REVISTA DO DEPARTAMENTO DE GEOGRAFIA
Universidade de São Paulo
www.revistas.usp.br/rdg - ISSN 2236-2878
V.35 (2018)
DOI: 10.11606/rdg.v35i0.137804

Detecting Stepping-Stones for Connectivity Planning in Local-Regional Scale

Detecção de Stepping-Stones para Planejamento da Conectividade na Escala Local-Regional

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Recebido (*Received*): 08/09/2017
Aceito (*Accepted*): 17/04/2018

Resumo: A detecção de habitats para o planejamento da conectividade em escala local e regional é essencial para a conservação da biodiversidade, especialmente em uma variedade de diferentes tipos de uso da terra, como na Mata Atlântica. Este artigo apresenta um modelo baseado no uso de métricas de paisagem e características do ambiente físico, com procedimentos fundamentados no AHP, uso do custo da matriz e análise espacial para a detecção de fragmentos florestais que podem atuar como stepping-stones. Essa modelagem pode ser realizada para diferentes cenários de movimentação de espécies na paisagem, e o planejamento pode ser direcionado de acordo com uma proposta de manejo em relação ao comportamento das espécies-alvo que se pretende conservar.

Palavras-Chave: Planejamento da Paisagem; Métricas da Paisagem; Método AHP; Distância de Custo; Direção do Custo.

***Abstract**: Habitat detection for local and regional connectivity planning is essential for the conservation of biodiversity, especially in a variety of different types of land use, such as in the Atlantic Forest. This article presents a model based on the use of landscape metrics and features of the physical environment, with procedures based on AHP, use of matrix cost and spatial analysis for the selection of forest fragments that can act as stepping stones. This modeling can be performed for different scenarios of species movement in the landscape, and the planning can be directed according to a management proposal in relation to the behavior of the target species to be conserved.*

***KeyWords**: Landscape planning; Landscape metrics; AHP method; Cost distance; Cost direction.*

1. Introduction

Landscape planning is the key planning instrument for nature conservation and landscape management (BfN, 2002). The aim of landscape planning is a development concept which includes all the space, and considers the other aspects of land use (LANG and BLASCHKE, 2009).

Most areas in tropical regions do not have an integrated plan of protected areas implemented by public or private agents. Thus, the detection of habitat patches for planning connectivity in a local-regional scale is an important strategy for sustainability and the conservation of biodiversity. This selection of habitat patches is even more relevant in highly fragmented tropical environments with such diversified uses as has the Atlantic Forest. Atlantic Forest is a biodiversity hotspots (MITTERMEIER *et al.*, 2011) that is threatened in Brazil due to the agricultural and urban areas expansion (MORAES *et al.*, 2017), and its original cover has been reduced to 89% approximately (RIBEIRO *et al.*, 2009). In this Biome a connectivity network should be incorporated into local-regional conservation plans, particularly in regions where there are no protected areas that create an effective network connectivity and in places where human activities have been consolidated.

Structural connectivity (spatial arrangement of habitat patches) can be used to infer functional connectivity (inter-patch movement intensity of the organisms). The displacement of species will depend on whether the species needs a corridor to get from one habitat to another, whether the species is able to cross the matrix, or if the species makes use of stepping-stones (METZGER, 1999). In regions where the matrix is composed principally of consolidated human activities (e.g. urban and agricultural areas) the stepping-stones have an important role in inter-patch connectivity. Habitat patches need not be physically connected by contiguous habitat in order for organisms to move among them. A species may be capable of crossing habitat gaps, or the matrix separating patches, and thus functionally connect areas that are not structurally connected (VOGT *et al.*, 2009).

Small natural-vegetation patches serve as stepping-stones for species dispersal or recolonization, protect scattered rare species or small habitats, provide heterogeneity in the matrix, and habitat for an occasional small-patch-restricted species. In effect, small patches provide different benefits than large patches, and should be thought of as a supplement to, but not a replacement for, large patches (FORMAN, 1995). However, there are studies that show the role of trees outside forest environments can act as ecological trampolines, and in agricultural landscapes these trees can have a positive effect on species richness, bringing benefits to fragmented landscapes (HENRY *et al.* 2017; ROSSI *et al.*, 2016; FISCHER *et al.*, 2010).

An example of the importance of stepping-stones in fragmented tropical environments was described in Boscolo *et al.* (2008). The authors concluded that the implementation of stepping-stones in the open matrix may enhance the functional connectivity for Lesser Woodcreepers (*Xiphorhynchus fuscus*) in the Atlantic Forest and can contribute to its conservation in sparsely forested landscapes.

It is noteworthy that many regions in tropical environments have no systematic data about biodiversity. In addition, most local-regional governments lack the financial and human resources to carry out surveys of flora and fauna. This fact leaves a knowledge gap that allows the detection of strategic areas for biodiversity conservation to be disregarded by planners of landscapes in a local-regional scale.

An alternative to the lack of data about biodiversity is the use of landscape metrics as habitat quality indicators. Landscape-based indicators can help to identify areas of high conservation value, which can then be preserved, or to identify sites where values can be enhanced by restoration. Additionally, landscape-indicators can also indicate which strategies should be pursued to increase the value of these sites, e.g. increase connectivity, reduce edge effects (BANKS-LEITE *et al.*, 2011). These authors suggest that landscape-based indicators might often be a better, simpler, and cheaper strategy for informing decisions in conservation.

Opdam *et al.* (2002) highlight the importance of developing an approach for generalizing and aggregating ecological knowledge for application in spatial, and emphasize the need for development modeling studies to produce guidelines and general rules and tools for integration to the landscape level, so that application in multidisciplinary landscape studies becomes possible.

In this context, this paper aims to present a stepping-stones detection model for planning connectivity on a local-regional scale. To this end, we carry out these steps: (i) selection of habitat patches for planning connectivity using an indicator based on landscape metrics and physical environmental characteristics; (ii) organization of raster images to create a Landscape Resistance Matrix; (iii) generation of the Cost Distance Matrix and Direction Cost Matrix; (iv) best path definition; (v) stepping-stones detection. Thus, we model the spatial arrangement of habitat patches in order to plan the inter-patch connectivity and to assess the potential landscape for functional connectivity.

2. Selection of Habitats Patches

As a first step in the planning of connectivity inter-patches, a selection of rainforest habitats was carried out. The habitat patches was taken from layer land use, which was mapped by manual vectorization and photo-interpretation techniques from seven orthophotos with a spatial resolution of 1 meter. In order to make a qualified selection of the patches, an indicator (indicator patches) was created composed of data of landscape metrics (LANG and BLASCHKE, 2009), combined with the physical environmental parameters (**Table 1**).

For this patches indicator to be adjusted to habitat characteristics, a differentiated measurement was carried out for each of the themes and their variables. We understand that the themes do not contribute linearly to the selection of patches, but instead, they contribute in varying degrees of importance.

In order to determine this differential contribution, the method of Hierarchical Analytical Process (AHP) (SAATY, 1987) was adopted to make the calculations of varying degrees of importance of the issues and variables that make up the indicator. In applying the AHP method it is necessary to establish a hierarchy of importance measuring the degrees of contribution of the topics and variables in the indicator (SAATY, 1987). To this end, the topics and variables were assessed through consultations with experts, and then the hierarchical importance of each of the topics and variables was determined (**Figure 1**).

Based on this hierarchy of importance, the weight for each respective topic and variable was calculated using the prerogatives of AHP (**Table 2**).

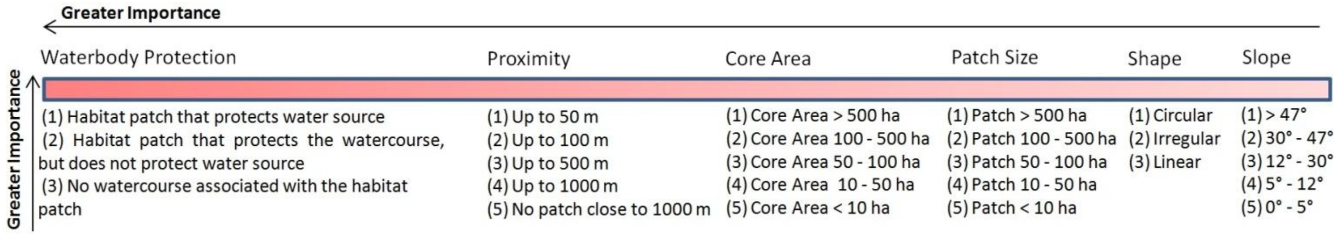


Figure 1: Hierarchy of themes and variables determined for the classification of habitats in relation to their importance for the planning of connectivity.

Table 1: Landscape metrics and characteristics of the physical environmental selected to comprise the indicator for selecting the habitats of greatest interest to the planning of connectivity.

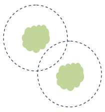
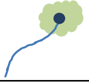
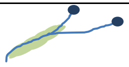
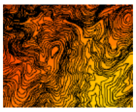
Theme		**Variable**	**Application**
Landscape metrics of habitat fragments selection			
Proximity		Up to 50 meters Up to 100 meters Up to 500 meters Up to 100 meters No patch close to 1000 meters	$PX = \sum_{i=1}^{n} \frac{S_i}{d_i}$ S= size; d = distance
Size of Core Area		Core Area > 500 ha Core Area 100 - 500 ha Core Area 50 - 100 ha Core Area 10 - 50 ha Core Area < 10 ha	$CORE = a_{ij}^{c} \left(\frac{1}{10000}\right)$ $a_{ij}^{c} = core\ area\ (m^2) of\ patch\ ij$ $based\ on\ specified\ edge\ deppths\ (m)$
Patch Size		Patch> 500 ha Patch 100 - 500 ha Patch 50 - 100 ha Patch 10 - 50 ha Patch < 10 ha	$AREA = a_{ij} \left(\frac{1}{10000}\right)$ $a_{ij} = area\ (m^2) of\ patch\ ij$
Shape of Habitat Patch		Circular Irregular Linear	$SHAPE = \frac{p}{2\sqrt{\pi . s}}$ p = perimeter; s = size
Characteristics of the physical environment for habitat patches selection			
Watershed protection		Habitat patch that protects water source	*GIS Application* Selection attributed by location
		Habitat patch that protects the watercourse, but does not protect water source	
		No watercourse associated with the habitat patch	
Land slope		> 47° 30° - 47° 12° - 30° 5° - 12° 0° - 5°	*GIS Application* Slope

Table 2: Weights were derived from the Analytic Hierarchy Process (AHP) for each theme and its respective variables.

THEME	AHP THEME	VARIABLE	AHP VARIABLE
Watershed protection	**0.316**	Habitat patch that protects water source	0.669
		Habitat patch that protects the watercourse, but does not protect water source	0.243
		No watercourse associated with the habitat patch	0.088
Proximity	**0.214**	Up to 50 meters	0.429
		Up to 100 meters	0.267
		Up to 500 meters	0.171
		Up to 1000 meters	0.086
		No patch near 1000 m	0.046
Core Area	**0.139**	> 500 ha	0.426
		100 - 500 ha	0.259
		50 - 100 ha	0.159
		10 - 50 ha	0.097
		< 10 ha	0.059
Patch Size	**0.101**	> 500 ha	0.416
		100 - 500 ha	0.262
		50 - 100 ha	0.161
		10 - 50 ha	0.099
		< 10 ha	0.062
Patch Shape	**0.092**	Circular	0.581
		Irregular	0.309
		Linear	0.110
Land slope	**0.027**	> 47°	0.502
		30° - 47°	0.254
		12° - 30°	0.119
		5° - 12°	0.076
		0° - 5°	0.049

In order to standardize an index for each variable was created. The value of each index is equal to the quotient of: the difference between the observed value and the minimum possible limits; and the difference between the maximum and minimum possible limits (Martines *et al.*, 2017) **(1)**.

Normalization of $\text{indices}_{ij} = (v_{ij} - v_{i.min}) / (v_{i.max} - v_{i.min})$ **(1)**

Where:
v_{ij} = value of the indicator l of variable j;
$v_{i.min}$ = minimum indicator value i among all variable values;
$v_{i.max}$ = maximum value of l indicator i among all variable values;

With the normalized values it was possible to calculate the equation for the category indicator for each of the patches **(2)**:

Patches Indicator = $\sum\{(i)(Var * (j)\}$ **(2)**

Where:
i = AHP weight value related to the theme;
Var = value theme normalized variant;
j = value of AHP weight of the variable.

By calculating the indicator it was possible to determine which were the most significant patches for planning connectivity. In this study we selected three of the most significant patches to apply the model for detection of stepping-stones.

3. Model of Stepping-Stones Detection

3.1. Organization of Raster Images

To obtain the landscape resistance matrix (**Figure 2A**) a raster image of land use with a spatial resolution of 10 m was generated. With this raster image the pixels were classified for each land use (14 different land uses were determined - **Figure 2A**) with the grading of 1-100 (**Figure 2A**) in relation to landscape resistance, considering the barriers (high landscape resistance - 100) and sites that can facilitate the movement of fauna inter-patches (low resistance landscape - 1). We applied the AHP method for weighting the data of the land use matrix by their respective cost notes (SAATY, 1977). Upon completion of the hierarchy of raster image costs of land use, the images of distance and direction of cost were prepared.

3.2. Cost Distance Matrix and Cost Direction Matrix

Functional connectivity plays an important role in Landscape Ecology, considering the interval spaces inter-patch. Functional connectivity can be modeled through explicit consideration of the resistance landscape. The key role of the GIS analysis, therefore, is to calculate the plan of costs (LANG and BLASCHKE, 2009).

The cost functions are similar to the Euclidean model but rather than calculating the true distance from one point to another, these functions determine the smallest weighted distance of each pixel from the source pixel, i.e., the cost of distance represented as the costs accumulated as the pixel moves away from the origin (LOUZADA *et al.*, 2010).

To determine the distance of inter-patch cost, calculations were carried out based on the lowest values obtained for the classes of pixels specified in the Landscape Resistance Matrix. Thus, the calculation of the Pixel Distance Cost - PDC - (**Figure 2B**) begins in the pixels comprising the habitat of interest in the Landscape Resistance Matrix (e.g. pixel 51). Based on this pixel value we calculated the cost of distance values of other surrounding pixels (e.g. pixels 41, 52, 42). The pixel 42 has the smallest value resulting from calculations carried out from the corresponding habitat pixel of interest (pixel 51), thereby becoming the source for obtaining the distance values of the following pixels cost. That is, the calculations for the other pixels in the matrix always have as their origin the lower adjacent pixel value, determined by the formulas shown in Figure 2B (LOUZADA *et al.*, 2010).

To elaborate the cost of direction matrix (**Figure 2C**) each pixel of the Landscape Resistance Matrix received the direction code of the next pixel minimum cost, i.e., the cost of direction determines the path to the position of lower cost back to origin (LOUZADA *et al.*, 2010).

3.3. Best Path Definition

For this step we determined the best path for wildlife movement due to lower matrix resistance. To do this, we used the cost of distance and cost direction matrices to combine the shortest distance data cost with the best direction effective path (**Figure 2D**). The full path is the lowest sum of the values of the inter-patch pixels (LOUZADA *et al.*, 2010).

3.4. Stepping-Stones Detection

The best path was digitized and overlaid with the layer of land use for selecting features of the habitat class. This selection was carried out by considering the spatial relationship between sections of the layers to better path and habitat inter-patch. The detection of the stepping-stones (**Figure 2E**) occurred in places where the target layer characteristics (best path) intersect with the source resource layer (class habitats). This spatial analysis enabled the detection of potential patches for planning the functional connectivity through stepping-stones.

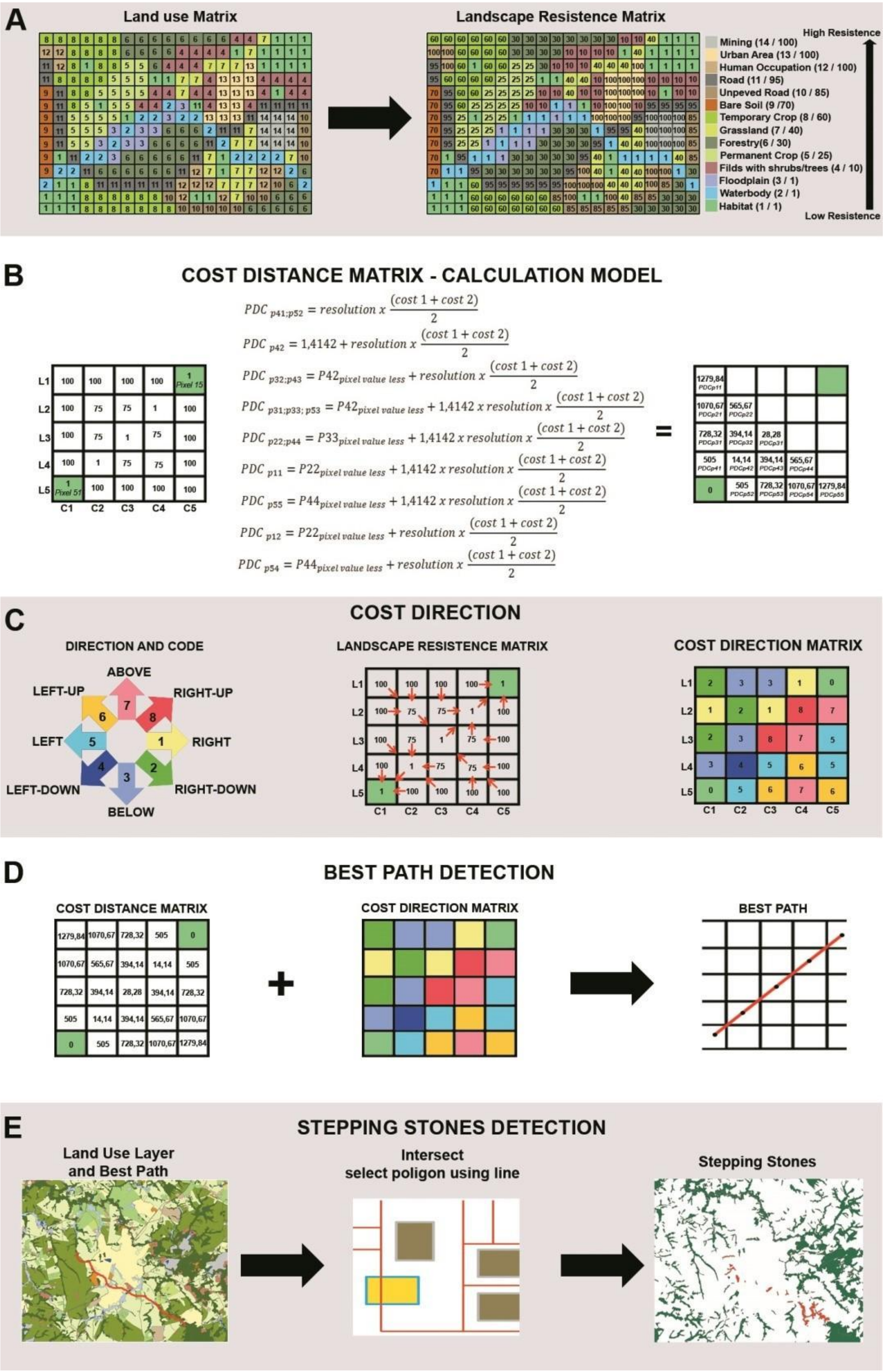


Figure 2: (A) Example of the spatial arrangement of different land uses and their respective cost values to compose the Landscape Resistance Matrix (land uses shown in the legend were mapped for the realization of this model); (B) Calculation model for the development of the Cost Distance Matrix (PDC - Pixel Cost Distance; Resolution 10 m) - the details of the application of the formulas can be found at Louzada *et al.* (2010); (C) Representation scheme for the preparation of Cost Management Matrix; (D) Representation scheme to define the best path inter-patch; (E) Representation scheme for selecting the stepping stones associated with better inter-patch path. The A-D schemes were adapted from Louzada *et al.* (2010).

4. Model Application

For the application of the model, the municipality of Salto de Pirapora in state of São Paulo, Brazil, was selected. This area has a typical pattern of Atlantic Forest area with different types of land use associated with rainforest habitat (PIRES *et al.*, 2016). In addition to the heterogeneity of the landscape, the municipality has regional importance because in a radius of 50 kilometers important protected areas are located: Carlos Botelho State Park, Jurupará State Park, Ipanema National Forest and the Environmental Protection Areas: Tietê, Itupararanga, Cabreúva, Jundiaí, Cajamar, Várzea do Rio Tietê, and a small area of the State Park of Serra do Mar.

Figure 3 demonstrates the application of the proposed model as an important aid in an analysis for the planning of connectivity. This model allowed a mapping of the connectivity of patches selected through diverse stepping-stones (**Figure 3F**). With the objective of submitting the model to a planning scenario, a proposal was prepared for movement of species with a distance of 100 m between the stepping-stones (**Figure 3G**). Despite the use of 100 m as an example of fauna dispersion threshold for the application of the model, many mammals and birds occurring in the Atlantic Forest have this potential of displacement in the matrix (CROUZEILLES *et al.*, 2010).

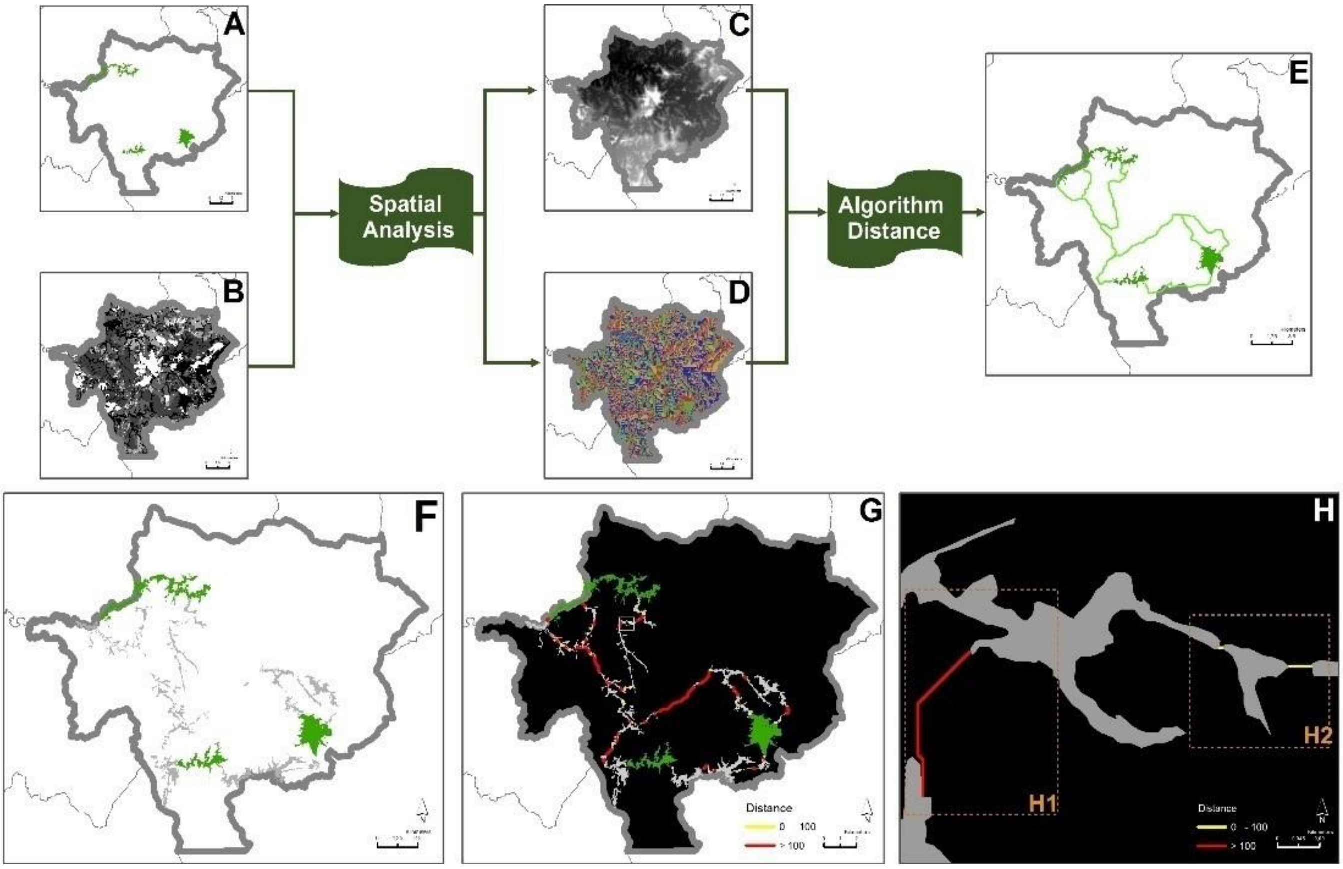


Figure 3: (A) Habitats selected through indicator patches; (B) Landscape Resistance Matrix, defined by the costs of the permeability of land uses; (C) Cost distance matrix; (D) Direction matrix; (E) Defining the best path inter-patches; (F) Distribution of stepping-stones detected; (G, H) Simulation of fauna moving a threshold distance of 100 m (Red lines - distances greater than 100 meters; yellow lines - distances up to 100 m).

As a demonstration of the results obtained, we selected two scenarios (**Figure 3H**). These scenarios reveal how the detected stepping-stones are arranged in the landscape in function of the displacement simulation of proposed species. In Figure 3 (H1), habitats do not have an effective spatial arrangement for functional connectivity, indicating a probable insulation for the species with the threshold displacement of 100 m. In **Figure 3** (H2) habitats have a spatial arrangement for functional connectivity.

According Fahrig (2003) as habitat is lost, inter-patch distances tend to increase. This may reduce habitat connectivity, and, as populations and communities become increasingly isolated, the likelihood of dispersal between them decreases (HANSKI, 1999). The idea of connectivity through stepping-stones as an alternative to the conservation of fragmented tropical forest, is in accordance with the view that connectivity in ecology is traditionally defined as how the movement of various ecological units or entities is facilitated by their surroundings. Connectivity is therefore important for understanding and managing ecological systems, and the relationships between individuals, populations, and communities with the surrounding habitats, landscapes, and regions which they inhabit (TAYLOR *et al*., 1993; LEIBOLD *et al*., 2004). Thus, the model proposes that the detection of stepping stones by means of the selection of inter-patches associated with land uses with the lowest cost of resistance, can enable the generation of distance simulations in an approach to multiple species allowing the evaluation of various connectivity scenarios, supporting the actions of planning and environmental management to facilitate the movement of organisms in the matrix.

5. Conclusion

The methodological approach allowed selecting habitat patches of greater interest to establish strategies for the biodiversity conservation. The definition of these patches was the first step for the application of the model to detect potential stepping stones in the landscape. The spatial analysis allowed defining the best path that overlaps forest remnants that could contribute to the connectivity planning among this selected habitat patches.

This modeling can be performed for different scenarios of movement of species in the landscape, and planning can be directed according to a management proposal in relation to the behavior of the target species that are intended to be preserved. Therefore, this is a proposal of spatial analysis that assists decision making for landscape planning in a local-regional scale to provide more efficient management and conservation of the fragmented tropical forest structures by means of detecting stepping stones and also considering their effectiveness for the connectivity of patches.

In addition, we understand that this analysis will allow defining the forest patches of greater interest to carry out field surveys, mainly to evaluate the ecological characteristics of possible stepping stones. This will allow the implementation of specific management actions for the effectiveness of the connectivity planning process for biodiversity.

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