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# Computational geometry applied to develop new metrics of road and edge effects and their performance to understand the distribution of small mammals in an Atlantic forest landscape

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ABSTRACT

Roads negatively affect many vertebrate species, whereas edge effect may favor some generalist species. This study aims to: 1) present a new way to calculate "line integral effects", represented by LIE and AVLIE, through new computer software, making this concept accessible to a broad audience of researchers interested in the study of Road Ecology and Tropical Forest Ecology; and, 2) test the performance of LIE and AVLIE indices, applied to road effect (LIE_road and AVLIE_road) and to edge effect (LIE_edge and AVLIE_edge), other road effect indices and forest area, using a data set on small mammal abundance in a human modified landscape in the Brazilian Atlantic Forest. Road and edge effects were represented by new metrics: Line Integral Effect (LIE) and Average Integral Effect (AVLIE), calculated using Line Integral from Differential Calculus of Several Variables through new free software developed by the second author. LIE_road and LIE_edge measure the total sum of the effect of roads (represented by lines) and edges (polygons), respectively, in relation to the forest fragment (point). AVLIE_road and AVLIE_edge measure the average of road and edge effect, respectively, in relation to the same sampling point. We used generalized linear regression models to explore the relationships between the abundance of the two groups of small mammals (forest specialists and habitat generalists) and the independent variables representing road, edge and forest effects. For forest specialists, the best model included AVLIE_road (negatively associated with abundance) and AVLIE_edge (negatively associated), while for habitat generalists, the best model included AVLIE_road (negatively associated) and LIE_edge (positively associated). Thus, there are more small mammals where road effect is lower. Forest fragments with higher edge effect showed more habitat generalists and less forest specialists. LIE and AVLIE could be useful metrics to explore edge effect separately to road effect on wildlife in forest fragments.

## 1. Introduction

Line integral effect has been used in Freitas et al. (2012) and Malcolm (1994) to study road effect (Laurance et al., 2009) and edge effect (Murcia, 1995) respectively. It is defined as $\int_c g(s,p)dl$ where $C$ is a curve in $\mathbb{R}^2$ that can model a road or edge of region and $g: \mathbb{R}^4 \to \mathbb{R}$ is a function so that $g(s,p)$ measures the effect of a point $s \in C$ over a fixed point $p$ in the studied region. Roughly speaking LIE($p$) is approximated by a sum of these effects multiplied by the length of parts of $C$.

The challenge in using a line integral effects index in a systematic way is the issue of how to best integrate along so many curves that appear to naturally model roads and edges. In Freitas et al. (2012), these issues were approached through a simple numerical process that would allow us to approximate the desired integral by a finite sum. This numerical process (that has a controllable numerical error) requires some work from the user. More precisely users must chose which curves they want to integrate and which would make less sense from a biologist point of view. They also have to collect length of roads in different discs (buffers) using GIS, making some calculations. All these steps in the numerical process require some time of the user, and some understanding of the process itself and therefore the user could make mistakes and introduce errors during the calculations. It was clearly desirable to have an automatic way to calculate this index with the least work as possible, and demanding less mathematical knowledge from the user than the previous procedure (Freitas et al., 2012).

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In this paper, we have not only achieved these goals with this new method to calculate LIE and AVLIE, we have also attained better performance compared not only to other road effect indices, but to the previous methods used to calculate them in Freitas et al. (2012). In addition we included the edge effect in models that were relevant to explain small mammal abundance. This software follows a more sophisticated approach. By programming with Python, it calculates the desired integrals, instead, to give an approximation. Also using visibility polygons, a concept of Computational Geometry (de Berg et al., 2008), the software chooses for the user the appropriate curves to be integrated. In summary, the new software, called "REEffects", provides indices with a better performance, saves time for users in calculating these indices, and provides a sensible systematic method to calculate them.

The aim of this work is twofold. First we present a new way to calculate "line integral effects", represented by LIE and AVLIE, through new free computer software developed by the second author, making this concept accessible to a broad audience of researchers interested in studying Road Ecology and Tropical Forest Ecology. Second we test the performance of these two new indices, LIE and AVLIE, applied to road effect (LIE_road and AVLIE_road) and to edge effect (LIE_edge and AVLIE_edge), compared to other road effect indices and forest area, using a data set on small mammal abundance in a human modified landscape in the Brazilian Atlantic Forest.

## 2. Materials, methods and calculations

### 2.1. A model of road effect

#### 2.1.1. Line integral effect (LIE) and average integral effect (AVLIE)

In this section, we review the concept of the function *"Line Integral Effect"*, presented and discussed in Freitas et al. (2012. LIE is defined using a line integral of a function $g_p$. The function $g_p$ will be defined using function $h$. As pointed out at the end of this section, function $h$ that we consider in this work and in Freitas et al. (2012) is defined with a forest function $F$ regarding data from our region.

Let $C$ be a combination of connected curves $C_i$ that models the roads or edge in the studied area. Consider p= $(p_1, p_2) \in \mathbb{R}^2$ a point in the forest. In what follows we will define Line Integral Effect of $C$ at point $p$ as the line integral of a function $g_p$ along $C$.

Let $g: \mathbb{R}^2 \; x \; \mathbb{R}^2 \to \mathbb{R}$ be a function, so that $g(\text{p,s})$ measures the effect of point s= $(s_1,s_2) \in C$ on the fixed point $p$. For example, it could measure how point $s$ on the road affects the forest density at point $p$. We will denote $g_p(s)$ as $g_p(s)$: =g(p,s) and this function will be called the *infinitesimal effect*.

We want to sum the effect of different points $s \in C$ on $p$. Let us start by considering a simple case. Assume that $C$ is a union of curves $C_i$ such that function $g_p$ is constant in each curve $C_i$, i.e., that all point $s$ in $C_i$ have the same infinitesimal effect. In this case we can define LIE($p$) as the finite sum $\sum g_p(s(i))L_i$ where $s(i)$ is some point in the curve $C_i$ and $L_i$ is the length of $C_i$.

Now we consider the general case where $g_p$ is not constant in pieces of $C$. We know from Differential Calculus that the *line integral of $g_p$ along a curve $C$* is a number that can be approximated by finite sums $\sum g_p(s(i))L_i$ when we consider an appropriate partition of $C$ by small pieces $C_i$; for more details about *Line Integral*, see Stewart (2000), chapter 13, section 13.2 Line integral; for a visual representation of line integral see also see Section 2.1.1 in Freitas et al. (2012). Therefore, the previous discussion motivates us to define the function *Line Integral Effect.*

LIE:$U \subset \mathbb{R}^2 \to \mathbb{R}$ as the next line integral:

$$\text{LIE}(p) = \int_c g_p \text{dl} \tag{1}$$

Where

$$g_p(s) = \text{h}(\sqrt{(p_1 - s_1)^2 + (p_2 - s_2)^2}) \tag{2}$$

if $s$ is contained in the disk $D$ of center $p$ and a fixed maximal radius $R_{\max}$, e.g., $R_{\max} = 1{,}000m$, because up to 1 km, road effect is more relevant to wildlife (Forman et al., 2003). Also note that the domain $U$ of the integral road effect LIE does not contain points of $C$, that is $p \notin C$.

Now that we have the function LIE we can define AVLIE as the average value of a function $g_p$ along a curve $C$, AVLIE($p$) = $\frac{\text{LIE}(p)}{L(C)}$ i.e., as where $L(C)$ is the length of $C$; see Section 2.1.3 in Freitas et al. (2012) for a discussion of the meaning of average value and integral lines.

Once we have defined LIE as line integral, it is natural to ask how to calculate this integral. Recall that if $C$ is a curve that is an image of a smooth parameterization $\alpha$: [a,b] $\to \mathbb{R}^2$ defined as $\alpha(t) = (x(t), \text{y}(t))$, then the line integral can be calculated, in fact defined, as below; see Stewart (2000), chapter 13, Section 13.2 Line integral:

$$\int_C g_p \text{dl} = \int_a^b g_p((x(t), \text{y}(t)))\sqrt{\left(\frac{\text{dx}}{\text{dt}}\right)^2 + \left(\frac{\text{dy}}{\text{dt}}\right)^2}\text{dt}$$

In Freitas et al. (2012), we calculate the integral above using a numerical algorithm that gives a fair approximation of the integral with an estimated error.

Here in this paper we follow a completely different approach. Roughly speaking, we do not use the output of GIS (length of the curves, radius of discs, etc.) to start to deal with the integration. Instead the roads and edges $C$ are read as a union of large numbers of straight lines $C_i$. Then, by programming with Python, the integral is explicitly calculated in each straight line segment $C_i$. Also using a ***visibility polygon,*** a concept of Computational Geometry (de Berg et al., 2008), the new software chose the appropriate curves to be integrated, providing standardization in the calculations. In the next section we briefly explain how the software, called "REEffects", works in several steps.

We conclude this section with a brief review of the function $h$. As explained in Freitas et al. (2012), we assume that there is more forest far from roads and thus we calculate a linear regression using forest and road data from São Paulo State (Sousa et al., 2009) resulting in a linear equation, called forest function, with constants A and B. In particular, the values of A and B depend on the studied region; see Section 2.1.4 of Freitas et al. (2012) for more details about $F$ and how one can calculate the constants A and B, using the R software (Hornik, 2017), through a linear regression with Gaussian distribution. Thus, we have a *forest function* $F$: $\mathbb{R} \to \mathbb{R}$ defined as $F(R) = \text{AR+B}$, for $A$: =0.057 and $B$: =16.12. Function $F$ measures how the density of forest in the region increases when the distance from roads increases. Using the assumption that LIE is inverse to $F$, we inferred that $h(R) = \text{K}/(2\pi\text{R}\cdot F(R))$ (see Section 2.1.2 in Freitas et al. (2012) for explanations about this model). In our case, we set the constant $K$ as K= 100 in order to avoid very small integrals, which are usually poorly processed by numerical programs.

#### 2.1.2. The "REEffects" software

In this section we briefly explain how the new free software developed by the second author works to calculate LIE and AVLIE. More details how to install and use REEffects Software can be found in Appendix A. The "REEffects" software is available at http://professor.ufabc.edu.br/~simone.freitas/.

Step 1: In the first step the user has to write in the script (using as example below and a text software, such as Note Pad) the path to two shape files (compatible with ArcGIS software), one containing the information about the lines (forest fragments or roads that model edges or roads respectively) and the other file containing the points$p_j$ (j=1 to$n$), which represent, in that study case, sites where small mammals were studied. The constants A and B of the forest function $h$ are also defined in the script and hence can be changed by the user. Once the user has edited the script they can run the software, for more details see the manual. The shape files are read by the GDAL library (http://gdal.org/ ). When reading edges, this library converts polygons in lines to