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A multi-scale looping approach to predict spatially dynamic patterns of functional species richness in changing landscapes

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ABSTRACT

Land-use/land-cover (LU/LC) change is one of the main drivers of global biodiversity change. However, the lack of detailed data on species' local distributions is frequently a major constraint to identify effective indicators of impact and to prescribe effective conservation and management measures. Here we aim to describe and demonstrate the applicability of a novel looping approach to predict spatially dynamic ecological responses to LU/LC changes. The methodology integrates statistical downscaling, multi-model inference, stochastic-dynamic modelling and simulations, and spatial projections under a common and interactive framework. We illustrate the approach with a study of passerine foraging groups and their potential indicator role under LU/LC change scenarios. Based on the coarse occurrence data from published atlases, this approach allowed transposing species richness to fine resolutions in order to assess regional ecological integrity by up scaling the local responses of those indicators again at the landscape level. Overall, our proposed framework was able to provide realistic patterns of passerine foraging responses to LU/LC changes, highlighting the usefulness of existing databases for model-based research in addressing complex emergent problems across scales. Comparative analysis between simulations and independent field data showed a promising model performance, with consistent projections of the local passerine functional composition for a significant number of point-counts tested. Our approach represents a contribution for more universal applications in the scope of conservation and landscape planning, especially when fine resolution data is difficult to obtain due to resources constraints.

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1. Introduction

Land-use/land-cover (LU/LC) dynamics is one of the main drivers of global environmental change, which includes shifts in biodiversity composition, landscape structure and ecosystem services (Foley et al., 2005). Predicting the ecological consequences of LU/LC changes is therefore a subject of greatest scientific and political interest in order to support strategic options for sustainable development, land use planning and natural resources management (Turner et al., 2007). In this context, ecological assessment and monitoring are important tools to support effective management of ecosystems and natural resources, in which the use of pertinent indicators is crucial to measure and evaluate the status and trends of target environmental systems (Niemeijer and de Groot, 2008). In fact, some holistic ecological indicators provide useful systemic information by capturing trophic responses to land use gradients of change, both in composition and functioning terms (Carignan and Villard, 2002; Santos and Cabral, 2004). This is, for instance, the case of passerine community metrics, which exhibit several characteristics that justify their relevance as ecological indicators facing LU/LC changes, namely because: (1) they are placed at

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an intermediate functional position in the food webs (e.g. Herrando et al., 2005), (2) they provide cheap and easy measurements if standard methodologies are applied (e.g. Sutherland et al., 2004), (3) they are sensitive to landscape and climatic changes (e.g. Regos et al., 2015), (4) several species were studied intensively with regard to their natural variation (e.g. Martin et al., 2006), and (5) they have the capacity for population recovery in response to good management procedures in previously disturbed ecosystems (e.g. Perkins et al., 2011). However, the lack of data on species distribution is frequently the major constraint in using community metrics as ecological indicators at local scales, where most of the effective conservation measures often take place (Araújo et al., 2005a; Cabral et al., 2007). In this context, Atlas databases have been increasingly used to infer species distribution patterns at different spatial scales, from which downscaling techniques have been proposed to convert regional species distribution data from coarse to finer resolutions (Bombi and D'Amen, 2012; McPherson et al., 2006). Furthermore, since the model-based research can contribute with innovative tools to improve the prediction of relevant ecological responses under possible spatiotemporal changing environmental scenarios (e.g. Bastos et al., 2015), ecological modelling has been gradually required in conservation assessments, supporting the design of optimized and cost-efficient management strategies (Santos et al., 2013).

The integration of empiric, mechanistic and correlative modelling approaches, is a promising research field that enables to complement the understanding of the main drivers implicated on species distribution and therefore to assess the potential changes in habitat suitability (D'Amen et al., 2015; Santos et al., 2013). Moreover, it enables to perform simulation tests for the implementation of the most adequate management actions (Bastos et al., 2012; Franklin et al., 2013). Species Distribution Models (SDMs) have been widely applied in predicting species distributions under global change scenarios (Zimmermann et al., 2010). However, in spite of the high predictive potential at the macro-scale, the SDMs deterministic assumptions and the lack of integration with dynamic and/or stochastic processes limit their accuracy in capturing ecological responses under scenarios of more local changes (Dormann et al., 2012; Zurell et al., 2009). On the other hand, the System Dynamics ecological modelling has been developed to reproduce the structure and functioning of real-life systems in a more environmental interactive way (Jørgensen, 2008). This approach can be combined with the classical correlative techniques in a sequential model-based procedure known as Stochastic Dynamic Methodology (StDM) (Santos and Cabral, 2004). In the StDM, the cause–effect relationships between response variables and dynamic environmental predictors are holistically established based on the premise that the general statistical patterns of ecological phenomena are emergent indicia of complex processes that do indeed reflect the operation of universal law-like mechanisms (Cabral et al., 2007). Recently, the StDM has been coupled with Geographic Information Systems (GIS) in a spatially-explicit framework, providing a powerful protocol to link fine-scale local dynamic interactions to coarse-scale regional conditions, taking into account stochastic influences that characterize the real ecological processes (Bastos et al., 2012). This approach provides a step forward in order to spatially represent the ecological status of changing ecosystems, from which management strategies can be designed and tested (Santos et al., 2013).

Based on the StDM principles, here we describe and demonstrate the applicability of a novel approach to predict ecological responses to LU/LC changes by combining several statistical and modelling techniques under the same spatially-explicit dynamic framework. For demonstration purposes, our StDM framework was designed to allow the use of coarse species occurrence data from a National Atlas of breeding birds (Equipa Atlas, 2008), projecting functional trends of the local passerine species richness at finer scales. In this perspective, our underlying hypothesis was that the regional ecological integrity could be partly assessed by up-scaling those responses, assuming the role of local processes as drivers of emergent ecological patterns only perceptible at the landscape level. This is the "heart" of the multi-scale looping concept used in this StDM approach. The final goal is to demonstrate the potential applicability of the proposed framework to anticipate ecological assessments and guide regional conservation planning, highlighting the added value and modelling versatility of the existing databases from National atlases.

2. Methodology

2.1. Study area

Our approach was tested by using passerine foraging groups as potential ecological indicators of LU/LC changes within a small river catchment (263 km^2) in North Portugal. The study area coincides with a watershed located in the Minho region (northwest of Portugal), which includes the Vez river valley and the Soajo and Peneda mountains (Fig. 1). The climate exhibits a Mediterranean type of rainfall regime in lowlands, whereas in highlands the rainfall seasonality is not so sharp and thus considered more as a Temperate Atlantic with a sub-Mediterranean regime (Mesquita and Sousa, 2009). The average annual precipitation and temperature are 1500 mm/year and 13.8 °C, respectively. The topography is complex with the elevation ranging from 20 m to 1400 m above sea level, and slopes above 25% shaping 58% of the watershed. Regarding land cover, highlands are characterized by open areas of bare rock and heath, shrubland (broom) and transitional forest areas, which are mostly coincident with the Peneda-Gerês National Park, whereas agricultural and forest areas (i.e. common oak, maritime pine, and eucalyptus) are more common in lowlands (Caetano et al., 2009). Overall, this is a highly diversified and dynamic landscape that has been shaped by a marked rural abandonment and afforestation in the last decades, with anthropogenic fires playing an important role as driver of landscape change (Moreira et al., 2001a).

2.2. The framework

The proposed framework is a sequential modelling process initiated by the analysis of landscape and habitat structure at coarse-scale spatial resolution (Fig. 2a), which defines the convenient parameters that contextualize the physical and environmental descriptors to predict fine-scale species distribution. This procedure involves a downscaling technique (Fig. 2b), based on an ensemble approach of a set of regression models, which allow getting projections at the convenient grain (i.e. field sampling units and/or pixels) and spatial extent (i.e. study area) (Fig. 2c). The fine-resolution projected data, when combined with local environmental predictors and submitted to a robust information-theoretic approach based on Generalized Linear Models (GzLMs) (Fig. 2d), provides the requirements to establish the interaction criteria between the construction of the dynamic model (Fig. 2e) and the resulting stochastic dynamic simulations for each study unit (i.e. at the fine-scale resolution/grain selected). These simulations, projected into a geographic space and submitted to an appropriate geostatistical interpolation create an integrative and emergent picture of the indicators response to the gradients of LU/LC changes at the landscape level, in space and time (Fig. 2f).

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