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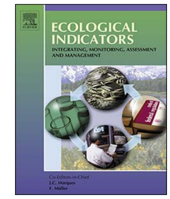

Original Articles

Delimitation of ecological corridors in the Brazilian Atlantic Forest

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ABSTRACT

The Atlantic Forest is an intensely fragmented and globally important ecological hotspot. In this context, the objective of this study was to analyze the landscape ecology and submit proposals for creating ecological corridors (ECs) in a Brazilian Atlantic Forest region. Landscape ecology metrics, based on the forest fragments map, were used for the analysis. Suggested corridors were based on least-cost path analysis, considering land use, declivity, permanent preservation areas (PPAs), and forest fragment sizes. Although the predominant class sizes in the study area are small fragments, landscape ecology analysis has shown good environmental quality for fragments larger than 100 ha that do not lose their central area, even for the largest edge distances. Four ECs were proposed, with an average length of 53.86 km, average width of 5.39 km, and average area of 28,786.32 ha. Land use conflicts showed that the fragments within the corridors were situated in a matrix dominated by grassland. PPAs within the proposed corridors were dominated by misused land and did not comply with environmental legislation. The proposed corridors were efficient in using the largest fragments, which have the least edge effect and provide necessary support for most wildlife. However, we emphasize that other factors can influence the delimiting of ECs; additional studies are required to obtain more effective ECs to connect habitats. The proposed methodology can be applied to other Brazilian and global ecoregion.

1. Introduction

The fragmentation of natural habitats is defined as a landscape-scale process involving forest loss, where the changing configuration or arrangement of forest cover (Fahrig, 2003; Long et al., 2010) is considered one of the main causes of biodiversity loss in habitats (Benítez-Malvido et al., 2016; de Albuquerque and Rueda, 2010; Gibson et al., 2013; Kupfer et al., 2006; Rodríguez-Loinaz et al., 2012). Disordered land use and occupation, current economic models, and population growth (Ribeiro et al., 2009; Tabarelli et al., 2010; Tabarelli and Gascon, 2005) drive the fragmentation process and change the floristic and structural patterns of forest communities (Augusto et al., 2000; Carvalho, et al., 2016; Sousa et al., 2017). The barriers created by fragmentation include difficult dispersal between forest fragments, reduced gene flow and genetic variability, and increasing risk of species extinction (Pelorosso et al., 2016; Tabarelli et al., 2010).

The Brazilian Atlantic Forest is a globally important ecological hotspot (Araujo et al., 2015), considered one of the most important ecoregions in the world and is a priority for biodiversity conservation (Myers et al., 2000). This forest is home to about 5% of the world's flora and 2% of endemic vascular plants (Stehmann et al., 2009); 42.5% of Brazilian mammal species, of which 30% are endemic (Paglia et al., 2012); 75.6% of endangered species and endemic birds in Brazil (Marini and Garcia, 2005); and the second largest diversity of reptiles in Brazil (Sousa et al., 2010). However, the Atlantic Forest is also one of the most fragmented ecosystems and most explored Brazilian biome (Araujo et al., 2015), which, for centuries, has endured timber exploitation, agricultural development, farms, exotic tree plantations, and

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hunting (Laurance, 2009). This ecosystem originally covered about 150 million ha and is comprised of different types of vegetation as a consequence of the fragmentation process, maintaining only 12% of its original forest cover (Ribeiro et al., 2009).

In this context, assessing the fragmentation and continuously monitoring forest areas are essential for understanding the characteristics of the landscape (Lele et al., 2008). Previous studies have analyzed the landscape ecology and structure in regions of the Atlantic Forest (da Silva et al., 2015; dos Santos Costa et al., 2016; Kauano et al., 2012; Pirovani et al., 2015; Saito et al., 2016). The Brazilian Government created and maintains Conservation Units (CUs) to protect and maintain the great remnants of natural ecosystems (Saito et al., 2016). However, CUs alone are insufficient to maintain the biodiversity of an ecosystem. (Beier and Noss, 1998). Conservation scholars have suggested regional networks of protected areas, interlinked with forest corridors, to prevent mass species loss (Lopes et al., 2009), also known as Ecological Corridors (ECs). ECs can be defined as vegetation strips linking forest fragments or CUs separated by human activity, promoting genetic flow between plant and animal communities and maintaining ecosystem functions and process (Beier and Noss, 1998; Harris and Gallagher, 1989; Harris and Scheck, 1991; Noss and Cooperrider, 1994; Noss, 1991).

According to Perkl (2016), in the anthropogenic landscapes of the Atlantic Forest, connecting fragments using ECs is extremely important to increase conservation services. ECs are considered a viable solution both for connecting fragmented ecosystems and maintaining biodiversity (Seoane et al., 2010). Law n° 9.985/2000 (Brasil, 2000) defines ECs as "portions of natural or semi-natural ecosystems, linking CUs, which enable gene flow and biota movement, facilitating species dispersal and recolonization of degraded areas, as well as maintaining populations that demand for their survival areas with greater extension than that of the individual units".

Given the importance of ECs in the context of restoring fragmented landscapes and conserving protected areas, proposals to connect these areas are needed. In particular, proposing and deploying ECs along the landscape require, first at all, identify the most important aspects of the problem. One currently available technique is the least-cost path analysis (LCP), which is implemented in most Geographic Information Systems (GIS) (Driezen et al., 2007). The LCP analysis allows decision-makers to determine the ideal way to connect two places within a cost surface. This can be accomplished by combining different criteria such as environmental impact and economic investment (Effat and Hassan, 2013). This modeling tool, derived from graph theory, is being increasingly applied to land and species management projects and research (Adriaensen et al., 2003; Effat and Hassan, 2013).

The LCP has been used in conjunction with GIS in several studies to interconnect ecosystems mainly aimed at maintaining wildlife (Adriaensen et al., 2003; Carroll and Miquelle, 2006; Driezen et al., 2007; Ferrari et al., 2012; Hoctor et al., 2000; Larkin et al., 2004; LaRue and Nielsen, 2008; Li et al., 2010; Louzada et al., 2012; Rouget et al., 2006; Schadt et al., 2002; Walker and Craighead, 1997). In this context, the objective of this study is to analyze the landscape ecology and establish proposals to create ECs for a region in the Atlantic Forest in Brazil. In particular, we focus on interconnecting the Caparaó National Park, a priority area for conservation, using geotechnology.

2. Material and methods

2.1. Study area

The study area covers the Caparaó National Park (Parna Caparaó) and an additional priority area for establishing ECs located approximately 60 km from Parna Caparaó, the Saíra Apunhalada (IEMA, 2006) (Fig. 1). The Parna Caparaó is located between the states of Minas Gerais and Espírito Santo, southeast Brazil, occupying an area of 317.61 km^2 (ICMBio, 2016), centered around the geographical coordinates 41°47′11″ S, 20°26′46″ W. The Saíra Apunhalada covers an area 373.18 km2, located in southern Espírito Santo, centered around the coordinates 41°16′14″ S, 20°15′38″ W.

According to the Köppen classification, the predominant climate in the region is of a subtropical altitude variety (Cwb), characterized by dry winters and mild summers (Oliveira et al., 2008). The study area is primarily in the Atlantic Forest, with formations of dense ombrophylous forest and seasonal semi-deciduous forest, and altitude fields in Parna Caparaó (Brasil, 2008). The region has an annual mean temperature of 18.9 °C and a mean precipitation of 1390 mm. The topography is characterized by fairly rugged relief, interspersed with reduced flat areas (Oliveira et al., 2008).

2.2. Landscape ecology analysis

The analysis of the dynamics of landscape ecology was conducted using the following methodological steps:

2.2.1. Step 1. Spatial database

Images acquired by the Landsat-8 OLI satellite, all processing and analyses were performed in the software ArcGis® *10.3.1* (ESRI, 2015). The study area was delimited using as the vector files (*shapefile*) database for Parna Caparaó and Saíra Apunhalada, available from the Chico Mendes Institute for Biodiversity Conservation (ICMBio, 2016) and State Institute of Environment and Water Resources (IEMA, 2016). A 10 km buffer zone from the boundary of each area was applied, and then the files were edited to delimit the study area.

2.2.2. Step 2. Classification of land use and cover

The land use and cover map of the study area was developed using the algorithm *Segment Mean Shift* for unsupervised classification, which identifies the segments in the image by grouping pixels with similar characteristics (ESRI, 2015). The image classified in raster format was converted to a shapefile (vector), and then the land use and cover map was trimmed (*clipped*) to the boundaries of the study area.

2.2.3. Step 3. Landscape ecology analysis

The polygons of forest fragments were selected from the land use and cover map, and a shapefile file of the forest fragments was extracted. The fragments were classified according to their size in the following classes: a) very small (< 5 ha), b) small (5–10 ha), c) medium (10–100 ha), and d) large (> 100 ha). The forest landscape was analyzed using landscape ecology metrics in the software Fragstats®4.2 (McGarigal, 2013), based on the map of forest fragments in raster format. The metrics presented in Table 1 were selected to quantify landscape elements.

The class area (CA) was calculated by size class, the area of all forest fragments of each class, corresponding the total area of the fragments present in the landscape, as well as the total edge (TE) is the sum of the lengths of all edge segments involving the corresponding patch type and edge density (ED) is the TE divided by the total landscape area. The number of patches (NP) measures the number of fragments for each type of land use and cover, indicating their fragmentation. The mean patch area (AREA_MN) is the calculation of the mean area of all fragments.

Total core area (TCA) is the sum of all core areas, which are defined as the area within a fragment separated from the border by a predefined distance. Number of disjunct core areas (NDCA) is the sum of the number of disjunct core areas contained within each patch in the landscape. Mean core area (CORE_MN), standard deviation of core area (CORE_SD) and coefficient of variation of core area (CORE_CV) are the statistics mean, standard deviation and coefficient of variation calculated by core areas. Index area-weighted mean (CAI_AM) is the sum, across all patches in the landscape, of core area index (CAI) value multiplied by the sum of each patch area. CAI is used to calculate CAI_AM, being the patch core area divided by total patch area, in