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A proposal for an integrated modelling framework to characterise habitat pattern

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A B S T R A C T

Harmonized information on habitat pattern, fragmentation and connectivity is one among the reporting needs of the biodiversity policy agenda. This paper presents a generic, reproducible and integrated characterisation of patterns into one modelling framework. Three available conceptual landscape model components are customised, revisited and partly combined to derive a set of indices organized into four families: general landscape composition, habitat morphology, edge interface and connectivity. A harmonized mathematical description is provided for known and suggested new indices. Their unambiguous and easy computability is ensured with the integrated use of publicly available software (GUIDOS free-download software, Conefor Sensinode free software) and of newly programmed tools. An edge interface tool combining morphological analysis and a moving window landscape mosaic tri-dimensional model is presented; a "Power Weighted Probability of Dispersal" (PWPD) function is proposed to make connectivity indices sensitive to the landscape resistance.

The methodology is demonstrated for the focal forest habitat, by using sixty-five in-situ based habitat maps from the EBONE project ("European Biodiversity Observation NEtwork"). Twelve indices are applied. A statistical analysis is then conducted using classical linear correlation and nonlinear Brownian Distance Correlation (Mastrave free software modelling library) as alternative to traditional dimensionality-reduction techniques and with an effort towards reusability in other contexts and reproducible research, by means of concise semantic array programming codelets. The results highlight the less correlated and fundamental pattern components, corroborating the hypothesized hierarchical organization of the indices into four families, and also the feasibility of reducing further the number of indices within each category.

Software availability

The described modelling integration entirely relies on publicly available software (Fig. 3). Key passages are implemented by means of:

- GUIDOS Toolbox. Free-download software available at: http://forest.jrc.ec.europa.eu/download/software/guidos/.
- Conefor Sensinode. Free software (released under GNU GPLv3) available at: http://www.conefor.org/.

The statistical analysis is implemented by means of:

- Mastrave modelling library. Free software (released under GNU GPLv3+): http://mastrave.org/.

The complete modelling steps are summarized in Fig. 3 where straightforward passages integrate the use of well-established GIS tools (ESRI ArcGIS or GRASS GIS) and concise array programming codelets (Mastrave within GNU Octave, Python) A non-monolithic approach led to the use of semantic array programming for expressing less trivial steps as concise data-transformations easy to reuse and adapt (available in the article and online Supplementary materials).

1. Introduction

This research is motivated by the need for a reproducible and concise characterisation of landscape patterns based on key generic

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ecological principles and integration of available approaches. Despite the plethora of landscape pattern measures available in literature, methodological guidance is still missing on how to conduct pattern assessment (Bogaert, 2003; Riitters et al., 2009) to ease and better support the (non-expert) user community in implementing policy, such as for continental reporting on habitat fragmentation and connectivity in the biodiversity policy agenda (European Commission, 2011; European Environment Agency, 2012; Convention on Biological Diversity, 2010; Forest Europe, 2011). This research used scientifically well-founded landscape ecological (inter-related) principles which exist in literature (Lindenmayer et al., 2008) and policy guidance documents for reporting on impact of fragmentation and climate change (Fischer and Lindenmayer, 2007; Kettunen et al., 2007).

The use and combination of more than one landscape conceptual measure index is strongly recommended to provide more insight for landscape conservation, yet it is rarely done (Lindenmayer et al., 2008). Indeed, no single measure can fully capture the complexity of the spatial arrangement of patches. Often, studies concentrated on measuring one component of spatial pattern, like landscape composition, spatial pattern or connectivity while such components are inextricably linked. On the other hand, the combination of multiple components of a pattern into a single value (Bogaert et al., 2000) or the reduction of the number of indices using factor analyses failed to render the ecological meaning of the designated index to the analyst (Herzog et al., 2001). Where the intrinsic multiplicity of problem dimensions appears so evident, modelling integration should avoid hiding their trade-offs, of possible relevance in the science–policy interface, and should transparently use multiple criteria (de Rigo, 2013) so as to help multifunctional analysis (O'Farrell and Anderson, 2010). Indices should be more effective in terms of their ability to capture different aspects of spatial pattern, their simplicity and their ease of interpretation (Li and Wu, 2004), regardless they are applied at large scale (Riitters et al., 2000, 2009) or at habitat scale (Wrbka et al., 2004). The indices should be organized into landscape pattern components which remain ecologically meaningful and easily understood by the user community – including non-experts. For meaningful inferences in pattern–process correlation analysis, simple measures[1] (patch size, edge, inter-patch distance, proportion) are recommended rather than with complex nonlinear indices (evenness, etc.), as well as relative and well explained range of index values (range from 0 to 1 with clear ecological meanings of the minimum and maximum values). A low redundancy of indices is further required within and across the different landscape components.

To address the integration of indices into a concise modelling frame organized into landscape pattern model components, the current study proposes to concentrate on four key pattern related principles which are listed below and for which three available landscape modelling approaches are potentially relevant. The three approaches that will be tested, revised, customised and programmed when necessary have already been proved valuable at different application scales and geographical regions.

- First, easily computable measures are required to describe a focal habitat in a given landscape in terms of its total amount, its pattern and landscape context. Habitat pattern (spatial arrangement of patches) is inextricably linked to habitat amount in assessments (Koper and Schmiegelow, 2006). Habitat pattern affects the interactions between and within species both within and between patches. The landscape context of habitats, in other terms the interstitial environment between patches or habitat matrix (Dennis et al., 2003) influences habitat content (e.g. vegetation condition).
- Second, morphological shapes of habitat play an ecological role. For example, the geometry of habitat edges (protrusions, corners) and the presence of clumps of habitat in the landscape matter for aggressive edge specialists (Taylor et al., 2008); linear strips of habitat enhance the spatial continuity in a fragmented landscape; interior areas of patches do not experience strong influences from neighbouring patches of other land cover categories (Rutledge, 2003). The mathematical morphological spatial pattern analysis (MSPA) application in the free-download software GUIDOS,[2] developed by Soille and Vogt (2009), provides automatically and unambiguously a segmentation of geometric features from any binary map. It particularly allows the detection of linear connecting pathways between patches and branches at edges as well as disconnected patches. The results are mutually exclusive morphological pattern classes ('core' and non-core as 'perforated,' 'edge,' 'islet', 'connector', and 'branch'). The software was applied for different purposes, among others in the US (Wickham et al., 2010), Europe (Mubareka et al., 2011; Clerici and Vogt, 2013) and Africa (Bucki et al., 2012). The method provides at all scales more precise spatial and thematic pattern classification than the amount-adjacency model based on image convolution from Riitters et al., 2002 (Vogt et al., 2007a,b). Because pattern classes are mapped at pixel level, it is also better suited than aggregated measures over fixed area grid as in traditional patch area and edge based measures (McGarigal et al., 2002). Furthermore, because MSPA uses geodesic distance to implement edge width and derive all non-core classes, edge widths are not rounded to the nearest distance in increments of the cell size as in traditional edge measure like in McGarigal et al., 2002. However, MSPA requires a customisation of entry parameters and outcome classes adapted to the field of application. Its main limitation is the over-simplification of the landscape in a binary model.
- Third, habitat edges are interfaces between two types of habitat. Edge effects may be positive (high biodiversity) or negative (spread of exotic species) features for a landscape. The permeability of edges influences habitat quality for interior-inhabiting species (Ries and Sisk, 2004) depending on the similarity of the adjacent habitat types (Lidicker and Peterson, 1999). The discrimination between natural/semi-natural types of interfaces and more anthropogenic ones are relevant to the edge permeability or "hardness" that is, its resistance to being crossed by focal organisms. For example, human-induced edges are more short-term "hard" landscape features such as woodland-cultivated interfaces, while natural edges are more a long-term "soft" feature (due to soil type, topography, etc.) with high structural diversity (Ries et al., 2004; Ries and Sisk, 2004). The landscape-level mosaic approach from Riitters et al. (2009) describes the landscape mosaic context of a focal land cover class and enables the mapping of edge interface zones at pixel level while other traditional edge contrast measures provide statistics at patch, class or landscape level (McGarigal et al., 2002). It was recently applied to evaluate the anthropogenic risks of grassland and forest habitat degradation from land cover maps over the United States. The model 'integrates' but is not explicit enough on the geometry of patches of a focal land cover (whether the edge is from a patch including interior habitat, a linear connecting path, a protrusion at edge of a patch) and on

[1] Mostly, non-additive measures.

[2] http://forest.jrc.ec.europa.eu/download/software/guidos.