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# DETECTING AND RESTORING GAPS AMONG FOREST PATCHES: AN ACHIEVABLE AND REPLICABLE PROPOSAL TO BOOST THE LANDSCAPE CONNECTIVITY

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Abstract

It is well known that one of the main impacts caused by land cover change is the process of forest fragmentation. Connecting the remaining fragments is always an exercise for technicians and academics, and even corridors of remaining vegetation usually present places of forest discontinuity, lacking connection strategies for the corridor to gain a real function. In this paper, we applied a model structured to identify priority locals to implement connectors. We used a GIS package and a digital, georeferenced satellite image. We complemented the project by surveying a database through a drone-based field survey. The integration of data revealed that for our studied area (Sorocaba, SP Brazil) 42.5% need assisted restoration. The mapping also revealed the existence of 25 forest fragments larger than 50 ha, arranged chiefly in one single corridor but disconnected from each other. Hence, through the application of the model, we could localize nine strategic locations in distances as short as possible among the fragments, feasible to implement a connector with the economy of resources and expect satisfactory performance in ecological terms. The database generated by the drone-based survey helped us to assert

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the effectiveness of the model in choosing areas that require assisted restoration to re-establish the connection of the landscape.

Keywords: ecological connectivity; connector selection methods; ecological connectors; matrix permeability; wildlife corridors

## 1. INTRODUCTION

Human population growth causes significant changes to the landscape, threatening the biodiversity through activities such as (i) land cover change (for agriculture and/or urban expansion) provoking loss of forested sites, (ii) pollution, (iii) dissemination of exotic species with the potential of bioinvasion. Ideally, land-use and land-cover changes should occur through a planned trajectory to minimize harmful impacts and to promote sustainability [1, 2]. Often, however, urban expansion creates a landscape mosaic that is less than ideal for ecological and genetic sustainability. Forests, for example, are frequently fragmented and disjointed, which results in lower habitat quality and restricted migratory corridors [3, 4].

Associated with forest fragmentation, the alteration of the forest also reduces habitat area and creates fragment shapes that may not be the most ideal [5]. Such changes (disconnection, reduction of size, and deformation of the shape), modify the ecological characteristics, both structurally and functionally. Further, they lower the chances of self-perpetuation of local species and make them fragile and of great importance for the conservation of biodiversity [6, 7, 8].

Some landscape features might obstruct the movement of wildlife between ecologically vital areas. On the one hand, an alternative to improve the connectivity remove the barrier(s). On the other hand, there are situations where installing connectors could result in better results. The technical and academic community has developed several modalities and strategies for ecological restoration, always aiming to reach efficacy in terms of ecology and reduction of costs. Efficient habitat restoration and conservation through the connectivity of the landscape, is a major research topic in the ecological literature linked to land use planning [9, 10]. Actions that aim to connect and reconnect forest patches are important to make feasible the transit of wild animals among the fragments and to avoid the arising of metapopulations or similar problems [11, 12] and permit them disperse seeds, once the survival of plant metapopulations in disjointed landscapes crucially depends on the potential of the dispersers [13]. Planning the implementation and maintenance of structural patch-connectors might mitigate the effects of landscape fragmentation. Furthermore, providing connectors constitutes an important basis for planning urban infrastructure [11, 12].

Several studies [14-22] showed that models for the identification of fragmented areas have been developed, as they are suitable to promote the connection between fragments. Among these, the vast majority use methods based on studies of ecological linkage networks (based on graph theory) to define paths between habitat areas, while others apply qualitative methods based on empirical judgment. There are also those who determine the locations for the establishment of corridors through resistance to the movement of the species. In this context, it can be said that all methods are effective and can be applied to regions in terms of their characteristics.

However, there is only one hybrid method that takes into account the qualitative strengths, such as local ecological knowledge and diagnoses, added to the quantitative ones, that is, extremely important factors such as the potential of the matrix based on human actions, in relation to permeability or resistance of movement to species, taking into account even the smallest effective distance between the vegetation fragments. An example is the "Suitability Index for Restoration" (SIR), or suitability index for restoration, developed by Bortoleto [23]. This method identifies matrix patterns that occur in the land cover in terms of suitability for restoration, that is, it selects regions with potential for application in ecological corridor project applications and also allows the user to identify areas with potential for landscape restoration, based on the relationship between the permeability or resistance of the landscape and the effective distance between fragments. Therefore, the SIR will be used in this work as a pre-selector of areas for the implementation of ecological corridors. Research on connectivity of vegetation fragments as a way of restoring and preserving the landscape has been an important topic in the ecological and conservation literature [24].

Active restoration considers activities of direct seeding, planting of nursery-grown seedlings, as well as thinning and burning to accelerate the recovery trajectory. On the other hand, we name natural restoration the spontaneous recovery of native tree species that colonize and occur in abandoned area or natural disturbances. Simple human interventions such as controlling of weeds, fencing to control livestock grazing, and prevention against the fire, can complement the works following this approach [25].

In view of the heterogeneity of models concerned with the relationship between habitat connectivity and land-cover patterns, in this study we explain the creation and application of an approach created to evaluate the quality of landscape at regional scale, and also present an innovative scheme to select location of connection between forest remnants where intervention is needed to recover and enhance the connection of the landscape.

The objective of this research is to test the feasibility of using the SIR methodology coupled with high resolution unmanned aerial image interpretation, to identify ideal locations for habitat connectivity for subtropical forest of southeastern Brazil. We postulate that the methodology reported herein will provide a convenient and accurate path for identifying locations to build connections for active restoration of forests in a fragmented landscape. Solving the concerns described earlier is vital to establishing policies for conservation in both agricultural and urban regions [26, 27].

# 2. MATERIALS AND METHODS

## 2.1. Study Area

We developed and tested our models in the municipality of Sorocaba, which is located in Sao Paulo state, Southeastern Brazil (Figure 1). Throughout the São Paulo State region, the forest is highly fragmented with few connecting corridors [32], and the Natural Remaining Vegetation (Wood Site) currently represents 22.0% of the study area of forest remnants. The region has a total area of 449 km² and a population of 651,434 inhabitants (in 2019), being about 98% considered urban. Its demographic density is approximately 1,446 inhab.km$^{-2}$ [28].

The local topography ranges between 539 and 1,208 meters above the sea level [29]. We classify the regional climate of the local area as humid subtropical (Cwa) following the Köppen classification system. The municipality usually presents rainy and warm summers (monthly precipitation of 176 mm and, an average temperature of about 24.6°C) and moderately cold and dry winters (47.6 mm, 19.0°C) [30].

The geopolitical area of Sorocaba is an ecotone region that integrates two important biomes: Atlantic Forest and Cerrado (Brazilian Savannah). Exemplifying some arboreal species that occur in region: *Poincianella pluviosa* (DC.) L. P. Queiroz, *Handroanthus chrysotrichus* (Mart. Ex DC.) Mattos, *Tibouchina granulosa* (Desr.) Cogn, *Eugenia uniflora* L., *Schinus terebinthifolius* Raddi, and *Cariniana legalis* (Mart.) Kuntze EN. In terms of invertebrate species, curiously the class Arachnida is largely predominant (much more than the Insecta), and the genera *Amblyomma* spp. presents the largest number of species [31]. Some regional wildlife animal species are: *Monodelphis iheringi* Thomas – a mammal endangered species, *Hydrochoerus hydrochaeris* L. – the largest Brazilian rodent, the bird *Aramides cajaneus* Statius Muller, the snake *Simophis rhinostoma* Schlegel, and the frog *Leptodactylus mystaceus* Spixs. Smith et al. [31] present a complete and rich set of lists of local animals and plants species.

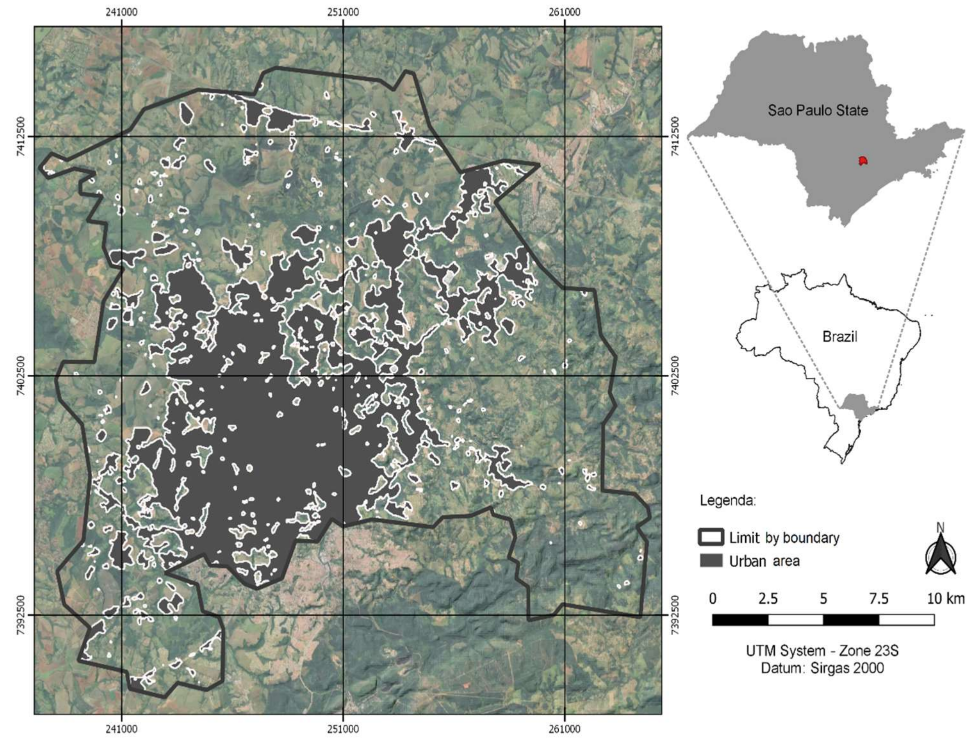



Fig. 1. Local of study area, highlighting the urbanized region of Sorocaba municipality

The regional ecological features address e for the necessity for implementing connections between forest remnants to strengthen the conservation of biodiversity [33]. We also have two Units of Conservation bordering the study area: The National Forest (Ipanema - 5,078 ha), and the Environmental Protection Area (Itupararanga - 93,000 ha) of natural forest. In this way, the local government plans to establish a strategic, ecological corridor connecting these conservation units.

The municipality is one of the main reference cities in Brazil in terms of economic and industrial development. The main economic activities are the machinery, automobile, steel, heavy metallurgy, auto parts and mechanics industries. Agriculture has less expression in relation to industry. The main agricultural productions in the city are: sugar cane, beans, cassava, corn and tomatoes. However, most rural properties in the municipality are not properly agricultural production units, but usually places for people who live in the city to spend their weekends or vacations there.

Hence, the region presents the ideal characteristics for the development of the present study, because the area is notorious in terms of the biophysical, demographic, and economic environment in both scenarios: São Paulo State and Brazil as a whole, and there are few studies on ecology and landscape restoration. Furthermore, the model here presented can be applicable to comparable ecosystems elsewhere in the world.

## 2.2. Application and Analyses

This study occurs at two spatial scales, which from heretofore are referred to as "Blocks." Block 1 represents the macro scale (landscape level) where we identified the most suitable forest fragments that could be connected. Block 2 is at the local, detailed scale, where we use imagery took from unmanned aerial vehicles (UAV) to validate the results for Block 1 and to identify small-scale features that promote or resist connections among fragments. We propose that this multi-scale approach is the most accurate and feasible methodology for identifying gaps in the corridors and ways to connect the corridors (i.e., eliminating the gap) for active corridor restoration within this habitat type. The Figure 2 describes the steps.

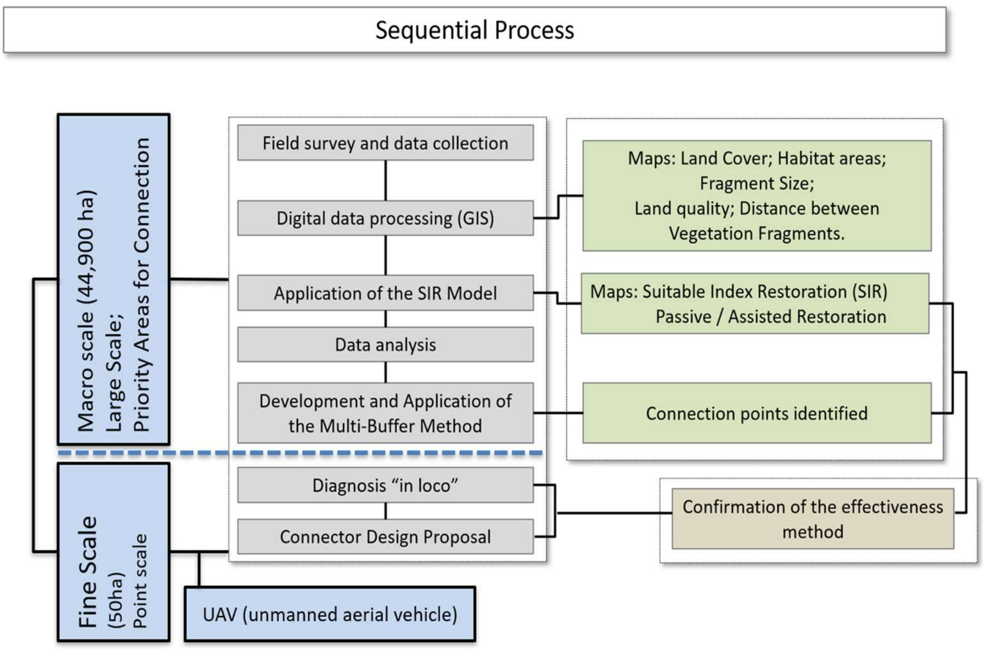



Fig. 2. The sequential process of appliance multi-scale methods

*Block 1*

In the first block or first step, we had the goal generates a map indicating the deforested sites (gaps) existing among forest fragments larger than 50 hectares and whose sites it is not possible to consider the passive restoration, meaning that should be to receive actions of assisted restoration. This final map will be fundamental for the steps of "Block 2".

*Block 1. Acquisition of Image satellite, field surveys and generation of the Land Cover Map*

We generated a land cover map using a georeferenced satellite image of spatial resolution of 30 meters (Landsat 8 - already radiometrically corrected, path/row = 220/76, of April 2016). We considered the technique "Maximum Likelihood" and considered 176 for ground thrust analysis. We considered the land cover categories as follows: remnant forests, pastureland, agriculture fields, urban settlements, bare ground, water bodies. We evaluated the accuracy of the classification using Kappa's index of agreement [34, 35]. For computing the value of the Kappa index, we, by means of early studies of our study place [23, 36], observed that the land cover categories occur heterogeneously (i.e., the land cover categories occur disproportionately). Hence, we established a proportional number of sampling points, considering the proportion of occurrence of each land cover category, with a total of 176 sampling points. The final, overall, Kappa value was 0.93. This value is considered excellent and permitted us to validate the classification. Hence, we proceeded with the next steps of the project.

*Block 1. Generation of the bimodal map and identification of forest fragments larger than 50 hectares*

Next and using the land cover map generated earlier, we generated a binary map, where we identified the forest patches as ID=1 and the patches of all land cover categories received ID=0 (zero). Next and using this bimodal map, we identified the forest fragments larger than 50 hectares. We considered such value (50 ha) as a minimal value since the fact that for our local biomes (Atlantic Rain Forest and Brazilian Savannah, or "Cerrado") forest fragments larger than 50 ha are self-sustainable [6, 37].

*Block 1: Generation of distance map*

Next and using the bimodal map, we generated a distance map, considering the map resolution of 30m. This map depicts a gradient of distances among the fragments larger than 50 ha.

*Block 1: Generation of quality of neighbor map*

We also prepared a map named "quality of neighborhood" following methodologies outlined in Bortoleto et al. [6] associating each category of land cover in terms of human activities. This quality map considers qualitative and quantitative methods in its development with the establishment of weights for each class of land cover (meaning the quality of each land cover category). In this method, values range from 1 to 6, with values close to 6 indicating areas with greater intensity of human use, that is, greater huma activity and, consequently, low-quality land cover [6].

*Block 1: Integration of the maps and generation of the SIR map*

The Suitability Index Restoration (SIR) model [6] provides a means to identify areas of permeability or resistance in the matrix of the movement of the species among the vegetation fragments. We elaborated the SIR map using the algorithm depicted in Equation (2.1). For further details about this method, we recommend consulting the study conducted by Bortoleto et al. [6].

$$\mathrm{SIR} = \mathrm{Gd} * (\mathrm{LQ})^2 \tag{2.1}$$

Where *SIR* represents Suitability Index Restoration; *Gd* represents the component of the distance between the fragments; *LQ* represents the quality component of the matrix surrounding the fragments.

Hence, the product generated with this operation is a map indicating areas suitable for passive restoration (i.e., where the main strategy is just removing the drivers of degradation and permit the self-regeneration of natural vegetation) or assisted restoration (i.e., locals where we assume that the simple passive restoration does not work, being necessary some kind of human intervention for boost and drive the process of ecological restoration).

*Block 1: Generation of map of gaps with assisted restoration*

The resulting map indicated, by the SIR method, a set (or group) of locations suitable for restoration, but does not identify gaps for the implementation of connectors. Therefore, we applied the multi-buffer method to locate the gaps between habitat areas. We consider that the multi-buffer method is a complementary step to the establishment of gaps and connection locations for reintegrate the fragmented landscape. In this multi-buffer method, we determine the connections between the vegetation fragments following pre-defined buffer intervals (Figure 3).

Hence, initially, using the bimodal map of largest fragments and the computing tools provided by the GIS platform, we generated a "buffer map". In this map, the GIS platform created a “belt” surrounding each polygon (remembering that each polygon corresponds to a forest fragment larger than 50ha). We considered the gaps exactly in the locations where the buffers of the polygons overlapped each other. We carried out this "exercise" four times. In each time (and map generated), we considered a specific buffer width, and all buffer values were multiple of 30m, because of the spatial resolution of the map (30m).

Hence, we generated maps with buffers of 30, 60, 90 and 120 meters. We did not consider distances longer than 120 meters, since in our evaluation, connectors longer than 120 were expansive economically and (ecologically) unattractive for wildlife [37].

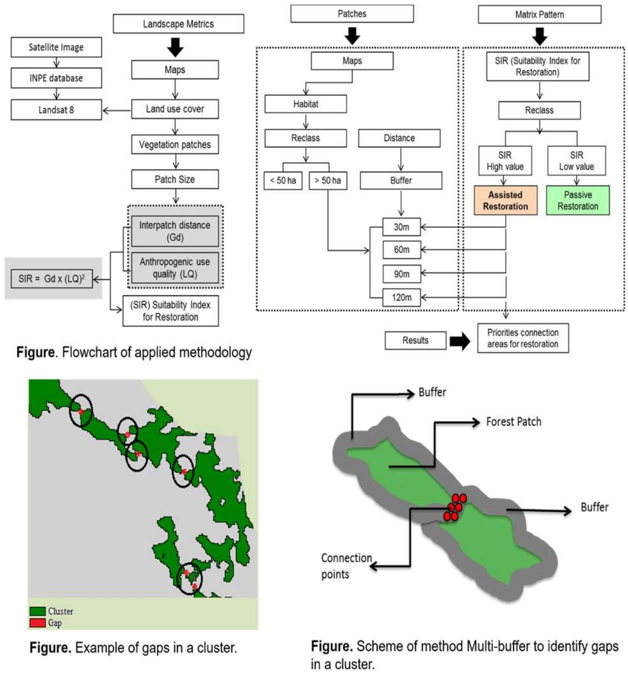
Indeed, the gap locations indicated in each map corresponds to the shortest distance among the fragments and it is a strategic value of the method because the shortest distance means that if you construct a connector in this location, the connector would be the cheapest one possible, and it is expected that is ecologically efficient for permit the passage by wildlife (obviously long connectors are not attractive for animals). Two main equations compose the multi-buffer method (equations (2.2) and (2.3)):

$$Pc_{ij} = Ab_i \cap Ab_j \tag{2.2}$$

$$Npc_{ij} = (Ab_i \cap Ab_j) / (Ap) \tag{2.3}$$

Where: $pc_{ij}$ represents the location for connection (gaps) between patches i and j; $Ab_i$ represents the buffer area of patch i; $Ab_j$ represents the buffer area of patch j; $Npc_{ij}$ represents the number of gaps between patches i and j; $Ab_i$, $Ab_j$ represent the buffer area of patches i and j; $A_p$ represents the area of the pixel.

After generate the map that indicates gaps among forest fragments, the next step was to overlay it to the SIR map, once that the location of some gap probably is in regions classified as passive restoration, so, such locations should not receive connectors. Hence, the final map generated indicates sites where there is a gap among the forest fragments and demand for assisted restoration.




$$Npc_{ij} = \frac{Ab_i \cap Ab_j}{Ap}$$

Where:
$Npc_{ij}$ = Number of connection points between patches i e j;
$Ab_i$, $Ab_j$ = Buffer area of patches i e j;
$A_p$ = Pixel area

Fig. 3. Methods of identifying gaps to promote the connection of landscape fragments

*Block 2*

For this part of the project, we used the map that indicates the strategic locations identified by the multi-buffer method. We initially visited each location indicated in the map and, using an Unmanned Aerial Vehicle (UAV - drone), we proceeded with a collection of aerial photos. It is important here notify that some locations where we took high-resolution (0.15m), georeferenced aerial photos (by drone) were of easy access, but most of them presented difficulties of access by car or walking.

We used a drone UAV DJI Mavic Pro. We elaborated the scenarios (mosaic of photos considering a radius of 500 meters from the focused location) containing the information in specific scales of the areas selected for connection through a computational routine of image clipping, using the software Idrisi version Selva [38]. Remembering that the goal of this second block or step was upscale the locals with gaps (locals pointed in the "low resolution maps") and we aimed to present a proposal feasible in terms of logistic, economy and effective in terms of ecology.

While the maps generated in the first block presented a spatial resolution of 30 meters, the photos took by the UAV presented a spatial resolution of 0.15 meters.

The construction of the mosaic of photos regarding each strategic site permitted us to analyze each site considering a set of complementary and important details that is impossible to examine in the low-resolution map. They are: (1) estimate physical characteristics of the gaps in details (quantification of the site measures: length x width for helping the sizing of the connectors); (2) observe where is the exact local with the shorter distance among the fragments; (3) observe what are the physical barriers (that drove the SIR classify the site as suitable for assisted restoration); (4) topographical aspects.

Reinforcing that the design project had as main objective to identify places where, once installed connectors, it would facilitate the movement of different species, reducing the effect of urban physical barriers, in addition to improving the local environmental quality.

## 3. RESULTS

### 3.1. Land cover, forest fragments and results of the SIR model

We detected a total of 661 forest patches occurring in 9,890 hectares, representing 22% of the total municipal area (Figure 4a). Of this total, we reported that 25 were large fragments (greater than 50ha). This category of land cover reached the highest percentage of occurrence in 2011 and in 2016 presented lower than 2011 (Table 1). Generation of new streets, ways and similar were the main causes that divided the large fragments in small ones.

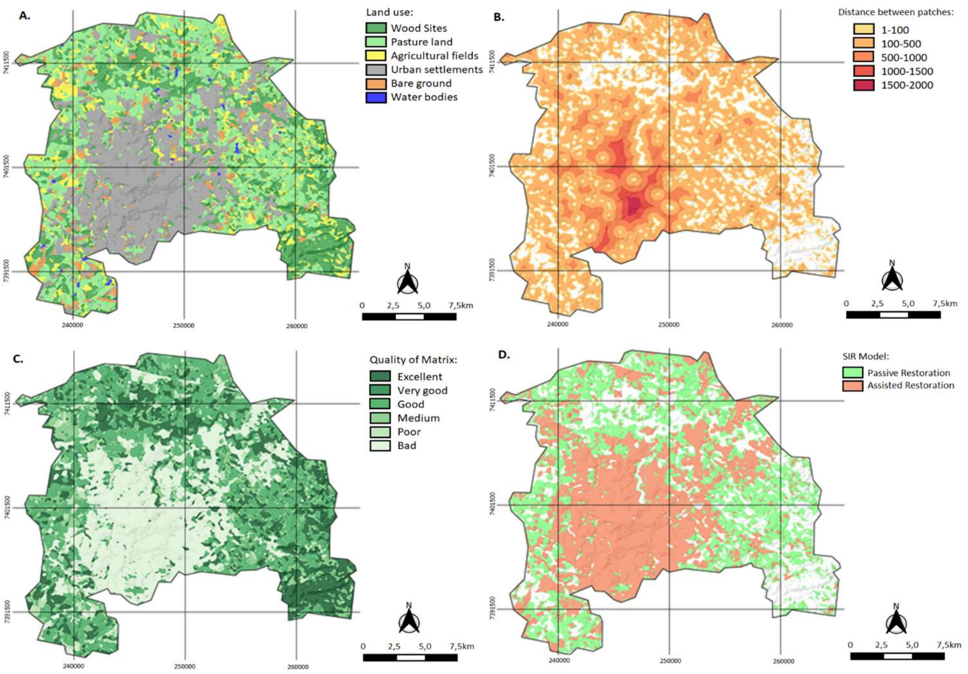



Fig. 4. Results of landscape metrics application. Datum: Sirgas 2000 (A) Land cover, (B) Distance between patches, (C) Quality of matrix – the intensity of human use, (D) Suitability of index restoration *"SIR"*. In the map (D) blank patches mean forested patches

Table 1. Land use dynamic. The study area during 1988, 1995, 2003, 2011, and 2016 (%)

| Land Cover classes | 1988 | 1995 | 2003 | 2011 | 2016 |
|---|---|---|---|---|---|
| Wood sites | 19.5 | 18.4 | 21.5 | 28.6 | 22.0 |
| Pastureland | 54.6 | 56.1 | 38.1 | 32.5 | 31.1 |
| Agriculture fields | 2.7 | 2.8 | 10.7 | 6.4 | 10.2 |
| Urban settlement | 10.7 | 14.6 | 19.4 | 28.8 | 31.4 |
| Bare ground | 11.8 | 7.5 | 9.8 | 3.6 | 4.8 |
| Water bodies | 0.6 | 0.4 | 0.6 | 0.2 | 0.5 |

Sources of the data for the years 1988, 1995, 2003 and 2011: [6, 23, 37].

The spatial distribution of the forest fragments was spatially irregular and asymmetrical among the regions of the study area. The peak of densification of urban settlements have been in the central-south region. The highest values of distances among the fragments coincides with highest density of urbanization (maps "A" and "B", of Figure 4). The distances reached 2,000m at a site located in the zone of greatest urban density. However, the distances shorten than 500m still occur in regions close to the large fragments (located at NW, N, NE, E, SE regions). Locally, this pattern of occurrence is an important indicator for establishing connections regarding the remaining vegetation [37].

In the same way, the quality map (Figure 4c), which depicts the local quality according to the category of land cover, indicates that the northern and eastern regions present the best indicator of quality. On the other hand, the central and southern regions have the longest distances among the fragments and had much lower quality values. As consequence, these regions (central and South) require more intensive actions of assisted restoration (Figure 4D).

Next, the relationship of resistance to the movement of species in the matrix, coupled with the values of buffers, identified sites of connection between the remaining vegetation with high priority for the implementation of landscape recovery projects.

### 3.2. Results of the multi-buffer method

The application of the method revealed 9 gaps considering the four distances: 30, 60, 90 and 120 meters. Six of these locations are in the eastern region (Figure 5), while three of them are in the south eastern region. The eastern region that concentrates the six locations is a corridor of vegetation and of high regional importance. It connects two important places for regional environmental conservation located out of Sorocaba: the Area for Environmental Protection of the Itupararanga reservoir east side, located mostly in Votorantim Municipality, it provides drink water for all Metropolitan Region of Sorocaba) and the Ipanema National Forest (left upper side (northwest), located mostly in Iperó Municipality and is a markable historical and ecotonal heritage, of very high regional importance, historically and ecologically). The map of Figure 5 is a scaled-up patch of the municipal map and that indicates specifically the locals with gaps along the corridor revealed by the modelling.

Such gaps are locals of shortest distance among fragments larger than 50 ha (distances up to 120 long), characterize structural connection gaps that effectively influence the functional connection (Figure 6), and they are regions that ask for assisted restoration. In other words, the municipal map (low-resolution map) did not permit us to perceive this limitation in the corridor, and that we identified using the multi-buffer method. These gaps are highways, unpaved roads, lots with sparsely vegetated soils, among other forms of land use, as discussed ahead. Such gaps are locals of shortest distance among fragments larger than 50 ha (distances up to 120 long), represent structural connection gaps that effectively influence the functional connection (Figure 6), and they are regions that ask for assisted restoration.

In other words, the municipal map (low-resolution map) did not permit us to perceive this limitation in the corridor, and that we identified using the multi-buffer method. These gaps are highways, unpaved roads, lots with sparsely vegetated soils, among other forms of land use, as discussed ahead. Such sites are strategic to install artificial connectors because they are the shortest distance among forest fragments larger than 50 hectares. Correspondingly, the other three locations located on the opposite side of the municipality, but not presented in Figures 5 and 6, have the same characteristics: similar conditions of land use, length of the gaps, are gaps located among fragments larger than 50ha and are regions that demand assisted restoration; however, they do not constitute part of the strategic Biodiversity Corridor. Hence, the method permits us to conclude that there are many physical barriers causing fragmentation of the landscape.

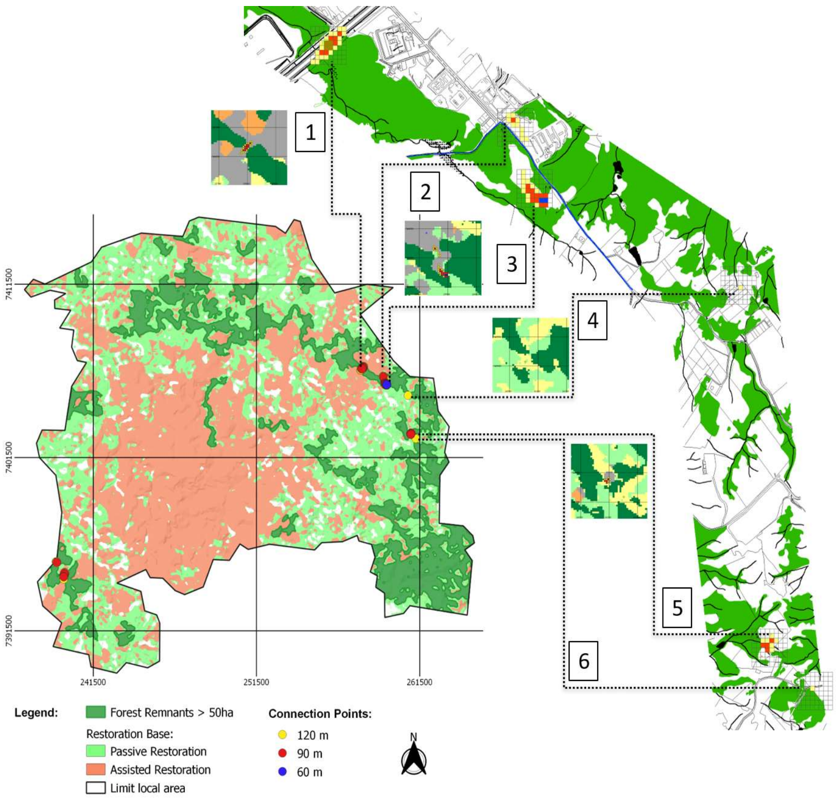



Fig. 5. Connections on multi-scale display. (a) Low resolution; (b) High resolution

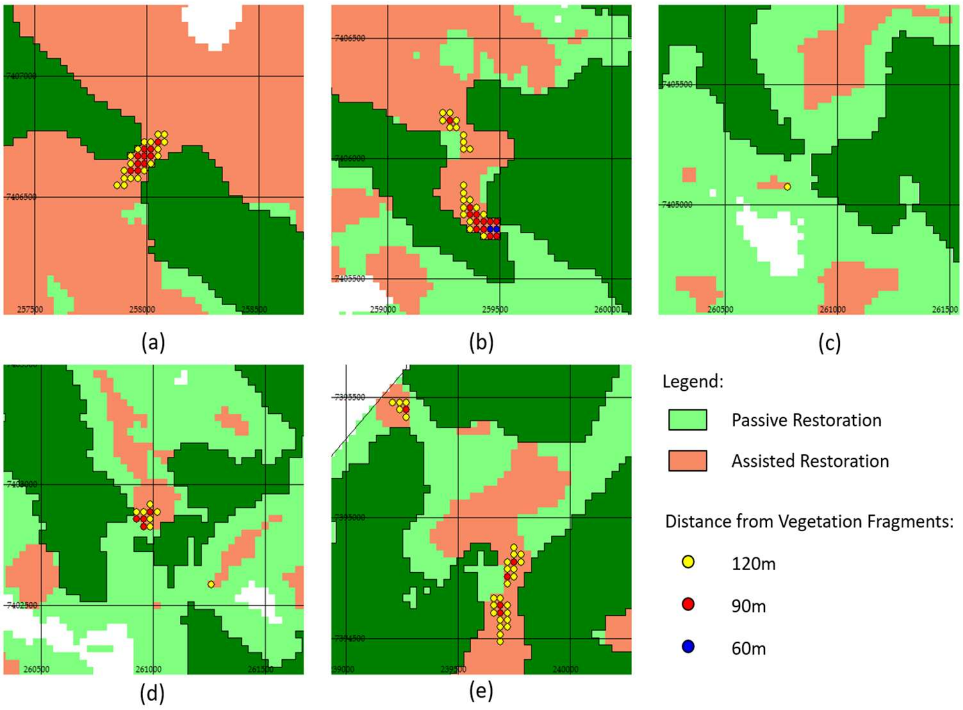



Fig. 6. Gaps and connection sites overlay the restoration passive and assisted classification map. (a) site 1, (b) sites 2 and 3, (c) site 4, (d) sites 5 and 6, (e) sites 7, 8 and 9

## 3.3. High resolution maps

After determining these gaps, the next step in the project was to place a "magnifying lens" on each location to scale up the information and permit to a more detailed analysis. We conducted such works using a UAV (drone) because the use of UAVs provides information much richer than information obtained on land. We depicted the results of this part of the project in Figure 7.

Sites 2 and 3 follow a sequence caused by the human barrier, interfering with the connection of habitat areas (see Figures 6b, 7b, and 7c). However, site 3 permits implementing a shorter connector (blue pixel = 60m). Site 4, evidenced by a single yellow pixel (Figures 6c and 7d), appears more distant (120m) from the habitat areas. This location required considerable attention for analysis. When observing only the image and the mapping, we inferred that there may be a connection between the fragments in a passive (natural) way, but that does not occur *in situ*.

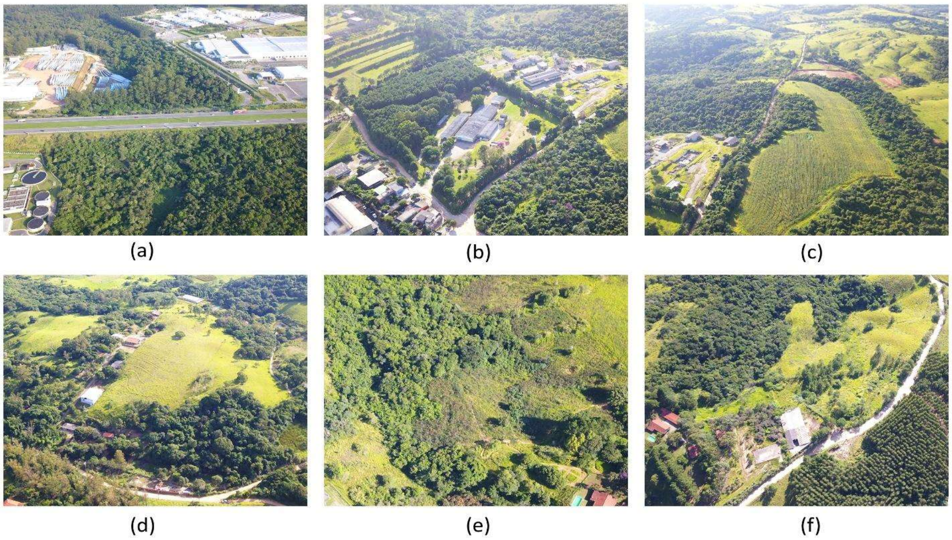



Fig. 7. Site that needs a connection, revealed by modeling. Photos took by an UAV. (a) site 1, (b) site 2, (c) site 3, d) site 4, (e) site 5 and (f) site 6

The field visits permitted us to observe that there were many small farms (rural properties smaller than 1 hectare), making it a strong barrier. In this case, the applied methodology demonstrated effectiveness in choosing the landscape to recover, as it is a region where there is a need for an intervention project to connect the fragments with a view to ecological conservation. Sites 5 and 6 (see Figures 6d, 7e, and 7f) are close among them, but they have different characteristics. Site 5 presented a connection distance of 90m, while at site 6 the connector must be at least 120m long. The scenario that contains site 5, unlike the other scenarios, lays fully in a private property of only one owner and has no physical barriers or delimitations in the region between habitat fragments. The aerial image (Figure 8) shows that the vegetation is recovering and planting trees of native species could effectively restore the local landscape to connect the fragments.

Fig. 8. Aerial photo of location 5, two different seasons, (a) April 2016 and (b) June 2017. Google Earth

## 4. DISCUSSION

Worldwide, urban areas have been gaining ground over rural areas, causing environmental degradation and triggering other problems generated by the rapid growth of metropolises in developing countries [39]. In our study area we have observed unplanned land cover changes, especially regarding the urban expansion, and the local landscape becomes altered both structurally and functionally [23, 40 - 42]. In this context, strategies are necessary to promote ecological restoration and the conservation of biodiversity, aiming to achieve sustainable development [42].

The analysis of the distribution of fragment size classes defined fragments larger than 50 hectares as elements of analysis. Furthermore, the potential for self-subsistence of large fragments is greater than small ones [31, 43, 44]. Although there were 25 large fragments of vegetation in the study area, we assume that they are under intense edge effect, since they present core areas (internal regions of the fragments) that are very small or null because of the shape of the fragment. The narrow, elongated shape of the forest patches increases the vulnerability to the external pressure and boost the alterations in the fragments' edge. This has a set of implications for fauna and flora in these places, with which, if precautions are not taken in the long term, the species of these fragments will likely disappear [45].

Our database suggests a trend to decrease the percentual of areas with high potential for restoration and increase in resistance. In this way, we presume that locals appointed as being of major resistance to species dispersion, in non-habitat areas, difficult and limit the moving through these areas [46, 47]. In this case, as the resistance matrix increased by 42.5%, we presume that the area should receive management actions to re-establish the capacity of percolation of the local landscape. Additionally, the expansion of areas destined for urban purposes is a competitive control process that needs to overcome landscape resistance to achieve landscape control [18].

Comparatively, researchers usually consider a method for prioritize areas for conservation or restoration projects based on the estimate of the shortest distance between “least cost” habitats [15, 21, 46]. However, such, method does not consider the effect of matrix patterns as resistance to movement. The application of the SIR associated with multi-buffer model, however, presented advantages in the selection of gaps in the corridors, as it considered the effects of resilience in the matrix.

Researchers have evaluated models constructed to enhance the connectivity of landscape and stressing the potential use to both evaluating and planning landscape-scale conservation for connectivity enrichment, among other possible purposes (exemplifying: [48, 49]). Our method here presented, although designed to test a conceptual model on the fragmented matrix, has also proven to be useful as a hybrid method. In general, hybrid models that involve quantitative data along with the parameters attributed by empirical (qualitative) analysis, have become remarkable and the analysis for the implementation of ecological corridors is essential.

Indeed, connectivity is critical for the conservation of spatially structured ecosystems, but human processes that impact habitat networks and disrupt this landscape structural element [48]. So, increasing and cumulative fragmentation of forest patches leads to the incapacity of the ecological corridor to retain this lined structure, creating a potential one constituted of fragmented portions of natural land [50]. When carrying out a suitability analysis and the identification of strategic locations for connectivity, our results become relevant due to the combination of parameters checked on site. Therefore, the integration of qualitative and quantitative analyses with spatial analysis forms an integral set of methods that complement each other and provide an important basis for the study of landscape connectivity.

The local analysis carried out by us, on a detailed scale, demonstrated that the strategic sites for connectivity are in fact in regions where there is a demand for immediate intervention projects to recompose the landscape. Therefore, we argue that the results obtained here revealed the current pattern of discontinuity of the vegetation and the methodology idealized by us was effective in the identification of gaps for ecological restoration of the local landscape. The results are locals where the costs are the lowest possible and the ecological efficacy is the highest possible. This is, above all, beneficial for nature conservation and spatial planning. Also, the application of model is feasible to any environment that needs to recompose the landscape through ecological connectors.

## 5. FINAL REMARKS

The proposed model successfully indicated the strategic locals for implementing connectors to establish a connection among forest fragments. The correlation between the area of the vegetation fragments and the methodology (SIR + multi-buffer) allowed us to find the voids (gaps) existing among the large remnants larger than 50 ha. There was also a direct and clear correspondence between the modelling results and the in-situ investigation of the scenarios.

In general, the increase in landscape fragmentation, because of the shifting in the land use intensified the physical barriers, evidencing that many habitats in the study area are under threat. The expansion of urbanization continues. However, there are opportunities to implement complementary ecosystem and landscape connectivity measures and projects at strategic locations in the study area.

This approach might collaborate to improve the landscape, mitigating, by consequence, the effects of fragmentation and making feasible the ecological processes of the great Ecological Corridor. For those who are concerned with landscape fragmentation and urban planning, the combination of SIR and the multi-buffer method provides a new understanding of modelling support for the disconnected landscape.

Future scenarios of fragmented landscapes can be more complex if short-term initiatives are not taken. Therefore, we believe that studies related to this theme should include methods to improve future ecological conservation under different scenarios of future environmental changes. Hence, the present work might contribute as an important stage in the research and in the process of elaboration of effective ecological conservation policies.

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## REFERENCES

1. Cobbinah, PB et al. 2020. Kumasi: Towards a sustainable and resilient cityscape. *Cities* **97**, 102567.
2. Zhou, T and Ke, X 2020. Which should be conserved according to priority during urban expansion? ecological lands or farmland? *Environmental Manage*ment **67**, 1-10.
3. Pirnat, J and Hladnik, D 2016. Connectivity as a tool in the prioritization and protection of sub-urban forest patches in landscape conservation planning. *Landscape and Urban Planning* **153**, 129-139.
4. Andreacci, F and Marenzi, RC 2020. Accounting for twenty-first-century annual forest loss in the Atlantic Forest of Brazil using high-resolution global maps. *International Journal of Remote Sensing* **41**, 4408-4420.
5. Gounaridis, D, Newell, JP and Goodspeed, R 2020. The impact of urban sprawl on forest landscapes in Southeast Michigan, 1985–2015. *Landscape Ecology* **35***,* 1975-1993.
6. Bortoleto, LA, Figueira, CJM, Dunning Jr, JB, Rodgers, J and da Silva, AM 2016 Suitability index for restoration in landscapes: An alternative proposal for restoration projects. *Ecological Indicators* **60**, 724-735.
7. Akçakaya, HR et al. 2020. Assessing ecological function in the context of species recovery. *Conservation Biology* **34**, 561-571.
8. Bortoleto, LA and Silva, AM 2020. Conectividade Ecológica em Pontos Estratégicos no Município de Sorocaba-SP [Ecological Connectivity at Strategic Points in the Municipality of Sorocaba-SP]. In: Welber Senteio Smith. (Org.). *Biodiversidade do Município de Sorocaba: Atualização e subsídios para a sua conservação [Biodiversity of the Municipality of Sorocaba: Update and subsidies for its conservation].* 2nd ed., Universidade Paulista, Grupo de Pesquisa Ecologia Estrutural e Funcional de Ecossistemas, Sorocaba-SP, Brazil pag. 81-98.
9. Lindenmayer, DB and Fischer, J 2013. *Habitat fragmentation and landscape change: an ecological and conservation synthesis.* Island Press, 352 p.
10. Lechner, AM, et al. 2015. A framework for incorporating fine-scale dispersal behavior into biodiversity conservation planning. *Landscape and Urban Planning* **141**, 11-23.
11. Ghazoul, J and Chazdon, R 2017. Degradation and recovery in changing forest landscapes: a multiscale conceptual framework. *Annual Review of Environment and Resources* **42**, 161-188.
12. Horte, OS and Eisenman, TS 2020. Urban Greenways: A systematic review and typology. *Land* **9**, 40-62.
13. Vittoz, P and Engler, R 2007. Seed dispersal distances: a typology based on dispersal modes and plant traits. *Botanica Helvetica* **117**, 109-124.

14. Zhang, Z et al. 2019. Enhancing landscape connectivity through multifunctional green infrastructure corridor modelling and design. *Urban Forest and Urban Greening* **38**, 305-317.
15. Ribeiro, JW et al. 2017. LandScape Corridors (lscorridors): a new software package for modeling ecological corridors based on landscape patterns and species requirements. *Methods in Ecology and Evolution* **8**, 1425-1432.
16. Hong, W et al. 2017. Sensitivity evaluation and land-use control of urban ecological corridors: A case study of Shenzhen, China. *Land Use Policy* **62**, 316-325.
17. De Montis, A et al. 2016. Urban–rural ecological networks for landscape planning. *Land Use Policy* **50**, 312-327.
18. Li, F et al. 2015. Evaluation of urban suitable ecological land based on the minimum cumulative resistance model: a case study from Changzhou, China. *Ecological Modelling* **318**, 194-203.
19. McRae, BH et al. 2012. Where to restore ecological connectivity? Detecting barriers and quantifying restoration benefits. *PloS One* **7**, e52604.
20. Galpern, P, Manseau, M and Fall, A 2011. Patch-based graphs of landscape connectivity: a guide to construction, analysis and application for conservation. *Biological Conservation* **144**, 44-55.
21. Gurrutxaga, M, Lozano, PJ and Del Barrio, G 2010. GIS-based approach for incorporating the connectivity of ecological networks into regional planning. *Journal of Nature Conservation* **18**, 318-326.
22. Saura, S and Rubio, L 2010. A common currency for the different ways in which patches and links can contribute to habitat availability and connectivity in the landscape. *Ecography* **33**, 523-537.
23. Bortoleto, LA 2014. *Análise da dinâmica de fragmentos florestais: estudo de caso de Sorocaba-SP [Analysis of the dynamics of forest fragments: a case study of Sorocaba-SP]*. Dissertation (MSc in Civil and Environmental Engineering), UNESP – Faculdade de Engenharia de Bauru, 78 p.
24. De Paula, FR et al. 2018. Multi-scale assessment of forest cover in an agricultural landscape of Southeastern Brazil: Implications for management and conservation of stream habitat and water quality. *Ecological Indicators* **85**, 1181-1191.
25. Crouzeilles, R et al. 2017. Ecological restoration success is higher for natural regeneration than for active restoration in tropical forests. *Science Advances* **3**, e1701345.
26. Siqueira, FF et al. 2021. Small landscape elements double connectivity in highly fragmented areas of the Brazilian Atlantic Forest. *Frontiers in Ecology and Evolution* **9**, 304.

27. Castro, RB et al. 2020. Identification of priority areas for landscape connectivity maintenance in the Xingu Area of Endemism in Brazilian Amazonia. *Acta Amazonica* **50**, 68-79.
28. SEADE (Secretary of Planning and Regional Development of the State of São Paulo) Fundação Sistema Estadual de Análise de Dados - SEADE 2016. *Perfil Municipal. São Paulo*. Available at: < http://www.perfil.seade.gov.br/#>. Accessed July 2021.
29. SEMA (Municipal Secretary of Environment of Sorocaba) 2011. *Plano Diretor Ambiental de Sorocaba [Sorocaba Environmental Master Plan]*. 56p. Available at: http://pt.scribd.com/doc/82943010/Plano-Diretor-Ambiental-de-Sorocaba. Accessed April 2020.
30. EMBRAPA. (Brazilian Federal Government Enterprise for Agricultural Research) 2003. *Banco de Dados Climáticos do Brasil [Brazil Climate Database]*. Available at: <http://www.bdclima.cnpm.embrapa.br/>. Accessed January 2021.
31. Smith, WS, Mota Jr, VD and Carvalho, JS (organizers) 2014. *Biodiversidade do Município de Sorocaba [Biodiversity of the Municipality of Sorocaba]***.** 1st Edition, Municipal Secretary of Environment of Sorocaba, 270 p.
32. São Paulo (Government State) 2017. *Sistema Ambiental Paulista - Área de Proteção Ambiental [São Paulo State's Environmental System - Environmental Protection Area].* Available at: < http://www3.ambiente.sp.gov.br/apa-itupararanga/>, Accessed: June 2021.
33. Smith, WS and Ribeiro, CA (organizers) 2015. *Parque Natural Municipal Corredores de Biodiversidade: pesquisas e perspectivas futuras [Municipal Natural Park Corridors of Biodiversity: research and future perspectives].* Municipal Secretary of Environment of Sorocaba SP, Brazil, 230 p.
34. Khoshnood Motlagh, S et al. 2021. Analysis and prediction of land cover changes using the land change modeler (LCM) in a semiarid river basin, Iran. *Land Degradation & Development* **32**, 3092–3105.
35. Tadese, M et al. 2020 Mapping of land-use/land-cover changes and its dynamics in Awash River Basin using remote sensing and GIS. *Remote Sensing Applications: Society and Environment* **19**, 100352.
36. Silva, AM 2005. Cobertura do solo do município de Sorocaba-SP e implicações na fragmentação dos remanescentes florestais [Sorocaba-SP soil cover and implications for the fragmentation of forest remnants]. *Revista de Estudos Ambientais* **7**, 38-46.
37. Bortoleto, LA 2019. *Seleção e diretrizes para o design de conectores ecológicos: uma abordagem metodológica [Selection and guidelines for the design of ecological connectors: a methodological approach].* Thesis (Doctorate in Civil and Environmental Engineering) UNESP – Faculdade de Engenharia de Bauru, 152 p.

38. Eastman, JR 2012. *IDRISI version Selva*. Worcester, MA: Clark University.
39. Zhang, XQ 2016. The trends, promises, and challenges of urbanization in the world. *Habitat International* **54**, 241-252.
40. Silva, AM 2009. *Ecologia da Paisagem: Fundamentos e Aplicações [Landscape Ecology: Fundamentals and Applications].* Papel Virtual Editora, Rio de Janeiro RJ, Brazil.
41. Damame, DB et al. 2019. Impactos ambientais pelo uso e ocupação do solo em sub bacias hidrográficas de Campinas, São Paulo, Brasil [Environmental impacts of land use and occupation in sub-watersheds of Campinas, São Paulo, Brazil]. *Acta Brasiliensis* **3**, 1-7.
42. Yin, H et al. 2015. Assessing growth scenarios for their landscape ecological security impact using the SLEUTH urban growth model. *Journal of Urban Planning and Development* **142**, 05015006.
43. Peres, CA 2001. Synergistic effects of subsistence hunting and habitat fragmentation on Amazonian Forest vertebrates. *Conservation Biology* **15**, 1490-1505.
44. Dos Santos, A et al. 2016. Geotechnology and landscape ecology applied to the selection of potential forest fragments for seed harvesting. *Journal of Environmental Management* **183**, 1050-1063.
45. Haddad, NM et al. 2015. Habitat fragmentation and its lasting impact on Earth's ecosystems. *Science Advances* **1**, 94-103.
46. Adriaensen, F et al. 2003. The application of 'least-cost' modelling as a functional landscape model. *Landscape and Urban Planning* **64**, 233-247.
47. Sawyer, SC, Epps, CW and Brashares, JS 2011. Placing linkages among fragmented habitats: do least-cost models reflect how animals use landscapes? *Journal of Applied Ecology* **48**, 668-678.
48. Hunter-Ayad, J and Hassall, C 2020. An empirical, cross-taxon evaluation of landscape-scale connectivity. *Biodiversity Conservation* **29**, 1339-1359.
49. Shirabe, T 2018. Buffered or bundled, least-cost paths are not least-cost corridors: Computational experiments on path-based and wide-path-based models for conservation corridor design and effective distance estimation. *Ecological Informatics* **44**, 109-116.
50. Luo, Y et al. 2020. Can policy maintain habitat connectivity under landscape fragmentation? A case study of Shenzhen, China. *Science of the Total Environment* **715**, 136829.

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