Modeling the ecological niche of long-term land use changes: The role of biophysical factors

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ABSTRACT

Land use/land cover changes (LULCCs) represent the result of the complex interaction between biophysical factors and human activity, acting over a wide range of temporal and spatial scales. The aim of this work is to quantify the role of biophysical factors in constraining the trajectories of land abandonment and urbanization in the last 50 years. A habitat suitability model borrowed from animal ecology was used to analyze the ecological niche of the following LULCC trajectories occurred in Emilia-Romagna (northern Italy) during 1954–2008: (i) land abandonment (LA) and (ii) urbanization (URB), both from agricultural areas (URBagr) and from semi-natural areas (URBfor). Results showed that the different LULCC trajectories were driven by different combinations of biophysical factors, such as climate, topography and soil quality. In particular, slope and elevation resulted as the main driving factors for rural processes, while slope and temperatures resulted as the main constraints underlying urban processes. This approach may represent a conceptual and technical step toward the systematic assessment of LULCC processes, thus providing an effective support tool to inform decision makers about land use transformations, their underlying causes, as well as their possible implications.

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1. Introduction

Land use/land cover changes (LULCCs) represent the result of the complex interaction between socio-economic and cultural conditions, biophysical constraints and land use history (Verburg et al., 1999); they act over a wide range of temporal and spatial scales and involve both changes toward different ecological functions and shifts in intensity within a function, sometimes resulting in a system’s resilience unbalance (Álvarez Martínez et al., 2011; Shao et al., 2006; Zurlini et al., 2015). Anthropogenic drivers are relatively active, and are the main determinants of short-term LULCCs. To the contrary, biophysical factors are relatively stable, and control the long-term macro-tendency of regional LULCCs (Shao et al., 2006). While human activity is the major force in shaping LULC, the underlying biophysical structure of the landscape (i.e. climate, soil, topography, hydrology, and vegetation) may constrain LULC, defining the natural capacity or predisposing environmental conditions for land use and influencing the orientations of LULCCs across space and time (Jingan et al., 2005; Lambin et al., 2001; Geist et al., 2006). At finer landscape scales, LULCCs can be related to their constraining factors more or less straightforwardly, but aggregating these changes over broader regions appears as a more difficult task (Verburg et al., 1999). Therefore, a clear understanding of the driving forces that cause LULCCs at regional scale is becoming a key issue (Shao et al., 2006; Van Diggelen et al., 2005; Chaplot et al., 2005).

In the last decades, the dominant LULCC trajectories observed at regional scales in the northern Mediterranean Basin are a biomass increase in marginal areas due to land abandonment (decreased human pressure) and, on the other hand, the sealing of agricultural soils due to urbanization (increased human pressure) (Millington et al., 2007; Bajocco et al., 2012). Land abandonment (LA) determines a progressive decline in agricultural land uses due to rural exodus; as a consequence, shrublands and forests have substantially increased in marginal lands, homogenizing the environmental mosaic, reducing the protection function of land management, altering the agricultural water use balance and increasing the biomass available as fuel for potential wildfires (Moreira et al., 2001; Lozano et al., 2008; Serra et al., 2008; Valipour, 2013, 2014). To the contrary, urbanization (URB) involves the
wholesale transformation of agricultural and natural ecosystems to more intensive uses, being among the heaviest anthropogenic impacts on earth (Seto and Kauffman, 2003). A pan-European study highlighted the rapid increase of urbanization particularly in the form of dispersed urban expansion, considering this as an “ignored challenge” for the on- and off-site effects on water storage, soil erosion, loss of organic carbon stock, decrease in biological diversity (Ceccarelli et al., 2014). The environmental consequences of both LULCCs trajectories entail, on one side, the gradual decrease in landscape diversity and complexity, and, on the other side, the increase of vulnerability to certain hazards such as forest fires, erosion, floods, and droughts (Serra et al., 2008).

Understanding the relationships among LULCCs and their constraining factors is thus extremely important for enabling scientists, landscape managers and policy makers to design nature conservation strategies and develop informed and appropriate land use policies with the aim of preserving some of the unique characteristics of both natural and anthropogenic landscapes (Álvarez Martínez et al., 2011; Biazin and Sterk, 2013). In this perspective, regional-scale LULCC modeling represent an essential tool for predicting the probability of occurrence of a specific change (Röder et al., 2008) and for identifying which variables provide the most suitable model (Seabrook et al., 2006; Álvarez Martínez et al., 2011). A variety of LULCC models have been developed to address different processes, scales of analysis and research questions (Shao et al., 2006; Verburg et al., 2009). Like multiple linear regression, ordination or clustering methods, multivariate statistical modeling tools can explain the proximate causes of regional LULCCs (Pan and Bilshower, 2005; Purna et al., 2005; Lesschen et al., 2005; de Freitas et al., 2013). These techniques can be used for two main purposes: to project future landscapes under different change scenarios (predictive models) and to explain the relationship between LULCC patterns and driving forces (explorative models) (Millington et al., 2007; Álvarez Martínez et al., 2011; Millington et al., 2007). In this framework, the present study uses a multivariate exploratory approach borrowed from ecological niche modeling (Hirzel and Le Lay, 2008; Warren and Seifert, 2010) to quantify the role of biophysical factors in constraining the trajectories of land abandonment and urbanization occurred in the Emilia-Romagna Region (northern Italy) in the last 50 years.

2. Study area

The Emilia-Romagna region covers an area of 22,446 km² in northern Italy and hosts about 4.4 million inhabitants. Nearly Emilia Romagna (48%) consists of plains (the Po river valley), while the remaining 52% is hilly or mountainous (the Apennines range) stretching for more than 300 km from the north to the south-east. Altitude ranges from the sea level along the Adriatic coast, to 2165 m a.s.l. (Mount Cimone).

Artificial areas (17% of the study site) are mainly located in the lowland. The Po river valley, which is the result of several reclamations starting from the Etruscan period and ending just after the World War II, is covered with fruit orchards and annual crops. The natural landscape has been severely transformed by humans, particularly in the lowlands. At higher elevations the natural vegetation ranges from oak forests dominated by Quercus pubescens and Quercus cerris to Fagus sylvatica forests, sometimes mixed with Abies alba, and grasslands.

The analysis has been performed solely in the hilly-mountain area of the Apennines (10,139.35 km² with an altitude >500 m a.s.l.) (Fig. 1) in order to limit the impact of socio-economic drivers related, for instance, to litorlization, tourism, transport and communication routes, that could bias the analysis of the biophysical factors role over LA, URB,agr and URB,for trajectories.

3. Data and methods

3.1. LULCC data

The land cover maps used in this study (scale 1: 25,000) for the years 1954 and 2008 were produced by the Regional Cartographic Service of Emilia Romagna (http://geoportale.regione.emilia-romagna.it/it/download/). Although the original classification scheme of both maps was not identical, their thematic content was harmonized by the Cartographic Service in order to render them comparable (Ceccarelli et al., 2014). The final classification scheme follows the third hierarchical level of the CORINE Land Cover nomenclature (http://www.eea.europa.eu/publications/COR0-landcover).

For this study the following land cover change trajectories occurred between 1954 and 2008 were analyzed: (i) land abandonment (LA) and (ii) urbanization (URB), which altogether involved about 16% of the study area (Fig. 2). LA included all LULCCs from Agricultural areas to more natural land cover types, such as shrublands and forests (1344.73 km²), corresponding to 82.7% of the changed surface. URB included all LULCCs from Agricultural areas (URB,agr: 230.63 km²: 14.2% of the changed surface) and from Semi-natural areas (URB,for: 50.98 km²: 3.1% of the changed surface) toward artificial land uses. URB,agr and URB,for were analyzed separately.

3.2. Background data

Seven biophysical background variables that are thought to influence LULCCs in the study area were considered in the analysis:

I. Minimum annual temperature (TMIN)
II. Maximum annual temperature (TMAX)
III. Total annual precipitation (PTOT)
IV. Aridity index (AI)
V. Elevation (ELE)
VI. Slope (SLO)
VII. Soil quality index (SQI)

The climate variables I–IV (CLIM) were extracted from the National Agro-meteorological Database of the Italian Ministry of Agriculture. The database contains daily gridded temperature and
precipitation data for the period 1960–1990, with a spatial resolution of 1000 m (see Salvati and Bajocco, 2011). The AI was computed sensu UNEP (1992); according to this procedure, low index values indicate arid conditions, whereas high index values indicate humid conditions.

The topographic variables V–VI (TOPO) were derived from the digital elevation model (DEM), generated by the Italian Ministry of Environment, using standard GIS operators at a spatial resolution of 100 m.

The SQI was derived following the MEDALUS procedure at a spatial resolution of 1000 m integrating information on soil texture, the nature of parent material, rock cover and soil depth (Kosmas et al., 1999). Low (high) values of SQI indicate soils of good (bad) quality.

3.3. Ecological niche factor analysis

The ecological niche factor analysis (ENFA; Hirzel et al., 2002) was used to analyze the environmental drivers of LULCCs in Emilia Romagna during 1954–2008. ENFA is a modeling tool formerly used by ecologists for the exploration of habitat selection by animals (Gallego et al., 2004; Compton, 2004; Hirzel et al., 2004; Dettki et al., 2003; Zimmermann, 2004). Generalizing the concept of habitat selection to every spatially distributed ecological process, the rationale behind using niche modeling tools for understanding patterns of LULCCs is based on the observation that a given land use type can be modeled like a ‘living organism’ with variable preferences for different resources (i.e. the underlying environmental conditions; Bajocco et al., 2011; de Angelis et al., 2012).

ENFA is released in the BIOMAPPER package freely available at http://www.unil.ch/biomapper/. The first type of input data needed by the ENFA is a set of quantitative raster maps (i.e. the above biophysical variables I–VII) describing the environmental characteristics of the entire study area (i.e. the available habitat). These ‘background data’ are then compared with the environmental conditions at the locations where the studied species (in our case the land cover change trajectories LA, URB for and URB Agr) have been detected (i.e. the used habitat).

The foremost indicator calculated by ENFA is the so-called ‘marginality’ (Dolédec et al., 2000; Hirzel et al., 2002), a measure of the distance between the average conditions of the available habitat and the average conditions of the used habitat. For instance, from a mathematical viewpoint, the realized niche of a given species is the density function of the species presence in multivariate ecological feature space. If the ecological variables are multivariate normally distributed, the mean vector of the distribution is the point with the highest species presence and represents the species ecological optimum (Calenge et al., 2005). The marginality is then defined as the distance of the species optimum from the mean vector of available habitat conditions over the whole study area, thus measuring the strength of habitat selection (i.e. the mean deviation, either positive or negative, of habitat use from availability; Calenge et al., 2005).

The global marginality index usually ranges between 0 and 1 (although in extreme conditions its value can be larger than one) and its size is proportional to the strength of habitat selection. For details see Hirzel et al. (2002) and Calenge et al. (2005).

If the landscape cells that are subject to LULCCs were randomly distributed across the territory, without any clear environmental driver, the resulting marginality would be zero, meaning that there is no difference between the mean ecological conditions of the study area and the ecological conditions at the sites where LULCCs occur. On the other hand, large marginality values indicate that LULCCs occur preferentially in particular environmental conditions in relation to the reference area (Basille et al., 2008).

For sake of consistency, to calculate the marginality of the selected LULCCs in Emilia Romagna, all background variables were first downscaled to pixel resolution of 1000 m according to the grain of the variables with coarsest resolution. Next, for analyzing the LA trajectory, since land abandonment typically affects only areas previously occupied by cultivated fields, the biophysical characteristics of all landscape cells that changed from agriculture to natural and semi-natural areas during 1954–2008 (used habitat) were compared with the characteristics of all cells that were labeled as agriculture in 1954 (available habitat). Likewise, for analyzing the URB Agr trajectory, all cells that changed from agriculture into artificial areas during 1954–2008 were compared with all cells
Table 1
Mean, minimum and maximum values for each biophysical variable associated to all cells classified as Agriculture in 1954 and for the corresponding LULCC trajectories LA and URB_{agr}.

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<tr>
<td></td>
<td>Mean</td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>AI</td>
<td>1.242</td>
<td>0.992</td>
<td>1.983</td>
</tr>
<tr>
<td>ELE (m)</td>
<td>530.2</td>
<td>201</td>
<td>1647</td>
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<tr>
<td>SLO (%)</td>
<td>19.536</td>
<td>0</td>
<td>83.395</td>
</tr>
<tr>
<td>Tmin (°C)</td>
<td>6.451</td>
<td>0.982</td>
<td>8.803</td>
</tr>
<tr>
<td>Tmax (°C)</td>
<td>15.453</td>
<td>11.709</td>
<td>17.617</td>
</tr>
<tr>
<td>PTOT (mm)</td>
<td>952.495</td>
<td>791</td>
<td>1371</td>
</tr>
<tr>
<td>SQI</td>
<td>1.468</td>
<td>1.149</td>
<td>1.788</td>
</tr>
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labeled as agriculture in 1954. Finally, for analyzing the URB_{agr} trajectory, all cells that changed from natural and semi-natural areas into artificial areas during 1954–2008 were compared with all cells that were classified as natural and semi-natural areas in 1954.

4. Results

Tables 1 and 2 show the mean, minimum and maximum values of each biophysical variable for agriculture and the natural and semi-natural areas in 1954 and for the analyzed LULCC trajectories. The coefficients of all ecological variables on the marginality factors of the three LULCC trajectories are shown in Table 3. The marginality coefficients range from −1 to +1. The higher the absolute value of a coefficient, the larger the difference between habitat use and availability for the corresponding biophysical variable. Negative coefficients mean that LULCCs occur at sites where the biophysical variables have on average lower values than the background mean, while positive coefficients indicate that LULCCs preferentially occur at sites where the variables have higher values than the background mean.

The ecological niche factor analysis of the LA trajectory provided a global marginality of M = 0.274. As shown in Table 3, for the LA trajectory, slope (SLO = 0.786) and elevation (ELE = 0.489) are the biophysical variables with the highest (positive) departure from the mean background conditions, while minimum and maximum annual temperature are the only variables with a negative departure from the background mean. The URB_{agr} trajectory showed a marginality value of M = 0.264. As shown in Table 3, the major biophysical drivers of this land cover change trajectory are slope (SLO = −0.789) and total annual precipitation (PTOT = 0.377).

5. Discussion

In spite of scientific and technological advances, relief, soils and climate still exert a significant influence not only on the agricultural and forest uses, but also on their future destinations (Walker, 1977).

In this study, the different LULCC trajectories were associated to different combinations of biophysical factors, which reflect relevant environmental differences between the available and used habitat of each trajectory. In this view, not surprisingly, the largest overall marginality value is associated to the URB_{agr} trajectory, meaning that the cells that change from natural to artificial areas during 1954–2008 show the largest differences from the mean environmental conditions of the corresponding background data (i.e. the environmental conditions of all cells labeled as natural and semi-natural in 1954).

Looking at the marginality coefficients of the single variables, slope represents the most relevant biophysical constraint for all LULCC trajectories. This evidence has been confirmed by many other studies. For instance, some authors (Feliciano et al., 2002; Serra et al., 2008) related the potential distribution of forests to lithology, latitude, slope, potential insolation and distance from the sea, while Álvarez Martínez et al. (2011) found that variables related to water availability (i.e., distance to rivers, rainfall, slope) and soil properties were the most important drivers of forest expansion. The influence of water availability on vegetation cover patterns was also demonstrated by Vicente-Serrano et al. (2006), who analyzed the role of aridity on vegetation in a semi-arid Mediterranean region under intense anthropogenic pressure. In terms of
topographic variables, Florinsky and Kuryakova (1996) showed that changes from grassland and shrubland to forest depend on relief parameters, which controlled the distribution and accumulation of water and sediment. Bakker et al. (2003) demonstrated that besides being a major driver of soil erosion, slope is also a direct driver of land use change because steeper slopes are more difficult to cultivate, affecting land abandonment through the loss of nutrients and water holding capacity.

In detail, the distribution of the abandoned agricultural pixels (LA) in multivariate biophysical space is preferentially linked to annual minimum and maximum temperatures that are both lower than the background mean. Such thermal conditions are expressions of cold winters that may, on one hand, harm crops and cultivations with prolonged frost and, on the other hand, delay the start of the growing season. Land abandonment tends also to occur at higher than mean conditions of slope and altitude, where cropping is disadvantaged both for the poor accessibility of the fields and for the difficulties to cultivate steep soils subjected to increased erosion and water scarcity. Finally, as expected, the abandoned agricultural fields are characterized by soils of worse quality (i.e. higher SQI values) than the mean background conditions.

Urbanization from agriculture (URBagr) tends to occur in more humid environments and in areas with lower maximum and higher minimum temperatures than mean background conditions. Furthermore, the URBagr trajectory occupies preferentially flat soils of better quality with respect to the mean background conditions. To the contrary, elevation is the least constraining biophysical variable for this trajectory. These results demonstrate that this urbanization process is mainly determined by socio-economic choices, which select the more comfortable and accessible areas at the expense of the high soil quality that characterizes such locations.

Comparing the two LULCC trajectories starting from the agricultural background, it is interesting to notice that the factors leading to the different final uses are totally opposite: e.g. cold winters, high altitudes and steep soils of bad quality are the environmental characteristics underlying the abandonment of cultivated fields; while, mild winters, cool summers and flat soils of good quality, regardless the elevation, represent the main biophysical constraints for the urbanization process.

Finally, urbanization from deforestation (URBfor) showed the highest global marginality value, meaning that this trajectory represents the LULCC more constrained by the environmental conditions of the background. In detail, the URBfor preferentially occurs at lower altitudes where minimum and maximum temperatures are usually higher than mean background conditions. Like for URBagr, in semi-natural areas urbanization tends to occur in the more level and accessible portions of the available habitat, thus exploiting deeper and higher-quality soils compared to the mean background conditions.

In summary, as for the agricultural background, the biophysical conditions, when adverse to crops and cultivations, has a direct role on the land abandonment process, preventing the long term persistence of the initial land use; to the contrary, even if favorable to the existence of plantations, the biophysical conditions indirectly drive the change from cultivated fields toward urban uses, by influencing the land managers choices toward more accessible and comfortable environments. Also for the urbanization of natural and semi-natural areas, the role of the biophysical factors is mostly linked to the accessibility of the background conditions which evidently represents the main driver to the viability of artificial land uses. In this perspective, given the irreversibility of the soil sealing processes, the role of the factors guiding urbanization trajectories should be analyzed at finer scales in order to identify the most appropriate strategies for a sustainable land management.

In conclusion, the environmental modeling tool used in this paper enables to explore the main biophysical constraints of landscape dynamics, to quantify to what extent each identified factor acts and to summarize the main differences between rural and urban processes. Furthermore, the possibility to repeat the analysis any time the LULCC data are available, with any kind of background variables, together with the independence of the model from site-specific information, makes the proposed methodology a potential standard tool applicable to any type of ecosystem.

The proposed approach can be thus considered a conceptual and technical step toward the systematic assessment of LULCC processes that can be enriched by adding (where available) also data from the socio-economic domain. It provides a synopsis of major change processes and their spatial dimension and, therefore, has the potential to inform decision makers about land use transformations, their underlying causes, as well as their possible implications. Future perspectives of the methodology could take into account, where possible, not only the presence, but also the absence data, in order to identify the areas where a given LULCC trajectory preferentially occurs, those that are preferentially avoided, and the related constraining factors.

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References


