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Prioritizing landscape connectivity of a tropical forest biodiversity hotspot in global change scenario

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ABSTRACT

The probability that a propagule reaches, establishes and persists in a certain site is affected by the distance and quality of the environment. Fragmented landscapes promote the isolation of forests surrounded by a matrix that hinders or impedes the movement of species, affecting their distribution and threatening their conservation. Studies of landscape connectivity are essential to provide information for ecological conservation planning. Based on the classification of the landcover of the Rio Doce Basin - RDB and on the circuit theory, we used a habitat / non-habitat approach to assess the connectivity of the RDB to tree species. We built six resistance surface models based on habitat and non-habitat areas, using the GIS plug-in and Linkage Mapper to generate least cost paths maps. Three models explained the Jaccard similarity index matrix of 78 fragments used as a proxy of connectivity to test the models by GLMs, and one out the three was the simplest and most parsimonious. The map generated by the chosen model showed that the RDB is very fragmented but still has well-connected regions. The west to northwestern and southeastern portions of the RDB are well-connected and demand conservation of remaining fragments as well as the creation of reserves, while the center-north, east, and the far southwest of the basin are regions with greater resistance to connectivity as a result of anthropic pressures that reduced and fragmented the forests, requiring intervention through restoration projects to re-establish landscape connectivity.

1. Introduction

Landscape connectivity is a major concern in landscape ecology and land conservation in the current global change scenario (Saura et al., 2014). A well-connected vegetation patch receives more dispersers and also provides more propagules (Taylor et al., 1993). In addition, landscape connectivity allows plant species to move, use resources, colonize new habitats and maintain genetic flow through the pollen and seeds dispersal (Tumas et al., 2018). These processes can be affected by the lack of landscape connectivity threatening the conservation of plant populations (Santos et al., 2019).

In a global change scenario, landscape connectivity alleviates the consequences of changes in environmental conditions, allowing species to move, change their distributions (Opdam and Wascher, 2004), and maintain biodiversity in fragmented landscapes (Matos et al., 2016). Therefore, studies that assess landscape connectivity are essential to ensure that conservation planning considers connectivity and its associated ecological processes.

Regarding the dispersal process, the probability that a propagule reaches an available habitat is affected by the distance from a source of propagules. In other words, the greater the distance, the less likely a species is to reach an appropriate habitat and persist in the landscape (Levey et al., 2008; Weber et al., 2014). Consequently, fragmented landscapes, such as the Brazilian Atlantic Forests, have isolated habitats and hinder or impede the movement of species affecting their distributions and threatening them when local conditions become inappropriate for their existence (Magnago et al., 2015; Matos et al., 2017). On the other hand, areas with adequate habitat connectivity such as small patches of forest between larger neighboring fragments act as corridors allowing species movement in the landscape (i.e. landscape connectivity; e.g., Matos et al., 2019). Therefore, the landscape connectivity can be modeled considering the distances between

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patches of suitable habitats in the landscape.

Even with known distances between habitat fragments, the complexity for modeling connectivity for plant species is challenging. The dispersion of pollen and seeds depends on biotic and abiotic factors, which in turn are affected by the landscape (Auffret et al., 2017). However, the resistance distance method solves part of these problems as it considers different levels of suitability for the dispersion of plants and animals (McRae and Kavanagh, 2006; Thiele et al., 2018). This method is advantageous because it explains random movements in the landscape considering more than one possible path (McRae and Kavanagh, 2006; Thiele et al., 2018) and provide reliable data for conservation planning and decision making (Fuller et al., 2006; Correa Ayram et al., 2014).

Here, we used landscape connectivity to analyze the Rio Doce Basin (RDB), assessing modelled connectivity between fragments on the landscape scale. We used a comprehensive set of data with the taxonomic composition of 78 tree communities across the RDB in addition to information on land use. We also used a habitat/non-habitat approach to assess the connectivity of the RDB landscape for tree species making models with native forest fragments defined as habitat and with other types of land use defined as non-habitat. This study aimed to map the remaining fragments of the native Brazilian Atlantic Forest in the RDB, and the paths with less resistance to connection between them showing the most liable areas maintaining the landscape connectivity with associated ecological processes. The objective was to indicate areas where conservation measures are necessary and areas where restoration measures need to be implemented for improvement and maintenance of landscape connectivity.

2. Materials and methods

2.1. Study area

The RDB stretches on Minas Gerais and Espírito Santo states in Brazil, with an area of 86,715 km^2. It is the largest hydrographic basin fully inside the Brazilian Atlantic Forest Domain (Meira-Neto et al., 2020) with many economic activities, especially agriculture, livestock, and mining. These economic activities are the main cause of fragmentation, and environmental disasters in this biodiversity hotspot (Saiter et al., 2015; Meira et al., 2016; Nazareno and Vitule, 2016). The soils of the RDB are dystrophic with high saturation of aluminium, predominantly Red-Yellow Latosols, and Red Cambisols (Nunes et al., 2000; Marangon et al., 2013; Soil Department of Universidade Federal de Vicosa, 2020). The RDB's Brazilian Atlantic Forests varies slightly between tropical rainforests forests and tropical semi-deciduous forests (Veloso et al., 1991). The RDB’s climate has a dry season during the winter with the average rainfall varying from 150 mm to 250 mm, and in a rainy season with the average rainfall varying from 800 mm to 1300 mm (Alvares et al., 2013).

2.2. Floristic data set

The tree occurrence matrix for 78 sites in the RDB (Fig. 1) was extracted from NeotropTree, a database containing a checklist of tree species in the Neotropics (Oliveira-Filho, 2014) for the analysis of landscape connectivity (see below). The checklists were obtained from records of the occurrence of different works with checklists of trees species, mainly published floristic research, taxonomic monographs and herbarium records available in the Flora and Fungi virtual herbarium (“SpeciesLink Network - Herbário Virtual da Flora e dos Fungos,” 2020). The taxonomic information was verified with the help of experts and of the taxonomic literature. Due to the high density of floristic surveys for certain locations, the data within a radius of 5 km was compiled and merged into a single checklist for a site. As a result, a total of 1944 species distributed in 100 families, for a total of 22,007 individuals, were recorded for the entire RDB.

2.3. Landcover map and landscape connectivity analysis

In this study, we used the classification of land use and occupation (see Fig. 2A). The classification included 12 classes: native forest, pastures, reforestation area, rocky outcrops, open areas, agricultural areas, beaches, mining areas, urban areas, airports, roads and water. The RDB's native forest has been largely suppressed by anthropogenic activity and most of the fragments are restricted to the steepest areas. In addition, pastures are also degraded with low soil coverage, soil compaction and intense trampling (Agência Nacional de Águas, 2013).

Our methodology was based on circuit theory (McRae and Kavanagh, 2006). We used the landcover map to build six hypothetical resistance surface models, where the elements in the landcover map were assigned with a different resistance value, in the Linkage Mapper plugin from ArcGIS software (McRae et al., 2014). Therefore, each hypothetical resistance model has a different set of resistance values (Table 1). The value of resistance added to a cell can be understood as the cost of moving through the cells (i.e., risk of mortality or difficulty). Native fragments were considered areas of low resistance and were assigned a value of 1, while other elements of soil cover, such as open areas, pastures, and urban areas, received arbitrary resistance values above 50, with 100 being the maximum value.

We used the six models as an input in Linkage Mapper Tool (McRae et al., 2014) to model connections between areas based on resistance and sampled sites (the 78 study sites). The link mapper calculates the cost-weighted distance from one site to another and these values are used to generate lower cost corridors and lower cost paths (LCP). The cost-weighted distance is normalized by the LCP between the areas, producing a normalized value of the lowest cost corridor so that the cells along the LCP are equal to 1. Then, the lowest cost normalized corridors are combined to generate the network of low cost-distance corridors.

We inserted the protected areas (PA) within RDB to verify the effectiveness and relation of PA with the connectivity between fragments on the landscape scale.

2.4. Data analysis

We generated a matrix of Jaccard similarity index using the species composition of the studied forests (Fig. 1). Then, we used the similarity matrix as a proxy of the landscape connectivity assuming that the greater the similarity, the more connected the forest communities, and the lower the resistance to landscape connectivity. The proxy of the landscape connectivity was used as response variable, and the models calculated by the landscape connectivity analysis were used as explaining variables. The rationale is that the connectivity will be best explained, and best related by the most reliable models of landscape connectivity. For that analysis, we generated Generalized Linearized Models - GLM to test the relationship between the Jaccard index in pairs with the Euclidean distance in pairs and the Lowest Cost Distance in pairs obtained from each of the 6 resistances models of landscape connectivity (Thiele et al., 2018). We used quasi-binomial distribution, since the binomial models were overdispersed. We selected the best model in quasi-AIC values, where models with Δ quasiAIC $>$ 2 were considered equally explanatory (Burnham et al., 2010). All models with ΔAIC less than 2 can be considered equally explanatory, so we used the model 3 as indicated in the results section (Burnham and Anderson, 2002).

The analysis were done in R environment 3.4.3 version (R Development Core Team, 2017), where the Jaccard index was calculated with ‘vegdist’ function in ‘vegan’ package (Oksanen, 2016), the linearity of the models were tested with ‘cumres’ function in ‘gof’ package (González-Estrada and Villaseñor, 2018), the best model was assessed with ‘dredge’ function constraining the selection to models with only one predictive variable in ‘MuMIn’ package (Bartón, 2018), and the stats value of the models were tested with ‘Anova’ function of

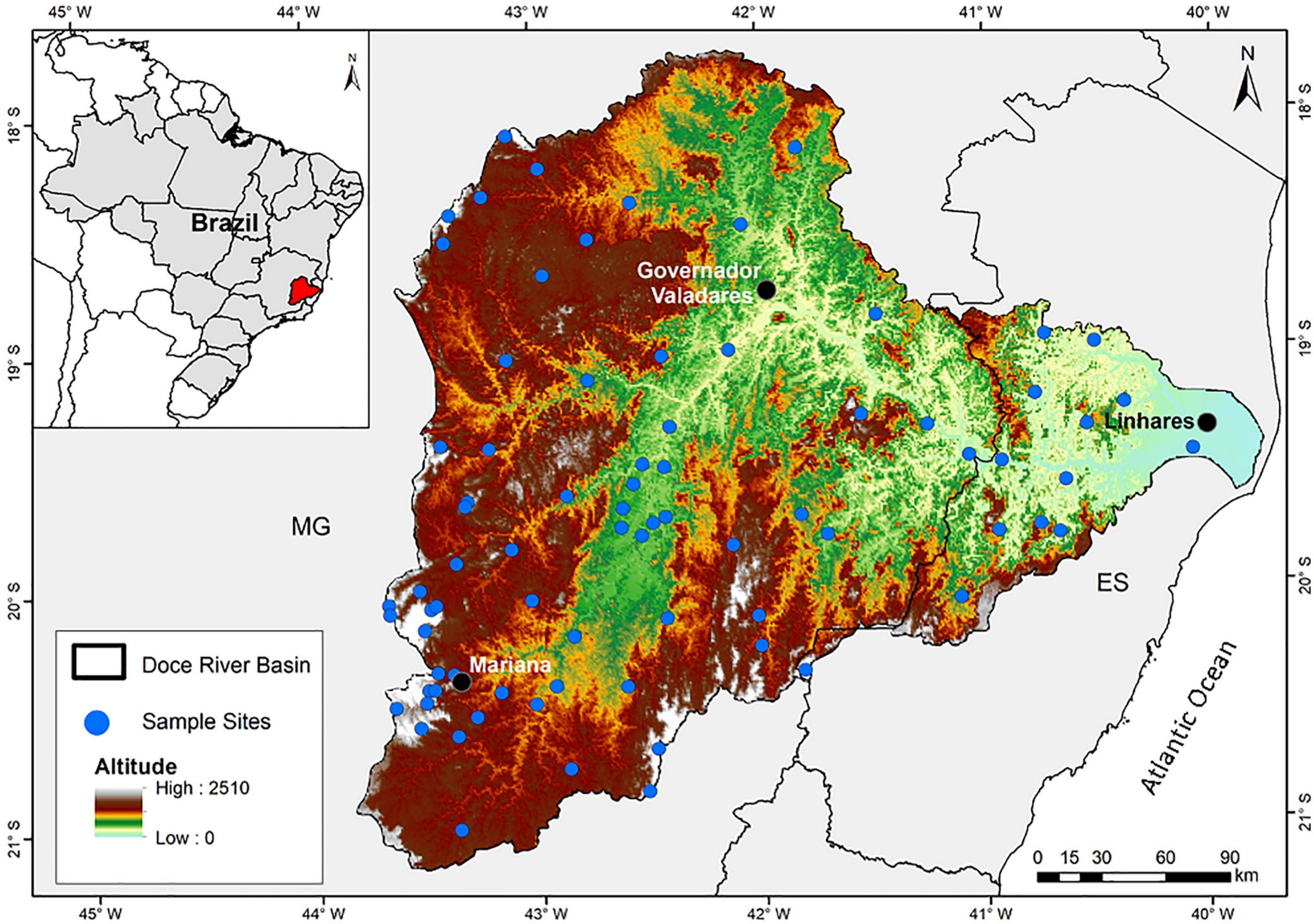

Fig. 1. Rio Doce Basin (RDB) with the 78 sample sites (blue circle); three of the main cities within RDB (black circles). In the top left corner, the RDB (red) location in South America.MG - Minas Gerais State; ES - Espirito Santo State. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

'car' package, using the argument type = II (Fox et al., 2019).

3. Results

From the six generated models (Table 1), three models were selected with ΔAIC < 2, and were considered equally explanatory with the simulated landscape connectivity provided by the Jaccard indexes. One selected model used Euclidean distance, so the shorter the distance between fragments, the lower the resistance to landscape connection (P = 2.418e-06, AIC = 0.00). Another selected model, the model 3, used land use with the native forest (forest fragments) as the least resistant and all other types of landcover as the highest resistance to landscape connection (p = 6.614e-07, quasi-ΔAIC = 1.59). The last selected model, the model 5, also used land use with forests fragments as the least resistance areas, open areas, rocky outcrops, pastures, forestry stands, agriculture areas, beaches, mining areas, urban areas, airports, and roads with increasing resistances, respectively, and ocean/water as the highest resistance areas to landscape connection (p = 7.221e-07, quasi-ΔAIC = 1.61). As all models with ΔAIC less than 2 were considered equally explanatory, we consider the model 3 the most parsimonious and simplest model for generating maps. Another strength of the chosen model is to generate paths that match to the current features of landscapes differently from the Euclidean distance model that generate paths that are less likely in natural landscapes.

The resulting land use map with the RDB's least cost paths shows that the hydrographic basin is highly fragmented, especially the areas close to the city of Governador Valadares and neighboring regions to the east, north and south (Fig. 2A). Most of the fragments are located in the west portion of RDB and promote greater landscape connectivity for tree species (Fig. 2C). The resulting set of least-cost paths provide a net of corridors connecting protected areas (Fig. 2C).

The regions that showed high levels of fragmentation and lower density of fragments showed high resistance to landscape connectivity for tree species, especially the regions of Governador Valadares and, Linhares, and the extreme southwest of the RDB (Figs. 1, 2B). Therefore, based on the map with lower cost corridors, these areas in the RDB have poor functional connectivity (Fig. 2C).

The resulting map of least cost paths shows that the areas around the Governador Valadares municipality are not connected due to the greater resistance of the matrix, resulting from anthropogenic activity (mainly pastures and agricultural areas) that caused a reduction in forest cover and density of fragments.

4. Discussion

Among the models we tested, the chosen habitat/non-habitat model to map the connectivity in the RDB worked well due the explanation of taxonomic connectivity (i.e., Jaccard similarities), due to its simplicity to apply and because allowed to identify reliable corridors and barriers across the RDB landscape. This model showed a main area with low landscape connectivity for tree species as a result of intensive land use in the Governador Valadares region. Other regions also showed large areas with medium to high resistance of landscape connectivity at the extreme east and extreme southwest RDB. For the most of the tree

Table 1
Models of Resistance created to model connectivity.

Resistance Value	EuclideanDistance	Model 1	Model 2	Model 3	Model 4	Model 5
1	–	Native forest	Native forest	Native forest	Native forest	Native forest
60	–	Open Areas, Reforestation, Pastures	Reforestation, Rock Outcrops, Pastures		Open Areas, Reforestation, Rock Outcrops, Pastures	Open Areas, Rock Outcrops, Pastures
70	–	Rock Outcrop	Open Areas	–	–	Reforestation
90	–	Agriculture areas, beaches, mining areas, urban areas, airports, roads,	Agriculture areas, beaches, mining areas, urban areas, airports, roads,	–	Agriculture areas, beaches, mining areas, urban areas, airports, roads,	Agriculture areas, beaches, mining areas, urban areas, airports, roads,
100	–	Ocean, Water	Ocean, Water	All other classifications	Ocean, Water	Ocean, Water

species, intensive land use results in hostile environments commonly found in agricultural landscapes around the world, such as arable fields and pastures, while areas suitable for dispersal and migration are rare (Thiele et al., 2018). In the Governador Valadares region, much of the forest has been converted to pasture. The extreme east RDB and the extreme southwest RDB has been converted mainly into agricultural areas, *Eucalyptus* plantations and pastures. Therefore, these regions have gone through habitat loss, which increases the distance between patches, and increases the resistance for landscape connectivity (Hanski, 1999).

Patches of native forest in the RDB are abundant in the west to northwest regions, restricted to steeper areas (Agência Nacional de Águas, 2013) due to mountainous topography. Despite, the majority of the fragments have reduced size, small patches can be important for dispersers as stepping stones to reach larger patches (Ribeiro et al., 2009). Therefore, in the western portion of the RDB there is greater probability of landscape connectivity (or less resistance to landscape connectivity). Previous studies have shown the importance of small fragments or free-standing trees in the matrix for the maintenance of landscape connectivity (Luck and Daily, 2003; Mueller et al., 2014; Matos et al., 2017). On the other hand, the susceptibility to habitat loss is higher in small patches for species with higher demand of interior habitat and little mobility (Laurance, 1990; Pfeifer et al., 2017).

The original distribution of plant species can explain the current plant species distribution in the RDB. For instance, the current diversity of plant species in grasslands in Sweden is not only a result of the current landscape connectivity but it is related to the historical landscape connectivity (Lindborg and Eriksson, 2004). The patterns of plant distribution in the past, when the RDB was well connected, is likely the explanation for the selection of the model based on Euclidean distance. However, there can be a long time lag between landscape changes and the populations demise (Eriksson and Ehrlén, 2001) reflecting the persistence of plant populations in isolated or in deteriorating environments (Lindborg and Eriksson, 2004). In addition to the original distribution of plant species, the current mosaic of native forest and other land uses also explain the current distribution of plant species. In two of the three selected models, land use explains the current species distribution in the RDB. Models based on land use produce paths for connectivity that match to the actual features of the landscape, differently from models based on similarities and distances that produce paths that are not likely in natural landscapes (Burnham and Anderson, 2002).

Land use can influence the distribution of plant species affecting the direction of seeds dispersal. Certain land uses such as roads, waterways and agricultural areas act as barriers to some dispersers preventing them to use these areas reducing the probability of dispersion (Taylor et al., 2006). For instance, northwards of Governador Valadares, there is an area that presents only one connectivity path, but there is no path southwards because of the high resistance to connection. As a consequence, important processes such as genes flow may be compromised. Another important example is the extreme southwest RDB, where there is little landscape connectivity in an area that has many springs of the Piranga River, the most important tributary of the Doce River.

Landscape connectivity has three main components: 1) patterns and behaviors of species movement; 2) structure of resource patches (size and arrangement) and 3) the matrix in between patches (Taylor et al., 2006). The first two components are not always possible to be managed properly, since the inherent behavior of the species cannot be changed and the addition of areas to the fragments is often not viable due to political, social and economic constraints. The matrix is commonly greater in area than remnants of native forest. Thus, managing the matrix may be more important than managing only fragments in order to promote landscape connectivity (Taylor et al., 2006). Despite the inherent difficulties, this may be the only remaining approach in the Governador Valadares region, in the extreme east and in the extreme southwest regions to increase habitat area and promote functional

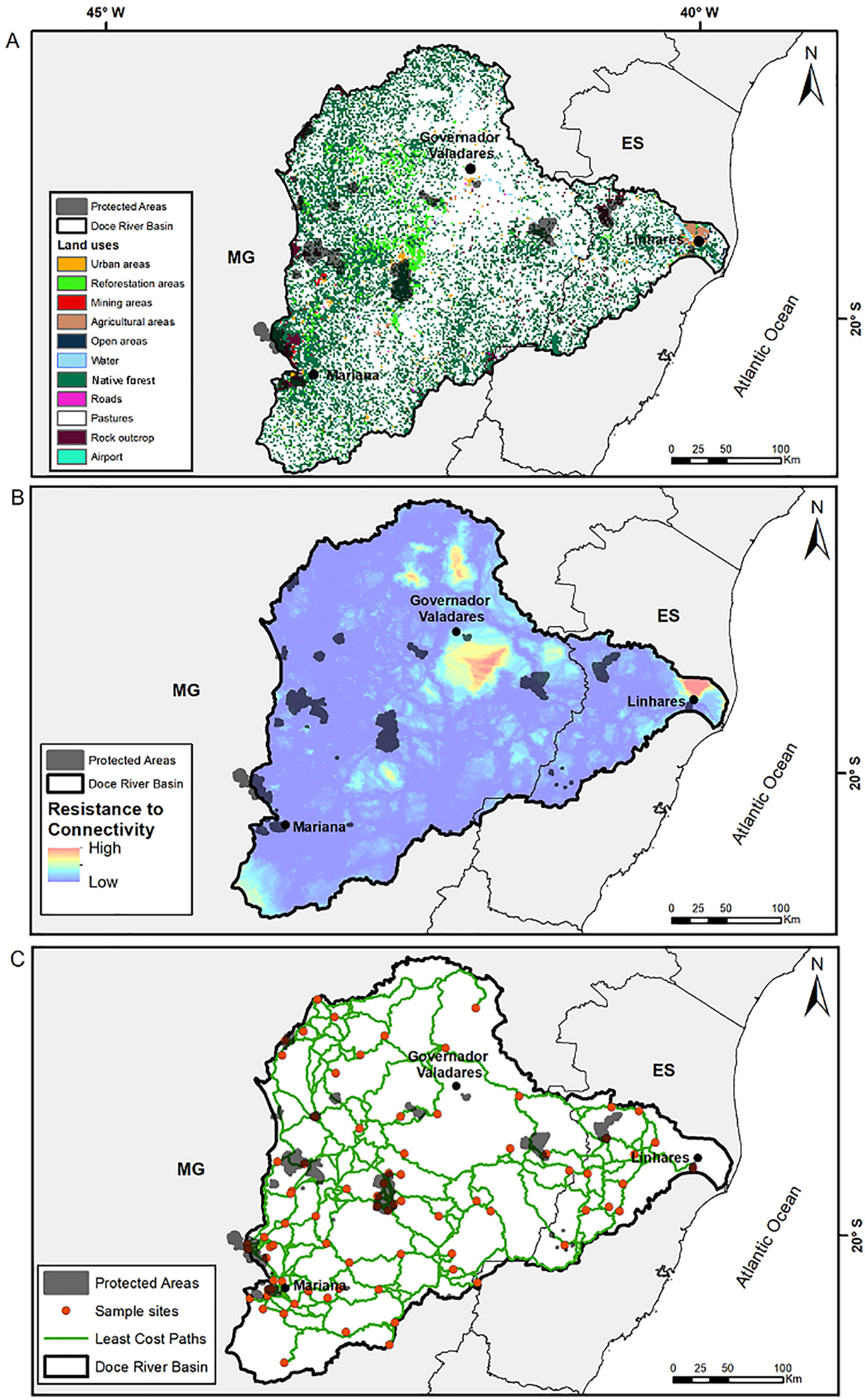

Fig. 2. Maps generated based on resistance distance. (A) Land uses of the Rio Doce Basin provided by Agência Nacional de Águas. (B) Resistance of landscape connectivity map based on the reclassification of land uses. (C) Least-Cost paths map. Black circles are the main municipalities, and red circles are the sample sites. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

connectivity. Therefore, attention must be given to these regions in order to restore landscape connectivity. Besides that the Governador Valadares region has crucial importance, the extreme east region has fragments of Atlantic Forests with very high biodiversity, endemism and a high number of endangered species (Magnago et al., 2015; Matos et al., 2017). The extreme southwest of the basin presented relatively high level of resistance and one of the greatest areas without detectable least-cost paths in an area with high precipitation (Meira-Neto et al., 2020), supplying the basin with lots of water.

Landscape connectivity for plants involves not only dispersal from source area, but also successful establishment and development in the receptor area (Auffret et al., 2017). The paths must be well connected to be functional. Thus, paths with enough area to receive propagules and to restore the functional connectivity are crucial. A path that is well connected, in turn, will receive more dispersers and will provide also more propagules (Taylor et al., 1993). On one hand, regions with high resistance for landscape connectivity and with few least-cost paths deserve a lot of attention in order to create least-cost paths suitable for tree species. On the other hand, the most important net of least-cost paths maintaining the landscape connectivity between RDB's fragments should be the priority for actions to maintain ecosystems functioning in the west to northwest portion. The actions should include prevention of clearcuttings and conservation of areas as reserves of ecosystems services that can be much cheaper, and more effective than planting (Meira et al., 2016; Meira-Neto and Neri, 2017). Moreover, the west to northwest least-cost paths connect the most of the protected areas in the RDB. The landscape connectivity is vital for protected areas, especially because Priority Areas for Biodiversity Conservation in the RDB accounts for 2,450,000 ha (or 28% of RDB area) of which only 109,000 ha (4.45% of total Priority Areas) are in Integral Protection Conservation Units (Agência Nacional de Águas, 2013). This is a very low amount of reserves, and new well-connected areas for conservation of ecosystem services must be added to existing reserves.

5. Conclusions

The results of modeling landscape connectivity using empirical data have proven to be a reliable tool explaining the current status of connectivity of remnant native forests. This method can be used for prioritizing actions conserving sites of greater connectivity or prioritize management of areas with poor connectivity. Despite the highly fragmented landscape found in the RDB, our approach allows to highlight that there is still a relatively well-connected west-northwest region functioning to ensure the persistence of tree species. Nevertheless, the central region of Governador Valadares, the regions of the extreme east and southwest of the RDB were strongly affected by habitat loss, have great resistance for landscape connectivity, and few least cost paths. Therefore, land restoration and reclamation projects in these areas should be encouraged to mitigate the lack of landscape connectivity, ensuring the persistence of plant populations, maintaining biodiversity and vital processes for ecosystems. Thus, we defend that public policies should focus on the restoration of degraded areas on landscapes with high resistance for landscape connectivity, while reinforce conservation actions of less degraded areas to preserve functioning and landscape connectivity in the RDB.

CRediT authorship contribution statement

Neil Damas Oliveira-Junior: Conceptualization, Data curation, Investigation, Writing - original draft. **Gustavo Heringer:** Conceptualization, Methodology, Formal analysis, Writing - review & editing. **Marcelo Leandro Bueno:** Data curation, Formal analysis, Writing - review & editing. **Vanessa Pontara:** Data curation, Formal analysis, Writing - review & editing. **João Augusto Alves Meira-Neto:** Conceptualization, Resources, Data curation, Writing - original draft, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

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

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2020.118247.

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