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A neutral model for the simulation of linear networks in territories

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ABSTRACT

A landscape matrix is the support of biotic and abiotic flows, and in that sense, requires increased interest from ecological modellers. This matrix is partly composed of linear elements, such as roads and field borders, that delimit land uses and are the result of socio-economic drivers. The geometrical properties of these elements could affect flows of water bodies, fauna, and flora. A large amount of research on landscape matrix simulation has been conducted using neutral models, but the efforts have been limited to 1 km^2 and have been principally devoted to field borders. However, simulating largest territories in neutral models requires consideration of supplementary elements, such as road networks. Furthermore, the sinuosities of the linear elements in territories have rarely been considered *per se*. We proposed a hierarchical model based on successive imbrication of deformed networks, with the deformation being realized on the basis of a reverse Douglas–Peucker algorithm. We first isolated the hierarchical levels of the landscape and analyzed their relative deformations. Then we constructed the hierarchical model and we tested it on a real territory in the Mediterranean zone. Its structural realism was tested against other common neutral models using the pattern-oriented modelling approach. The hierarchical model was the only neutral model able to represent simultaneously the variabilities of three patterns having implications in ecological processes: polyline lengths, sinuosities and polygon areas. Possible improvements of the model to address non-stationary processes and its potential for implementing geoprospective scenarios are discussed.

1. Introduction

A landscape is formed by the spatial arrangement of polygons delimited by interconnections (Turner, 1989). The interconnections are composed of linear elements, such as roads, ditches, hedgerows, lines of trees and field borders (van der Zanden et al., 2013). Several ecological processes that occur in landscapes are driven by those interconnections, especially biotic and abiotic flows (Vinatier et al., 2016). On the one hand, biotic flows can be blocked, such as the dispersal of crawling insects by steep ditches (Vinatier et al., 2010) or flying insects by scrub hedges (Purse et al., 2003). On the other hand, interconnections can act as ecological corridors for species that take advantage of the potential refugia of vegetation (Bertuzzo et al., 2007) or road networks facilities (Forman, 2003). Abiotic flows can be either blocked or accelerated by landscape interconnections, such as water flows by banks (Griffin et al., 2005) or ditches (Levavasseur et al., 2014). In addition to the properties of the interconnections, their organization in space has a strong influence on the flow. For example, the connectivities of linear elements greatly affected the migration fronts of fauna (Bertuzzo et al., 2007; Kramer-Schadt et al., 2004) or the sinuosities of successive elements affected water flow transport (Raska and Emmer, 2014). It is also of primary importance to understand the drivers affecting landscape interconnections for simulation purposes.

The drivers shaping territory structures are generally socio-economic and geomorphological. A large part of the literature has focused on the study of territory changes (Houet et al., 2010). For this purpose, researchers gathered diachronic maps of a given area to study the driving forces that shaped the land cover changes. These forces were latter incorporated into dynamic models for prediction purposes related to environmental issues. It is also possible to explore multiple change scenarios and their impacts on ecosystem services (Houet et al., 2010). It appears that driving forces affect the territory structure at a larger scale than previously encountered in landscape ecology (Houet et al., 2010). Consequently, models that consider both socio-economic forces and ecological processes necessitate to be addressed at a large scale and at fine spatial resolution.

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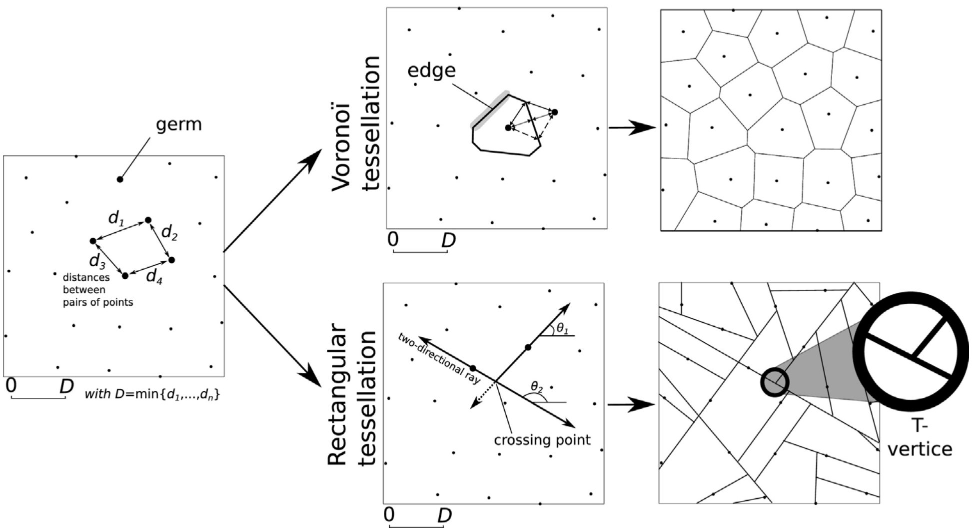

Fig. 1. Illustration of two vector-based approaches for the simulation of territory structures.

In the last decade, the simulation of territory structures has been widely studied in landscape ecology and agronomy (Adamczyk et al., 2007; Etherington, 2012; Gaucherel, 2008; Holland et al., 2007; Le Ber et al., 2009; van Strien et al., 2016). Models are generally considered as neutral, i.e. they model no explicit process giving rise to the landscape pattern (Le Ber et al., 2009). The neutral models rapidly shifted from a raster approach for which space was divided in a grid with homogeneous cells (Hargrove et al., 2002) to a vector approach for which space was divided in lines or polygons with varying shapes (Gaucherel, 2008; Le Ber et al., 2009). The vector approach appeared to be more suitable when considering the diversity of field borders. The extent of the considered area is generally restricted to a 1 km^2 window to simulate field polygons because the vector-based approaches are mainly devoted to effects of field mosaic on an ecological process, such as gene flow across agricultural landscapes (Le Ber et al., 2009). But the spatial rank of the linear elements in territories is not considered in the neutral models raised below, despite its primary importance to link ecological processes to drivers of territory changes.

When upscaling simulation models to a larger extent, i.e. several km^2, we need to include supplementary hierarchical levels such as road networks (Forman, 2003). They have ecological effects on the landscape they penetrate, affecting both biotic and abiotic components of terrestrial and aquatic ecosystems (Coffin, 2007). Roads differed from lower hierarchical levels with respect to their connectivities, their sinuosity levels, and their hierarchy (motorways, national roads, or local roads, for example, in France). To the best of our knowledge, there has been no attempt to simulate road networks because they are considered more static than field borders. Although rarely performed, the simulation of the different road networks at a large extent appears to be necessary in neutral landscape models. It is also necessary to take into account both the spatial hierarchy between the different networks shaping the landscapes and their relative sinuosities.

We propose a new approach to simulate territory structures called the hierarchical model. It provides a baseline for researchers studying spatial processes at a large extent. The main novelty of the paper is the attempt to finely parameterize the real sinuosities of territory networks at different scales.

We first expose the principles of vector-based approaches for the generation of neutral modelling, and then the principle of the deformation algorithm. Then, we define the hierarchical model and their calibration. We finally tested the hierarchical model against other vector-based approaches on a real territory covering 25 km^2 in the Mediterranean zone using the pattern-oriented modelling (POM) approach.

2. Material and methods

2.1. Presentation of vector-based approaches

The vector-based approaches are based on tessellation methods (Le Ber et al., 2009). The basic principle is to cover a surface area by polygons without gaps and overlaps. To this end, a set of points, called germs, is generated from which polygons are built. There are two different ways of creating the polygons, following Le Ber et al. (2009) and illustrated by Fig. 1. First, the Voronoï tessellation consisted in polygons for which every point of their edges is at equal distance from two germs. Secondly, the rectangular tessellation consisted in creating edges by crossing two-directional rays starting from a set of points, forming T-vertices at the intersection between edges (Fig. 1).

We defined the distance threshold D that governs the positions of the germs for both Voronoï and rectangular tessellations. We defined a supplementary parameter, θ, for the orientation angle of rays only for rectangular tessellation. By controlling D and θ, we could approximate the shapes of fields in agricultural landscapes (Le Ber et al., 2009; Gaucherel, 2008). For example, reducing D decreases the size of the fields, or having the same θ for all rays produces long and regular rectangles.

However, there is no possibility to constrain geometrical properties of the polygons' edges other than by the germs' positions and rays' orientations following the approaches described above. It is important to develop an algorithm that could simulate the deformation of linear elements with a set of parameters independent from D and θ to recapture roads or even large field borders' deformations.

2.2. Presentation of the Douglas–Peucker algorithm and its reversed form

Here are some definitions to understand the principles of this section. An endpoint is a node that connects more than two segments, and a polyline is a continuous line composed of a series of segments joining two endpoints. The points that connect exactly two segment situated at the middle of the polyline are called intermediate points (Fig. 2).