (i.e., Atlantic Forest birds).

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

The connectivity at the patch-scale, that is, the local contribution of each node and link to the global PC index (Foltête, Girardet, & Clauzel, 2014), was evaluated through the node removal methodology (Saura & Rubio, 2010). In this study, the connectivity was quantified through the dPCflux and dPCconnector. The first fraction considers the area of the removed element and its location on the matrix, and the second just considers its location (Saura & Rubio, 2010). The fractions were calculated from 0 to 1 (Saura & Rubio, 2010), and 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).

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 indicate the demand for improved connectivity (Hofman et al., 2018). The potential active links were grouped into five frequency levels using the Natural Breaks algorithm (very-high, high, medium, low, and very-low) on the GIS.

The forest fragments that stood out with the highest values of the fractions (dPCflux and dPCconnector) and active links were selected to map, representing the critical forest fragments to PAs connectivity.

3. Results

The resistance surface showed that resistance values increased when Atlantic Forest bird dispersion occurred outside the ideal habitats, that is, the native forest areas within PAs with resistances equal to one. These values reached up to 100 (maximum value, representing a barrier to species movement) for urbanized areas and mining areas (Table 1). Agricultural areas presented values from 50 to 70, anthropic fields 30, and riparian zones 10.

Table 1

Resistance values, based on endemic forest birds of the Atlantic Forest, for LULC of the Sorocaba, and its surroundings, in the São Paulo state (SP), Brazil.

LULC	Resistance value
Native forest areas within protected areas	1
Native forest fragments	2
Silviculture	65
Temporary crops	70
Anthropic fields	30
Permanent crops	50
Riparian zones	10
Urban areas	100
Mining	100
Water bodies	70
Rivers	50
Highways and railroad	90

The LCPs for endemic forest birds indicated that the study area has a forest structure in the landscape with 516 corridors (links) among 1873 forest fragments (Fig. 3). In the earlier study, we found that most of these landscape fragments have less than 10 ha, however, with high proximity among them (less than 50 m) (Ribeiro et al., 2020). A significant part of the LCPs are located predominantly in the periurban region, especially in the southwest, north, northeast, and east (Figure 3).

Nonetheless, despite the proximity among the fragments, the dPCflux fraction indicated that most forest fragments in the landscape (98.88%) have very-low connectivity among them (dPCflux < 0.06%) (Fig. 4). These 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. Among them, two forest fragments that belong to the Ipanema National Forest were emphasized, with higher connectivity values (dPCflux varying from 8.23–9.13%). In the southeast, near PA7, emphasize two forest fragments (outside PAs) showed high connectivity (dPCflux varying from 2.12–2.81%) (Fig. 4). The results showed some important forest fragments to connectivity along the main rivers in the study area.

The dPCconnector fraction highlighted just one forest remnant located in the southeast, near PA7 (Fig. 5), with very-high connectivity (dPCconnector = 0.57%), indicating the best location within the landscape. Besides, the dPCconnector index identified other 16 forest fragments that work as stepping-stones between PAs. These 17 forest fragments total 9170.91 ha of the native forest area (35.59% of the total) (Fig. 5).

However, 98.56% of the forest fragments had very-low connectivity (dPCconnector < 0,003%). This number indicates that the landscape is highly fragmented, and just a few forest fragments can improve the connectivity among PAs.

Comparing the 21 forest fragments indicated by the dPCflux fraction with the 17 indicated by the dPCconnector fraction, we considered 28 forest fragments that can support the connectivity among PAs (Fig. 6, Tab. 2). These forest fragments have the best connectivity potential, with the highest connectivity values for dPCflux or dPCconnector fractions. Among these 28 forest fragments, ten (10) were indicated by both fractions (dPCflux and dPCconnector), seven (7) exclusively by the dPCconnector fraction, and eleven (11) exclusively by the dPCflux fraction. They present different sizes, varing from 0.83 ha to 4,600 ha. The study area gathers fragments with an average area of 13.52 ha, and only 0.16% (three fragments) have size larger than 500 ha (Ribeiro et al., 2020).

Forest fragments near PA1 and PA7 are the most significant fragments that support landscape connectivity, presenting the highest values of 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. 6 - Tab. 2). Moreover, they are involved 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. Comparing the LCPs (Fig. 3) with link frequency (Fig. 6), we found regions highly fragmented (southwest) with many LCPs, but with neither high-connectivity link.

Our results revealed important dispersion paths among forest fragments following the study area's main rivers (Fig. 6), such as forest fragments #8, #11, #18 e #21. These forest fragments are in strategic positions and can promote the link between PA4 and PA5.

The PA3 is localized between other essential fragments, such as #13 e #11, but without links, consequently no species dispersion prediction. North was highlighted by forest fragments #22 and #23 with links between them, and the northeast highlighted the fragments #15, #17, and #24 too.

Table 2

Essential forest fragments were identified from the connectivity analysis of Sorocaba and its surroundings in the state of São Paulo (SP), Brazil, to promote corridors between PAs.

ID	AREA (ha)	dPCflux(%) or dPCconnector(%) values	Contribution fraction
1	4599.65	9.205	dPCflux and dPCconnector
2	365.65	8.248	dPCflux and dPCconnector
3	2892.25	2.820	dPCflux and dPCconnector
4	166.65	2.691	dPCflux and dPCconnector
5	53.43	0.595	dPCflux and dPCconnector
6	29.53	0.514	dPCflux
7	130.90	0.282	dPCflux and dPCconnector
8	346.14	0.264	dPCflux and dPCconnector
9	198.94	0.221	dPCflux and dPCconnector
10	13.57	0.194	dPCflux
11	98.22	0.187	dPCflux
12	8.16	0.168	dPCflux
13	111.39	0.155	dPCflux
14	13.49	0.117	dPCflux
15	259.84	0.117	dPCflux and dPCconnector
16	1217.92	0.097	dPCflux
17	84.05	0.091	dPCflux
18	48.56	0.089	dPCflux
19	6.38	0.087	dPCflux
20	13.94	0.077	dPCflux and dPCconnector
21	334.43	0.076	dPCflux
22	84.22	0.046	dPCconnector
23	37.36	0.036	dPCconnector
24	0.83	0.024	dPCconnector
25	2.99	0.012	dPCconnector
26	3.79	0.009	dPCconnector
27	12.18	0.008	dPCconnector
28	2.15	0.005	dPCconnector

4. Discussion

Here, we analyzed the PAs connectivity in an urban landscape and whether urban forest fragments can support the PAs connectivity. Our study showed that most forest fragments could not provide the necessary support for PA connectivity. We identified just 28 forest fragments, among 1,873 found in the study area, which had great importance for PAs' connectivity. Thus, few PAs are connected in the urban landscape of Sorocaba city and its surroundings. Among these 28 forest fragments, only four are located inside PAs. The other 24 are located in private properties or institutional areas, such as parks and squares. We identified near PA1 and PA7 the most significant forest fragments that support landscape connectivity, also the forest fragments along riparian zones in the study area. The PA1 is the largest protected forest fragment of the landscape. The PA7 is located in riparian zones, surrounded by critical forest fragments that support PAs connectivity.

The least-cost path modeling highlighted 516 LCPs for endemic forest birds (Fig. 3) within the complex matrix of Sorocaba and its surroundings. These paths revealed that the periurban regions have a significant amount of vegetation and they are important for the landscape connectivity. Periurban forests often represent the last forest fragments of metropolitan regions (La Rosa et al., 2013). Sorocaba is the city with the highest demographic density in the Metropolitan Region of Sorocaba (EMPLASA, 2018). With 99% of the population living in urban areas (IBGE, 2020), the landscape is considered highly fragmented and anthropized, with 73% of modified land uses, with the urban area the most representative class (Mello et al., 2016; Ribeiro et al., 2020). In this anthropic landscape, ecological paths (LCPs) were established among the periurban forest fragments present in small and medium rural properties, gated community, institutional areas, and PAs. The southwest, north, northeast, and east regions had the highest number of LCPs, representing regions with high levels of forest fragmentation (Fig. 3). Regions with larger fragments, such as the southeast and west, presented fewer links. In this sense, an ecological network project to promote the PAs connectivity with the forest fragments dispersed in the anthropic landscape, focusing on maintaining ecological functions in the territory, must be considered for human occupation planning in urban and periurban areas (Belote et al., 2016), minimizing the forest fragmentation and biodiversity loss with the urban sprawl (Peng et al., 2017).

Although we identified many forest fragments with flux dispersions among them (LCPs), few fragments were identified as functionally connected in the landscape of Sorocaba and its surrounding (Fig. 6). The dPCflux and dPCConnector fractions identified just 28 forest fragments contributing to landscape connectivity and supporting the PAs connectivity. It means that there is a great gap in landscape connectivity and, consequently, negatively affects biodiversity conservation. This shows the critical situation of the fragments of native vegetation in the Atlantic Forest Biome, where the Brazilian population is concentrated. This scenario of isolated fragments is common for most urban landscapes in the biome (Moraes et al., 2017). Thus, it is necessary to promote an ecological network to reduce forest fragments isolation (Ribeiro et al., 2009). Furthermore, Hatfield et al. (2018) warn of the importance of the PAs, particularly in the Atlantic Forest biome. The PAs cannot be reduced to isolated fragments surrounded by urban or agricultural landscapes because this makes them unsustainable and vulnerable to native species extinction (Hatfield et al., 2018; Laurance et al., 2012; Saura et al., 2018).

Through fractions dPCflux and dPCConnector, we observed the different ways in which a fragment can contribute to landscape connectivity or support connectivity between PAs (Correa Ayram et al., 2017; Renato Crouzeilles et al., 2013; Saura and Rubio, 2010; Tambosi and Metzger, 2013). Both fractions (dPCflux and dPCConnector) indicated fragments are located mainly west (near PA1), southeast (near PA7), and along the main rivers of the study area.

A high level of connectivity is observed in the western region (Fig. 4 and Fig. 5), led by the Ipanema National Forest, the largest protected remnant of the landscape (4,600 ha), located within PA1 and other forest fragments, such as #6, #10, and #12. Created in 1992, the Ipanema National Forest is the largest forest fragment of Seasonal Semideciduous Forest in the region, with native vegetation patches of Dense Ombrophilous Forest and Cerrado areas (ICMBio, 2010). It is configured as a sanctuary of biodiversity, as it has a flora with high diversity, that characterize a native vegetation formation of great genetic and conservationist value (ICMBio, 2010). Thus, this is the most important forest fragment in this landscape. It is a PA close to a city that still has a great forest cover and is connected to the landscape (high dPCflux and dPCconnector values, Table 2). Large fragments can serve as shelter and reproduction sites and promote dispersal flows to other forest fragments in the landscape (Saura and Rubio, 2010), especially tropical fragments, which hold a large part of global biodiversity (Gardner et al., 2010).

Surrounding PA7, there is another important nucleus of connectivity in the landscape (Fig. 6). The PA7 is an 11.7 ha reserve of Atlantic Forest Biome, and it is named Brigadeiro Tobias Municipal Natural Park. It is located in riparian zones and, in addition, surrounded by other forest fragments that had great importance for PAs' connectivity, such as #4 (166.65 ha) and #5 (53.43 ha), located outside protected areas. On private or institutional properties, these critical forest fragments are exposed to LULC changes, such as the majority (80%) of forest fragments on the landscape (Ribeiro et al., 2020). Thus, action to encourage the conservation of this native vegetation, existing on private properties, is necessary to ensure the maintenance of urban forests, besides gardens, squares, and tree-lined streets, in institutional areas (Guzmán Wolfhard and Raedig, 2019; Lamano Ferreira et al., 2021). Furthermore, the management and protection of forest fragments located in periurban areas and outside PAs can help fight urban expansion and reduce their negative impacts (Fábos et al., 2019). The institutional areas such as parks and squares in a city can promote biodiversity if connected with other forest fragments and PAs on the landscape (Wheeler et al., 2020). Thus, bringing the natural green solution to improve these public spaces can help promote biodiversity, improve ecosystem service, besides the well-being of the urban population (UN and WHO, 2020).

This study observed through fractions dPCflux and dPCconnector that along the main rivers of the study area, the riparian zones play a vital role in landscape connectivity. Tropical forest fragments surrounding the main rivers are frequent, especially in highly modified landscapes like the study area (Ribeiro et al., 2020). For example, Mello et al. (2016) highlighted that the mostly native fragments in Sorocaba city are in periurban areas, on high-altitude slopes, and in riparian zones. Here, we observed riparian forest fragments joining the PAs 4 and 5 (Fig. 6), designing natural corridors with species maintenance potential (Valente et al., 2017). Empirical research demonstrated that riparian corridors are considered natural corridors, playing a fundamental role in dispersing forest birds and acting as a habitat for birds, amphibians, and other vertebrates (Cruz and Piratelli, 2011; Sekercioglu, 2009; Şekercioğlu et al., 2015). Cruz and Piratelli (2011) research was developed in Sorocaba city. However, despite currently the riparian zones in Brazil protected by Native Vegetation Protection Law (NPVL; Law 12.651; Brasil, 2012, also known as the New Forest Act), much native vegetation was lost due to legalized suppression before this Law (Brancalion et al., 2016). Although we have prominent connectivity along the rivers, some riparian zones did not present forest cover and were characterized as anthropic fields of pioneer vegetation (Ribeiro et al., 2020). Thus, this situation highlights the importance of restoring riparian zones, mainly in urban areas. In addition to continuously contributing to landscape connectivity, these areas play a significant role in maintaining water quality (Brancalion et al., 2016; Mello et al., 2018). These vegetation are essential, especially in urban areas, where the surface water quality is impacted by sewage discharge and urban drainage, affecting the environment and human health (Eisenberg et al., 2016; Mello et al., 2020; Tromboni and Dodds, 2017; Walsh et al., 2005). In this sense, riparian restoration actions are considered actions that contribute to the conservation of species in the urban landscape and the health of humanity (Mello et al., 2018; Valente et al., 2021).

This situation highlights the importance of restoring these anthropic fields of pioneer vegetation, frequently found in the study area, totaling 20.4% of the landscape, only behind urban areas that predominate with 25% land use (Ribeiro et al., 2020). These areas represent an alternative for species that cannot cross areas with the highest surface values (such as urban areas). Nevertheless, the restoration or enrichment actions are an alternative to improve the use of these areas by native species (Latawiec et al., 2015). In addition, the anthropic fields are an opportunity for forest restoration actions. Since they are not productively explored areas, they may generate opportunities for restoration projects, especially in tropical landscapes such as the Atlantic Forest (Latawiec et al., 2015).

The suitable LULC surrounding the PAs is very important to the maintenance of the dispersion of biodiversity. The land-use surrounding the Piragibu Municipal Ecological Station (PA3) is formed by silviculture. Silviculture or any anthropic plantation are identified as limiting the dispersion of bird species, especially endemic forest birds (Giubbina et al., 2018). Thus, studies related to the increased permeability of the matrix around the PA3 should be directed by local planners. The actions to increase the connectivities among small municipal PAs with no ecological network aim to expand the movements of species dispersion and, consequently, benefit the increase in biodiversity (Baguette et al., 2013; Boesing et al., 2021; Fagan and Calabrese, 2006; Haddad et al., 2015; Zhang et al., 2019). Thus, the urban design of ecological networks must respect, conserve, and value the existing forest fragments and promote techniques and designs for conservation and restoration of biodiversity (Ignatieva et al., 2011, 2008).

In this anthropic landscape of the study area, the dPCConnector fraction highlighted forest fragments strategically located in the urban matrix (Fig. 5). Such elements are connectivity enhancers (Saura and Rubio, 2010), working as stepping-stones, helping compose the landscape's ecological network. These stepping-stones are critical in this urban matrix because they serve as strategic fragments destined to increase dispersion among large forest fragments (Baum et al., 2004). This study area is a highly anthropized matrix, presenting low permeability (Ribeiro et al., 2020). It has an urban matrix composed in the vast majority (83% of the total) by fragments smaller than 10 ha, but with beneficial proximity between them (Ribeiro et al., 2020). Thus, restoring these small-sized forest fragments could increase the matrix permeability and promote a potential ecological network, increasing connectivity among the 28 forest fragments supporting PAs connectivity.

These 28 forest fragments highlighted by dPCflux and dPCconnector have several sizes with not necessarily large areas (Table 2). Forest fragments, such as #20 or #25, which have respectively 13.94 ha and 2.99 ha, and are strategic fragments for landscape connectivity, located close to PA7 (Fig. 6, Table 2). So, the restoration of these forest fragments, principally those highlighted by the dPCconnector fraction, could help improve ecosystem services on this urban landscape. Ecological restoration projects are expensive and not always successful in biodiversity recovery (Rey Benayas et al., 2009). However, the choice of strategically located forest fragments enhances the success of forest restoration actions, improving essential services to human beings and also increasing the potential for dispersal of species in the landscape (Rey Benayas et al., 2008; Rodrigues et al., 2009; Stanturf et al., 2014).

At the moment, the restoration of degraded urban and periurban areas has focused on Nature-based Solutions (Bush and Doyon, 2019). For example, these solutions have been applied to recovering water quality and improving supply in southeastern Brazil (WRI Brasil, 2021). The Brazilian Southeast has been facing a severe water crisis, which includes the metropolitan region of Sorocaba, where water supply shortages to the population are already felt (SAAE, 2021). The frequency and severity of droughts have increased significantly, posing challenges requiring solutions that combine mitigation and adaptation to climate change (IPCC, 2021). In this regard, the restoration of strategic forest fragments can improve urban water systems, contribute to biodiversity conservation, and form an important strategy to support the quality of life of the urban population. Healthy forests, anywhere globally, filter water, reduce sediment pollution, and serve as a buffer against droughts and floods (Mello et al., 2020; Ozment et al., 2018). Thus, when the Nature-based Solutions is incorporated in water management in urban plans, it can increase the conventional infrastructure system's efficiency, performance, and resilience (Ozment et al., 2018).

The features mostly urban of this study area represent large areas of impermeable surfaces and built infrastructures. The specialists mention that the urban landscape is a consolidated structure almost irreversible (Forman, 2014; McKinney, 2006). Thus, some PAs on this landscape are totally isolated, surrounded by consolidated urban areas, such as PA6 (Fig. 4). The PA6, named Bráulio Guedes da Silva Ecological Station, is an urban protected area closed for public visitation (Sorocaba, 2016). However, the beneficial effects of contact with nature on human health are increasingly recognized (UN and WHO, 2020). Thus, we recommend opening this protected area to the population to enjoy the benefits of natural green space amid urban chaos.

Note that, on the landscape with massive urban expansion, such as Sorocaba and its surroundings, frequently prevail the socioeconomics interests at the expense of preserving natural areas. However, in the case of Sorocaba, the political-administrative sphere seeking to meet the recent Sima Resolution no. 17/2020, they signed with us a technical-scientific partnership to establish the ecological corridors. Thus, this study can significantly contribute to the city, presenting technical criteria and guidelines to the public administration for designing ecological corridors among PAs in the city of Sorocaba (Process nº. 2020/013463-3). With the growing pressure of climate change and the growing awareness of the environment, the political-administrative actors have been trying to comply with the existing laws. Furthermore, it is of great value that the public power seeking to incorporate new technical-scientific concepts capable of strengthening legislation and bringing technical-environmental preservation together with the development of human socio-economic-environmental activities (Pippi and Trindade, 2013).

Thus, the study presented on urban landscape connectivity is only the first step towards planning landscapes. The main challenge faced by the environmental agendas, public or private, is implementing conservation and restoration actions effectively. Nevertheless, studies like this must be presented to the governments and other social actors interested in landscape planning, as performed for Sorocaba. To the following steps, regional studies involving the RMS, or more embracing territory, are necessary. Regional land management involves different obstacles, such as various actors, cities, cross-border barriers, and many conflicts of interest.

5. Conclusion

Our findings suggest that few PAs are connected in the urban landscape of Sorocaba and its surroundings. Among 1873 forest fragments, we identified just 28 that support the connectivity among these PAs on the urban matrix. They are located in three connectivity cores, west of the landscape (near PA1), southeast (near PA7), and major rivers. It means a great gap in landscape connectivity and, consequently, negatively affects biodiversity conservation.

The Ipanema National Forest (PA1) is the largest protected forest fragment of the landscape. The PA7 is located in riparian zones and is surrounded by some of the most significant forest fragments that support landscape connectivity. The reserves PA4 and PA5 are in riparian zones and are involved by critical forest fragments promoting their link. The PA3 is surrounded by silviculture and PA6 by urban areas.

Furthermore, only four (4) forest fragments are fully protected, located within the Ipanema National Forest. Therefore, the other forest fragments with high connectivity are outside PAs, such as 80% of the forest fragments of the landscape. These other 24 remnants located outside PAs should be the center of attention for forest conservation and restoration actions, as they can improve the PAs connectivity.

Many crucial forest fragments for PAs connectivity are along the main rivers of the study area. So, this demonstrates the importance of the riparian forest for PAs connectivity for this anthropic landscape. Riparian zones were considered connection strategies since most municipal PAs are in this topological situation, facilitating the connection with other forest fragments that make up the APPs. Restoration actions of riparian networks are necessary and mandatory strategies, which result in the enhancement of PAs connectivity.

Besides restoration actions of riparian zones, we proposed strategies to increase the permeability of the matrix, increasing connectivity among small municipal PAs that do not yet have an ecological network as support, such as PA3. However, PAs involved in urbanized areas, such as PA6, are practically irreversible ecological situations. Thus, the useful strategies for this reserve must be linked to recreation, leisure areas, and the population.

We proposed that the planners improve green spaces in institutional areas (parks, squares, and tree-lined streets), encourage the conservation of the native vegetation in private properties, and restore the anthropic fields of pioneer vegetation, frequently found in the study area. Restoring the small-sized forest fragments can increase the matrix permeability, and restoring the forest fragments highlighted as strategically located enhances the success of forest restoration actions. These actions can promote a potential ecological network designed for increasing PAs connectivity on this anthropic landscape.

Thus, the PAs connection in urbanized landscapes depends on incentives to conserve native vegetation on private properties and increase the permeability of the matrix, such as improving institutional green spaces and private areas. Besides, the inspection and restoration of riparian zones and actions to restore strategically located fragments are indicated. Finally, actions with the LULC planning, focusing on biodiversity conservation and combating urban sprawl, are extremely necessary.

It is also worth mentioning that this study supported the technical-scientific analyzes in the political-administrative sphere in Sorocaba to guide the implementation of ecological corridors among the PAs (according to Sima Resolution no. 17/2020). The authors recommended regional studies involving the RMS or most extensive territory for the next steps.

Declarations

Competing interests: The authors declare no competing interests.

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Figures

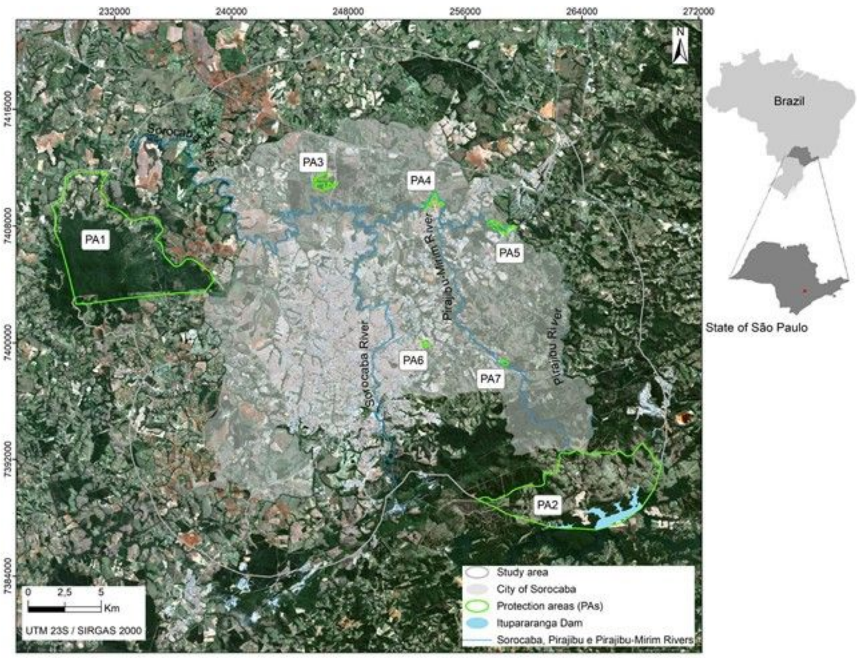

Figure 1

Sorocaba and its surroundings, in the São Paulo state (SP), Brazil: location and its Protected Areas (PA1-7).

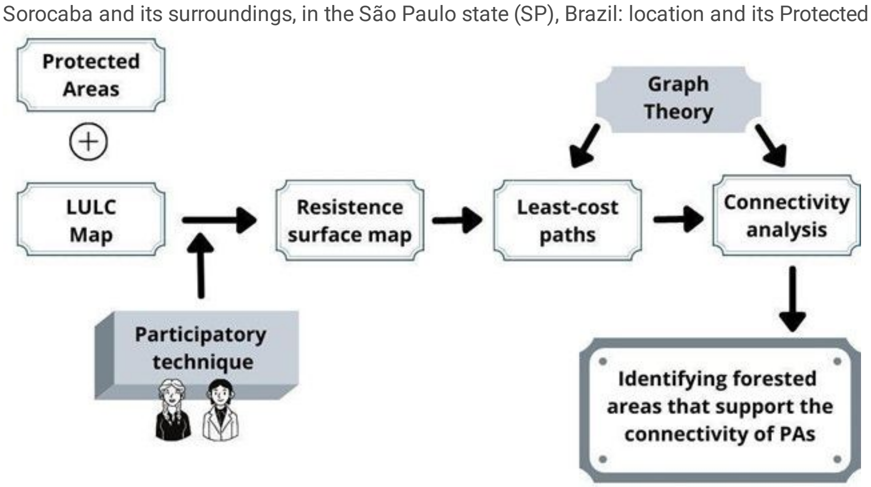

Figure 2

Conceptual model to evaluate the landscape connectivity between Protected Areas in Sorocaba city and its surroundings in the São Paulo state (SP), Brazil.

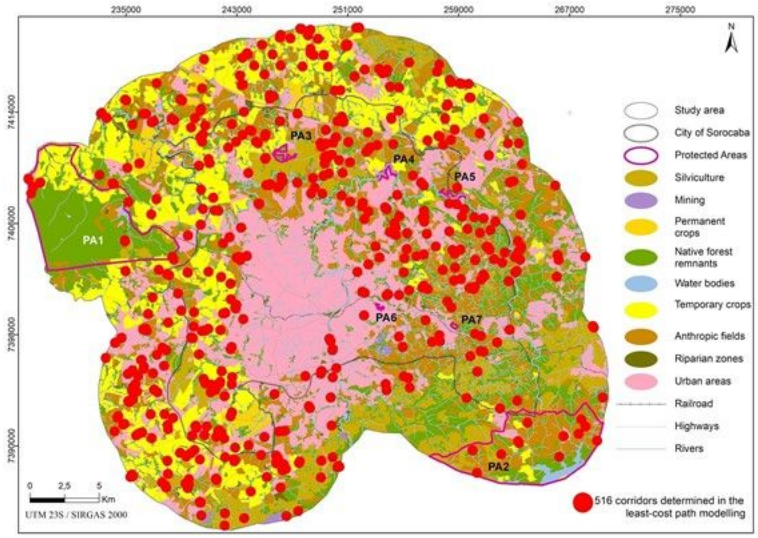

Figure 3

The least-cost paths linked native forest fragments overlapping land-use/land-cover of Sorocaba and its surroundings in the São Paulo state (SP), Brazil. Source: Adapted from (Ribeiro et al., 2020).

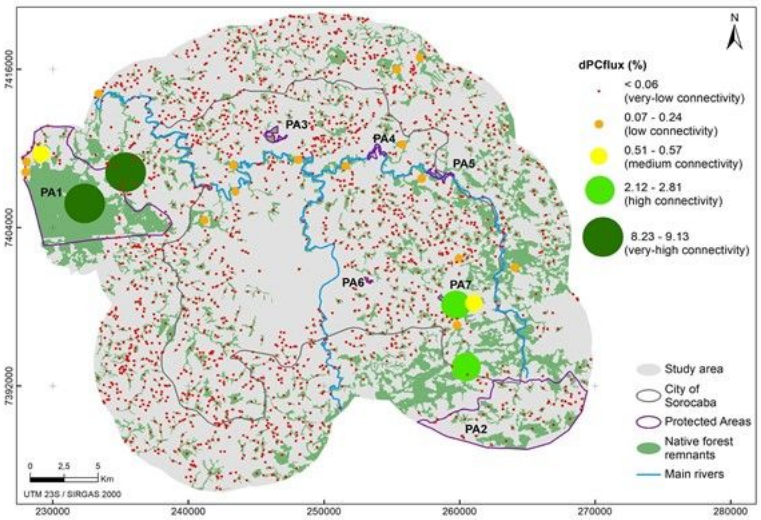

Figure 4

Spatial graphs with nodes and dPCflux (%) fraction. These dPCflux values come from the connectivity analysis of Sorocaba and its surroundings in the São Paulo state (SP), Brazil.

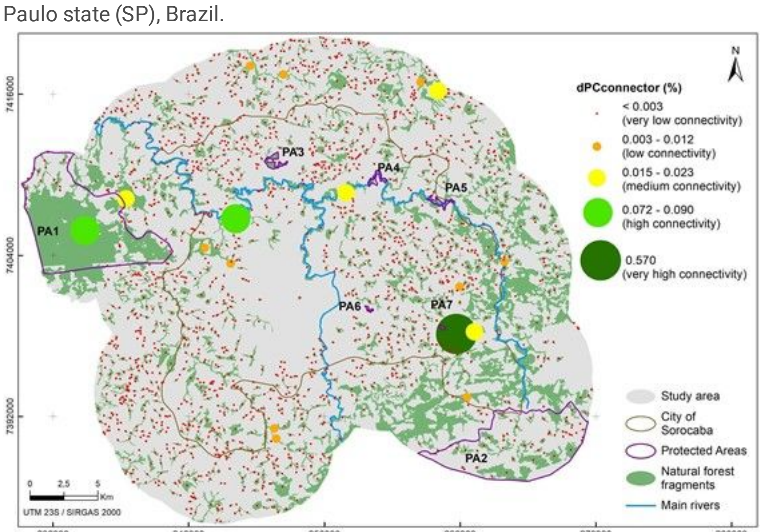

Figure 5

Spatial graphs with nodes and dPCconnector (%) fraction. These dPCconnector values come from the connectivity analysis of Sorocaba and its surroundings in the São Paulo state (SP), Brazil.

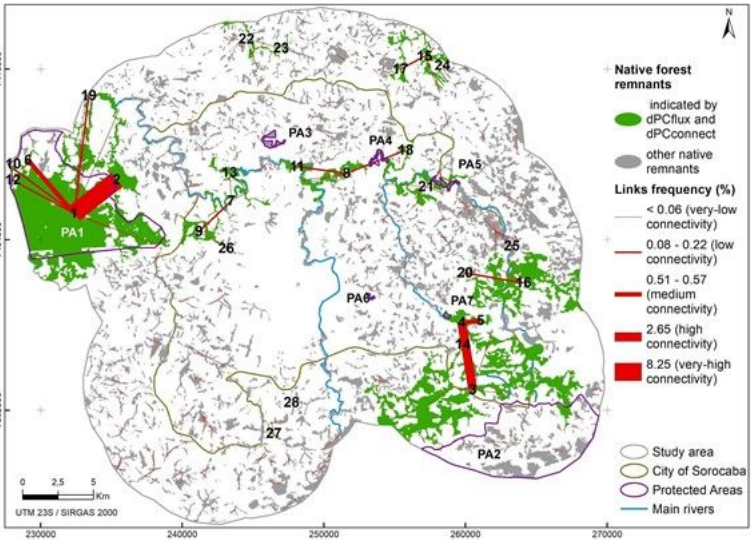

Figure 6

Visualizations of spatial-graphs with 28 nodes indicated by dPCflux (%) and dPCconnector (%) fractions and link frequency (%) come from the connectivity analysis of Sorocaba and its surroundings in the São Paulo state (SP), Brazil.