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Very high resolution Earth Observation features for testing the direct and indirect effects of landscape structure on local habitat quality

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ABSTRACT

Modelling the empirical relationships between habitat quality and species distribution patterns is the first step to understanding human impacts on biodiversity. It is important to build on this understanding to develop a broader conceptual appreciation of the influence of surrounding landscape structure on local habitat quality, across multiple spatial scales. Traditional models which report that 'habitat amount' in the landscape is sufficient to explain patterns of biodiversity, irrespective of habitat configuration or spatial variation in habitat quality at edges, implicitly treat each unit of habitat as interchangeable and ignore the high degree of interdependence between spatial components of land-use change. Here, we test the contrasting hypothesis, that local habitat units are not interchangeable in their habitat attributes, but are instead dependent on variation in surrounding habitat structure at both patch- and landscape levels. As the statistical approaches needed to implement such hierarchical causal models are observation-intensive, we utilise very high resolution (VHR) Earth Observation (EO) images to rapidly generate fine-grained measures of habitat patch internal heterogeneities over large spatial extents. We use linear mixed-effects models to test whether these remotely-sensed proxies for habitat quality were influenced by surrounding patch or landscape structure. The results demonstrate the significant influence of surrounding patch and landscape context on local habitat quality. They further indicate that such an influence can be direct, when a landscape variable alone influences the habitat structure variable, and/or indirect when the landscape and patch attributes have a conjoined effect on the response variable. We conclude that a substantial degree of interaction among spatial configuration effects is likely to be the norm in determining the ecological consequences of habitat fragmentation, thus corroborating the notion of the spatial context dependence of habitat quality.

1. Introduction

Landscape ecology has long sought a deeper understanding of the relationships between spatial patterns of land use change (particularly the extent and configuration of land cover classes) and ecological, biophysical, or socio-economic processes, in order to strengthen ecological 'pattern to process' linkages (Nagendra et al., 2004). Thus, a substantial component of landscape ecological research has focused on quantifying 'ecologically-relevant' metrics of landscape patterning (e.g. McGarigal and McComb, 1995; Jones et al., 2000; Niemi et al., 2004; Didham, 2010), and modelling the empirical relationship between surrogate measures of habitat quality on biodiversity (Mairota et al., 2014). However, this is only the first step towards understanding the impacts of land-use change on biodiversity. In order to better predict and manage the effects of land-use change, we must also develop better conceptual models of the way in which multiple components of landscape pattern interact to influence local habitat quality, and ultimately biodiversity.

Recently, Didham et al. (2012) critiqued the traditional approach of treating multiple predictors as if they were conceptually independent in landscape models, and instead called for a shift in

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conceptual thinking towards models that explicitly deal with the interdependence among predictors at multiple hierarchical levels. These authors considered that there can be both independent effects of habitat loss on organisms, as well as effects of habitat loss that operate via their shared influence on habitat configuration, and not independently of it (Didham et al., 2012). They predominantly discussed these types of 'indirect' effects in the context of the potential mediating effects of habitat configuration, such as might be determined through structural equation modelling approaches (Didham et al., 2012). However, they did not fully elaborate on another important way in which interaction among landscape effects could be tested in hierarchical causal models. Theoretically, if habitat amount in the landscape had an independent effect on biodiversity, irrespective of habitat configuration (Fahrig, 2003), then this would imply that each unit of habitat must have equivalent relevance (e.g., suitability, probability of occupancy) for species. By contrast, from the interaction among landscape effects described in Didham et al. (2012) we would predict that individual units of habitat will vary in their influences on biodiversity, because of the moderating influences of surrounding landscape context on local habitat quality. An empirical demonstration of this effect would provide an important match between model predictions and empirical observations, which has been lacking in traditional models.

Here, we develop a hierarchical model incorporating inherent direct and/or indirect (moderating) effects of multiple components of landscape pattern on local attributes of habitat quality that might influence species distributions. As advocated by Didham et al. (2012), such statistical modelling approaches (e.g., mixed effects models, or multi-level modelling) must be capable of incorporating sources of variability derived from different hierarchical levels, and must partition the relative contributions of habitat amount and habitat configuration to the inter-correlated component of variance (Didham et al., 2012).

We test the general theoretical expectation from hierarchical causal models that there will be dependence of local habitat quality on surrounding patch and landscape context. Here we use the term habitat as defined by Bunce et al. (2008), as the tangible set of biotic and abiotic variables which define species occupancy and demography within an area. Since the data required for hierarchical causal models are observation-intensive, we show how very high resolution (VHR) Earth Observation (EO) imagery can provide a relatively rapid approach to generate large datasets of features reflecting the internal heterogeneity of habitat patch attributes. Remotely-sensed measures of local habitat structure (e.g., NDVI, texture metrics) are known to correlate well with ecologically-relevant components of 'habitat quality' (e.g., productivity, vegetation structure), as perceived by different organisms (Lindenmayer et al., 2002), and seem particularly appropriate for use in cases where field data are lacking or insufficient. VHR-EO features represent many aspects of the proximate mechanisms related to habitat quality through which species community descriptors, or biodiversity surrogates (BSs), computed from measured field data might be explained (Burgman and Lindenmayer, 1998; Ferrier et al., 2002; Wintle et al., 2005; Marcot, 2006; Nagendra et al., 2013; Mairota et al., 2014). Moreover, VHR-EO monitoring can assist in inferring ecological changes (impacts) deriving from human pressure (e.g., land-cover/land-use change) over time (Nagendra et al., 2014).

This study was developed within the European Union's Seventh Framework Programme (EU-FP7) project Biodiversity Multi-SOurce Monitoring System: From Space To Species (BIO_SOS), that aimed to develop tools and models for consistent multi-annual monitoring of protected areas and their surroundings by the integrated use of RS and in-field data.

2. Methods

2.1. Study area and data collection

The study area is located in Southern Italy within the Natura 2000 "Murgia Alta" site (SCI/SPA IT9120007, according to Habitat Directive (92/43/EEC) and Bird Directive 2009/147/EC), and is one of the most important areas for the conservation of semi-natural dry grasslands in Europe (Mairota et al., 2013). These are among the most species-rich plant communities in Europe (Wilson et al., 2012), particularly within the Habitats Directive categories 62A0 and 6220*, and they host many endemic plant species, threatened birds, and insects listed in European and national red lists (van Swaay et al., 2010). However, agricultural intensification and land abandonment impact on habitat availability (e.g., grassland fragmentation), habitat quality (e.g., woody encroachment) and hence on biodiversity (Brotons et al., 2005).

A hierarchical nested sampling strategy was adopted for data collection (i.e., landscape pattern indices (LPIs) and VHR-EO features) at three spatial scales (extents) – landscape, patch, and plot – according to the protocols of the BIO_SOS project (Mairota et al., 2013). Twenty 1×1 km landscapes were selected according to a focal habitat fragmentation gradient assessed through site-specific quantitative landscape pattern analysis, QLPA (Mairota et al., 2013). Within each landscape, between one and 15 focal habitat patches ranging in size from 0.14 to 56.28 ha ($n = 111$) were selected, in each of which a 5×80 m plot ($n = 111$) was established.

For each of the focal patches within the 20 landscapes we used the QLPA to assign LPIs that are appropriate for describing habitat fragmentation at the study site (Mairota et al., 2013), and which are considered as the most likely variables to affect biodiversity responses in theoretical models (Didham et al., 2012). These are proxy variables for "habitat quantity" (H), "matrix quality" (M), and "habitat isolation" (I) at the landscape level, and for "patch area" (A), "patch shape" (S) and "edge effects" (E) at the nested patch level, respectively, as indicated by Didham et al. (2012). The landscape level variables (H, M and I) are represented by the proportion of focal habitat in the landscape (PLAND), Shannon's diversity index for complexity of matrix land-use types (SHDI), and the incidence of focal habitat classified as the structural class "islet" in a Morphological Spatial Pattern Analysis (MSPA, Soille and Vogt, 2009), respectively. The nested patch level variables (A, S and E) are represented by patch area (PA), the fractal index of shape complexity (FRAC) and the edge contrast index (ECON), respectively.

VHR-EO features included both the Normalised Difference Vegetation Index (NDVI), computed at the native image geometric resolution (2×2 m pixel) from a DigitalGlobe™ WorldView-2 image, April 2011, for an image of 10×10 km (regional landscape) acquired at a time close to the period of maximum biomass and species richness in the study area, and texture measures (i.e., Grey Level Co-occurrence Matrix, GLCM, metrics; Haralick et al., 1973), derived from the NDVI. Standard deviations of VHR-EO features for the 111 plots were extracted using the zonal-statistics tool in ArcGIS® Desktop 9.

Selected VHR-EO features represent vegetation productivity (NDVI) and provide information on different aspects of NDVI spatial pattern, i.e. similarity among the grey-levels (Information Measure of Correlation, IMC), local homogeneity (Inverse Difference Moment, IDM), and presence of variation (Contrast, CON), which are relevant from the point of view of animal perception of the habitat. NDVI-GLCM metrics were computed (using a 32-level quantization parameter, a 1 pixel shift, and considering all four canonical angles of 0°, 45°, 90°, and 135°) at a set of scales (grains) defined by three window sizes (in pixels) assumed (Mairota et al., 2014) to represent the lower limit allowed by the data and, probably, the mode of perception of many insects (3×3), the upper limit