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Assessing the effect of environmental and anthropogenic factors on land-cover diversity in a Mediterranean mountain environment

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This study assesses the factors that influence land-cover diversity, including the specific contributions of environmental and anthropogenic forces in determining landscape diversity (spatial variability in climate, lithological variations and human management). The proposed model was tested in Navarra (northern Spain), a region with a long history of human settlement and distinct management practices, ranging from mountain communities in the Pyrenees to Mediterranean lowland cropland systems. Variance in landscape diversity was divided into environmental- and human-influenced fractions, and generalized additive models within a GIS framework were used to evaluate the effects of environmental and anthropogenic factors. We also assessed the influence on the results of the number of land-cover classes by employing contrasting thematic resolutions of 220 and 24 classes. The model that includes only environmental factors, using 24 classes, accounted for 65 per cent of the total variance ($P < 0.005$). The residuals obtained from this model were then regressed against human variables (distance to settlements, accessibility, total municipality population and productive specialization). Residuals and productive specialization, which varies between areas devoted to grazing and forest exploitation in the Pyrenees mountains to lowland Mediterranean croplands, showed a strong correlation ($r^2 = 0.40$; $P < 0.005$), but weak correlations were found when 220 land-cover classes were used. Results based on the sign of residuals suggest that human activities have resulted in an increase in land-cover diversity in mountainous areas and have acted to homogenize land cover within the Mediterranean agricultural landscape. In summary, the model that uses the map of 24 classes as dependent variables and includes human and environmental factors explains 80.75 per cent of total land-cover diversity variance using only three variables: climatic spatial variability, lithological diversity and productive specialization.

Key words: *land-cover diversity, environmental heterogeneity, human management, GAM, GIS, diversification–homogenization*

Introduction

European landscapes have been shaped for centuries by human management, and the structure of the landscape has emerged and changed over time and space (Vos and Meekes 1999). In the twentieth century, these changes accelerated in response to a variety of forces such as agriculture, the global market,

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urbanization and the depopulation of rural areas. Thus, an intensification of land use in one region caused marginalization in others. These trends are currently creating new landscape patterns, and the regional diversity of European landscapes is decreasing (Mander *et al.* 2004). The consequences of landscape transformation are also affecting ecological processes such as hydrological responses, erosion and biodiversity (García-Ruiz *et al.* 1995; Kirkby *et al.* 2000; Beguería *et al.* 2003; Waldhart 2003). In relation to this issue, the ecosystem and landscape approach has been used to protect species diversity (Franklin 1993). Landscape diversity is one of the most widely accepted hypotheses used to explain the degree of species richness (see Nogués and Martínez-Rica 2004). Regional-scale landscape diversity generally indicates higher levels of resource variability and consequently a greater capacity to support species (Faith 2003). Consequently, evaluation of the factors that affect landscape diversity will improve our understanding of the diversification and homogenization of landscapes and, for example, the effects of these processes on biodiversity (Jongman 2002). Therefore, research on the way in which anthropogenic disturbances alter the spatial structure of landscapes is of great importance (Burel and Baudry 1999).

Changes in landscape structure are a result of diverse processes such as changes in land management and policies (Mander and Palang 1994; Mander *et al.* 1999; Kristensen 2003). Other studies have reported the importance of climatic change, wildfire and grazing pressure (Chuvieco 1999; Bartolome *et al.* 2000; Opdam and Wascher 2004). Therefore, the integration of geo-bio-physical and socio-economic drivers appears to be a prerequisite for studies of the processes that influence landscape change. Previous researchers have also stated the need to develop large-scale experiments (Hobbs 1997). However, some of these studies were conducted at a local scale, while others focused on general driving factors but with reduced spatial analysis. Thus, given the present global and regional dynamics in relation to climate change and changes in land cover (Parmesan and Yohe 2003), it is important to assess the effect of human activities on regional-scale landscape diversity and trends in landscape diversification–homogenization. Specifically for Europe, the homogenization of landscapes as a consequence of global economic trends (Stoate *et al.* 2001; Jongman 2002) must be addressed in geographical research, with conceptual and methodological approaches being called for. For this reason, we chose to investigate the driving factors behind land-cover diversity at a regional scale, as there are large areas that prevent the use of aerial photographs when comparing changes in land-cover diversity. In addition, remote sensing information is only available from 1970. The word 'regional' is used here in accordance with the definition of Forman (1995), since the larger spatial elements that comprise the regional mosaic of our study area are landscapes of different types: alpine and sub-alpine landscapes, montane landscapes and cropland landscapes, although only land-cover diversity is analysed (land cover is recognized as one of the main constituent elements of landscape).

Herein, the main aim is to assess aspects of land-cover diversity influenced by geo-bio-physical heterogeneity, meaning spatial heterogeneity mainly related to abiotic factors, and those aspects influenced by socio-economic drivers. This is considered over a large area (10 421 km^2), subjected to varied land management practices, using spatial information implemented in a geographical information system and statistical multivariate techniques. Specifically, the model was tested across an ecological transect from a mountain environment in the Pyrenees (alpine biogeographical province) to croplands within a lowland area near the Ebro River (Mediterranean province). To sum up, we hypothesize that:

1. The spatial pattern of land-cover diversity is the result of both environmental heterogeneity and anthropogenic activities, and that the pattern differs in relation to different land management strategies.
2. It is possible to develop a parsimonious and robust model to quantitatively assess hypothesis (1) using easily acquired spatial variables at large scales to develop similar studies in other areas.

Study area

Navarra is an area in northern Spain (Figure 1) located in a transition zone between the Mediterranean and Eurosiberian biogeographic domains. Navarra's climate in the northern regions is not strictly Eurosiberian, but more like the climate of the Lusitanian province. The extent of Navarra (10 421 km^2) includes the Pyrenees, the Basque–Cantabrian Mountains and the sedimentary basin of the Ebro River. There is a strong bioclimatic switch from the Pyrenees to the lowlands of the Mediterranean province (for a pioneering and lucid description of the climatic zonation of Navarra, see Mensua 1968). In general terms, the mountainous area in the

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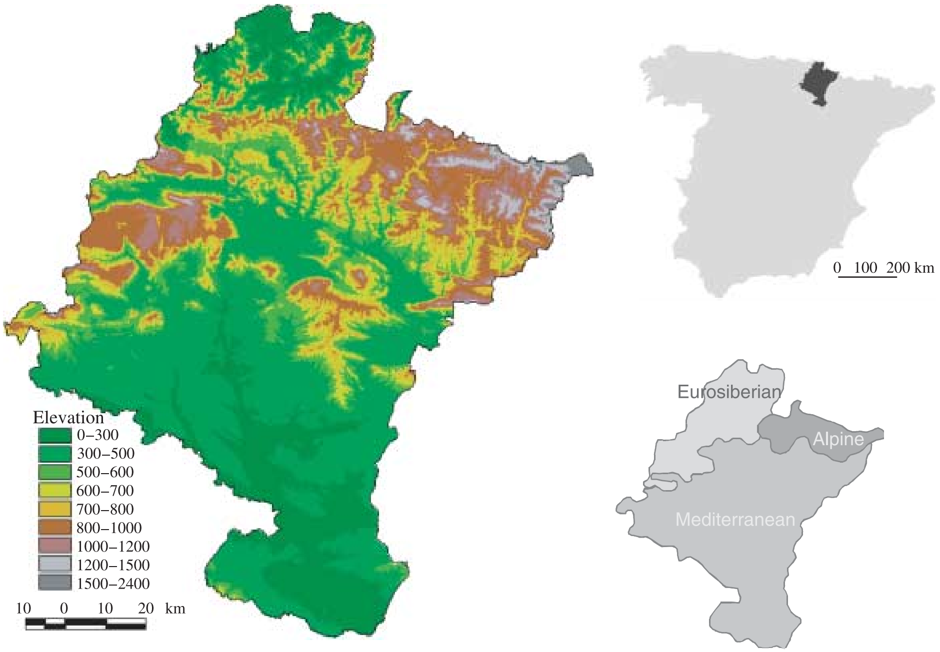

Figure 1 Map of the study area of Navarra. Navarra is located in northern Spain, with the Pyrenees to the north and Mediterranean lowland environments to the south

Pyrenees has abundant rainfall (1200–1700 mm/year) with monthly average temperatures that vary from 2°C in January to 14°C in August. Vegetation cover is temperate, with a high proportion of deciduous forests, including species such as *Fagus sylvatica* or *Quercus petraea*, and coniferous forest, *Pinus sylvatica* or *Pinus unicinata* in higher areas, as well as alpine pastures. The area contains the following altitude-dependent land-cover types from valley floors to mountain peaks: urban settlements, meadows, forest and pastures. The degree of landscape diversity is high because of this altitudinal and climatic variability, as well as the footprint created by traditional management practices of grazing, forest exploitation and subsistence agriculture in the southern Mediterranean zone. Rainfall is scarce and irregular (maximum 400 mm/year) in this southern zone, with a high thermal amplitude. The vegetation is adapted to semiarid Mediterranean conditions, with the most representative species being *Quercus rotundifolia*, *Juniperus comunis*, *Quercus coccifera*, *Pinus halepensis*, *Thymus vulgaris* and *Rosmarinus officinalis*. These Mediterranean landscapes are therefore characterized by a matrix of large-scale irrigated and non-irrigated croplands (mainly cereals) that alternate with patches of Mediterranean vegetal formations and the following riparian vegetation near rivers: *Salix fragilis*, *Populus nigra*, *Salicetum neotrichae* and *Tamarix gallica*, among many others. Between the Pyrenees and the Mediterranean sections there is a strong ecological gradient dominated by species such us *Quercus pubescens* and *Quercus faginea* and shrubs such as *Genista scorpius* and *Genista occidentales*.

Methods

The basis of the proposed methodology is the establishment of a robust model that uses easily acquired large-scale spatial variables that relate the diversity of land cover to that of the geological substrate and spatial variability in climate. The obtained residuals are then related to proxy variables that represent anthropogenic impacts on land-cover diversity.

Data

Two datasets were used to characterize the environmental factors that potentially summarize the main abiotic factors: a lithological map (scale

Table 1 Land-cover types following the reclassification procedure

Forests	Pasture and shrubs	Croplands	Others
Sub-alpine forest	Sub-alpine pasture	Non-irrigated fruit trees	Rock outcrop
Fir	Montane shrub	Irrigated fruit trees	Surface water
Beech	Heathland	Non-irrigated cropland	Wetland
Oak	Montane pasture	Irrigated cropland	Artificial surface
Other deciduous forest	Meadow		
Pine	Mediterranean shrubs		
Other coniferous forest	Steppe		
Mediterranean forest			
Riverine forest			

1:50 000) and an aridity index map (for a description of these climate data, see Nogués-Bravo and Martínez-Rica 2004). We obtained a 1:25 000 land-cover map from the Department of Agriculture of the Regional Government of Navarra. The map was compiled using orthophotos (1:25 000) and fieldwork undertaken to check the type of land cover in each patch. This land-cover map comprises 220 classes, mainly different kinds of crops; thus, a new group was created using just 24 classes (Table 1). The reclassification procedure, supported by botanists, groups land-cover types into 24 classes by taking into account physiognomic and biogeographical principles.

Road and settlement maps (1:25 000) were also obtained from the Department of the Environment of the Regional Government of Navarra. Population data for each municipality were obtained from an update of the 2003 population census, while production specialization data were obtained from the most recent agrarian census undertaken in 1999. A municipality, also called a commune in some European countries, is a local administrative area that generally comprises a clearly defined territory administered by a city, town or village government.

Development of variables

To obtain the cases to be analysed, 200 pixels were selected using a random non-stratified strategy in GRASS GIS (Geographic Resources Analysis Support System), thereby minimizing problems related to the dependence of spatial data and autocorrelation. Variables were calculated around each pixel using a window of 25 km^2. All pixels were assigned the same surface area to avoid the influence of area effects on the results, as larger areas show greater land-cover diversity; this relationship is usually fitted to power functions (Wu 2004). Data geo-referenced to non-continuous maps and municipal data such as population or production specialization were obtained from an average of the data for each municipality weighted by the area of the municipality within the window.

The Shannon Diversity Index (Shannon and Weaver 1949) was used to measure land-cover diversity (response variable) and lithological diversity (predictor variable). The inverse difference moment was chosen to measure spatial variability in aridity (Musick and Grover 1990). This index is used to measure heterogeneity in continuous variables such as NDVI and rainfall.

An accessibility map was obtained after a multi-criterion evaluation (MCE) process using fuzzy sets (Jiang and Eastman 2000). Four maps of distance-to-roads were made in relation to the hierarchy of the roads. After a standardization process, these maps were averaged using a weighted linear combination procedure to obtain the final map. The weights used in this procedure were as follows: map of distance to highways: 0.4; map of distance to national roads: 0.3; map of distance to regional roads: 0.2; map of distance to local roads: 0.1.

Finally, production specialization for each municipality was obtained using data from the agrarian census. Four variables (areas of croplands, pastures, forest and others) were reduced to two factors using a principal component analysis. These data were selected because from our perspective they provide a better synthesis of the spatial effect of economic activities than population or the number of fiscal licences in different productive sectors. Factor 1 synthesized 51 per cent of total variance, highlighting the transition from highlands that are dominated by grazing and forest activities (positive values of factorial scores) to lowlands devoted to agriculture

Table 2 Variables used in the present analysis

	Abbreviation
Dependent	
Land-cover diversity (24 classes)	LCD24
Land-cover diversity (220 classes)	LCD220
Independents (Natural factors)	
Variability in aridity	ARIVAR
Lithological diversity	LITHD
Independents (Human factors)	
Distance to roads	DISTROADS
Distance to settlements	DISTSETTLE
Population per municipality	POP
Productive specialization (per municipality)	PRODSPE

(negative scores). The r^2 between Factor 1 and the distance to the Pyrenees is 0.65. The interpretation of Factor 2 (78.8% of accumulated variance) is not clear, although it could be related to municipalities with large areas of 'other uses' such as urban areas, reservoirs or unproductive areas. The factorial scores of Factor 1 for each municipality were retained as a new variable that describes production specialization. Table 2 summarizes the variables used in the model.

Statistical approach

The total variance of Current Diversity (HC) is partitioned into natural and anthropogenic fractions to separate those components of diversity influenced by environmental conditions from those influenced by human management. Land-cover diversity, as the response variable, and lithological diversity and variability in aridity, as predictor variables, were introduced in a generalized additive model to develop two 'environmental models' using the 220 and 24 land-cover classes as dependent variables. Lithological and climate factors were selected because they synthesize and express an important component of the abiotic land-cover driving factors (rock substratum, heat and water availability) and because they are more easily obtained at large scales than soils or geomorphological units.

Residuals obtained from the model were regressed against human-influence variables: distance to settlements, accessibility, total population of the municipality and productive specialization. These variables were selected because they synthesize the processes that lead to changes in land cover: accessibility and its influence on planning for the location of different land-use types, urbanization and economical specialization within a global market (Klijn and Vos 2000). Finally, two different dependent variables were used: land-cover diversity for the original 220 classes (LCD220) and a reclassified map comprising just 24 classes (LCD24) (Table 1). Thus, two different models were developed to assess the effect of the number of land-cover classes on diversity.

Generalized additive models (GAMs) were used to explain the relationships between environmental and anthropogenic factors and land-cover diversity. GAM is a regression technique that supports non-Gaussian error distributions and non-linear relationships between these types of variables (Hastie and Tibshirani 1987; Guisan *et al.* 2002). GAMs are non-parametric extensions of linear model regressions that apply non-parametric smoothers to each predictor and additively calculate the component response. GAMs are commonly used in biodiversity models that focus on predictions of plant diversity or faunal species richness (Nogués-Bravo and Martínez-Rica 2004; Nogués-Bravo and Araújo in press). In this kind of regression, termed data-driven regression, no specific form of the function is selected (linear, quadratic or cubic), and the GAM improves upon the predictive capacity of linear approaches or classification trees (Pearce and Ferrier 2002; Thuiller *et al.* 2003; López-Moreno and Nogués-Bravo 2005).

Model validation was developed using an independent dataset of 40 new windows. The obtained model was then applied to the new data, and the Pearson coefficient and root-mean-square error (RMSE) were used to measure the predictive capacity of the model.

Results

Univariable models

GAMs using only one variable were used to evaluate the simple relationships among response and predictor variables. This was useful as a first interpretation of the relationships between variables because correlated predictor variables can hinder the estimation of additive surfaces. Using the reclassification of the original map into 24 land-cover classes (LCD24), the matrix correlation indicates that increases in the variability of aridity or lithological diversity result in an increment in land-cover diversity (Figure 2). Variability in aridity explains 81.6 per cent of the total variance of land-cover

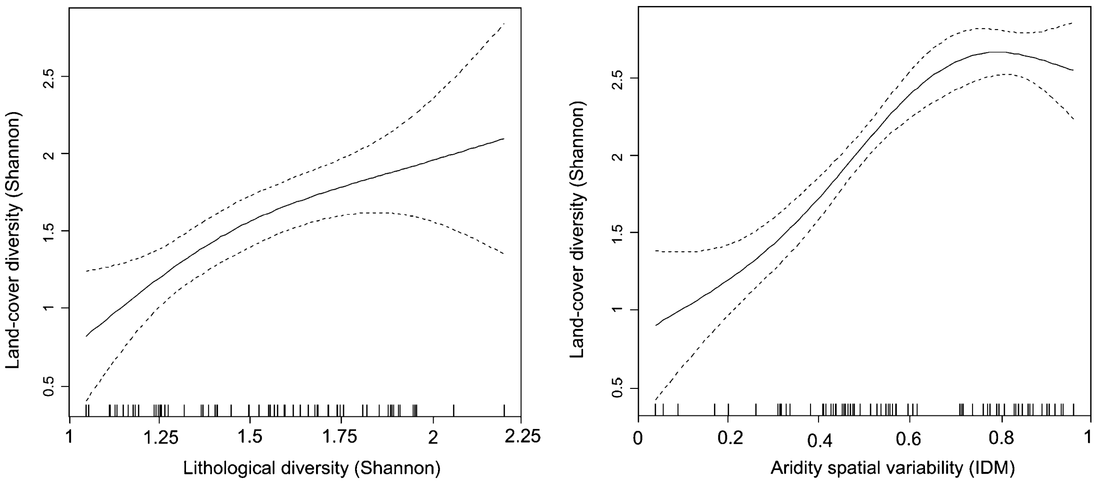

Figure 2 **Univariate smoothed terms of climatic variability and lithology. Estimates are shown as solid lines, with 95 per cent Bayesian intervals shown by dashed lines. Cases are plotted at their approximate locations along the base of the graph**

Table 3 **Coefficients of regression parameters of the multivariable model. The estimated degrees of freedom (edf) indicate the level of complexity of the adjusted splines. Chi square (X^2) is used to test the statistical significance**

Parametric coefficient	Estimate	Std error	t ratio	Pr(>|t|)
Constant	1.79	0.02487	71.96	<2.22e-16
Smoothed terms	edf	X^2	p-value	
ARIVAR	1.011	24.7	2.2342e-07	
LITHD	1.664	101	<2.22e-16	

diversity ($P < 0.005$), while lithological diversity accounts for 47.4 per cent ($P < 0.005$). Finally, greater variability in aridity is related to greater levels of lithological diversity, and accounts for 25 per cent of total variance ($P < 0.005$); however, this correlation was not high enough to justify the removal of predictor variables from the model.

The same analyses undertaken using the original land-cover map with 220 classes (LCD220) indicate a poor correlation between land-cover diversity and environmental predictor variables. Variability in aridity explains only 16.1 per cent of the total variance in land-cover diversity ($P < 0.005$), while lithological diversity accounts for 13.5 per cent ($P < 0.005$).

Multivariable environmental models

The model obtained using variability in aridity and lithological diversity as predictor variables of land-cover diversity (LCD24) accounts for 65 per cent of total variance ($P < 0.005$), and both variables are statistically significant (Table 3).

Plots derived from the multivariable model show a direct relationship between each variable and land-cover diversity (Figure 3). The model was validated by applying the Pearson coefficient between observed and predicted values and the RMSE using an independent dataset. These two tests demonstrate the excellent predictive ability of the model ($r^2 = 0.75$; RMSE = 0.28).

The final model explains less of the total variance than the climatic factor when regressed separately against land-cover diversity. This result is due to the use of penalized splines to reduce the complexity of the curves and control the estimated degrees of freedom. To obtain statistical significance, curve complexity was reduced and the estimated degrees

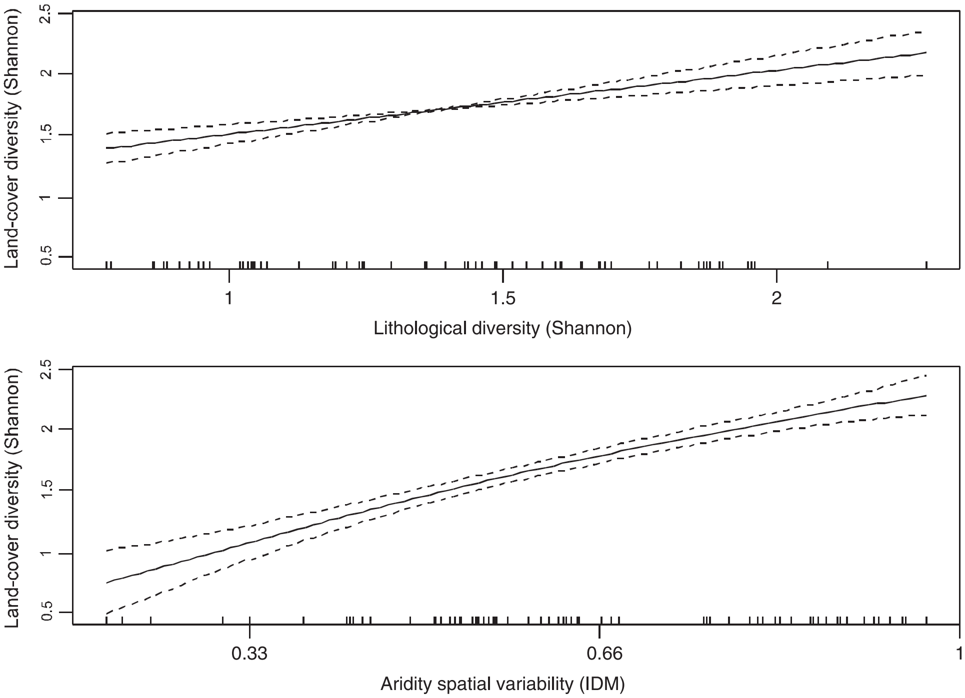

Figure 3 Smoothed terms of the multivariate model for 24 land-cover classes. Estimates are shown as solid lines, with 95 per cent Bayesian intervals shown as dashed lines. Cases are plotted at their approximate locations along the base of the graph. Complexity levels of adjusted splines were automatically reduced to obtain statistical significance

of freedom in the climatic variability variable and lithological diversity were 1.007 and 1.664, respectively. Nevertheless, separate regression of the climatic factor against land-cover diversity produced an estimated 2.9 degrees of freedom. Accordingly, the spline is more complex and a greater percentage of the observed variance is explained by the model (Figures 2 and 3).

The second obtained environmental model, using variability in aridity and lithological diversity as predictor variables of LCD220, accounts for 23.3 per cent of total variance ($P < 0.005$); both variables are statistically significant. The model was validated by applying the Pearson coefficient between observed and predicted values and the RMSE using an independent dataset. These two tests reveal the limited predictive ability of the model ($r^2 = 0.16$; RMSE = 0.78).

Relationships between residuals of environmental models and human variables

Productive specialization explains 40 per cent of the total variance of residuals obtained from the environmental model developed with 24 land-cover classes, while the other variables show weak correlations and low levels of statistical significance (Table 4). Positive values of productive specialization factor in areas traditionally devoted to forestry and grazing are related to positive residuals, while negative values for areas devoted to cropping in lowland areas are related to negative residuals (Figures 4 and 5). Only productive specialization showed statistical significance when regressed against residuals of the second natural sub-model with 220 land-cover classes (Table 4).

Discussion

In this study, I assessed the effect of two driving forces (environmental heterogeneity and human management) on regional-scale land-cover diversity in an area of ecological transition from mountains to lowlands. I used the area of Navarra to exemplify and test our model, and found that environmental heterogeneity explains 65 per cent of the total

Table 4 Explained variance of the residuals accounted for by human-induced variables and related statistical significance

Variable	Explained variance (LCD24) (%)	P-value	Explained variance (LCD220) (%)	P-value
PRODSPE	40	0.00	6	0.04
DISTSETTLE	0	0.77	1	0.46
POP	8	0.02	4	0.09
DISTROADS	5	0.06	3	0.16

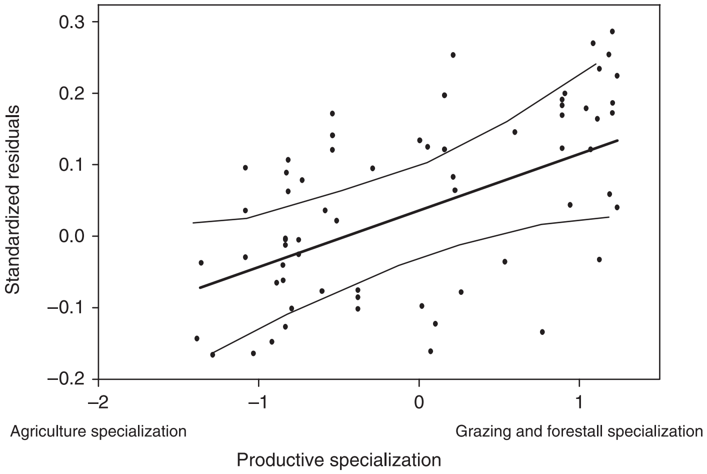

Figure 4 Standardized residuals of environmental multivariate model plotted against productive specialization. Positive residuals plot close to areas in the Pyrenees devoted to grazing and forestry (diversification by human management), while negative residuals plot in agricultural areas and cropland within lowland areas (homogenization by human management)

variance of land-cover diversity (for the model with 24 land classes). The relationship between the residuals obtained from the environmental model and productive specialization (40% of accounted variance) indicates that although environmental factors exert a greater control over land-cover diversity (Del Barrio *et al.* 1997), human influence alters land-cover diversity to an important degree. The combined model explains 80.75 per cent of observed variance in land-cover diversity by adding the variance explained by human factors to the variance explained by physical ones (the sum of 65% explained by physical variables and 40% of the unexplained variance of the natural model explained by productive specialization). Consequently, these quantitative results corroborate the character of the landscape, as with the synthesis of human and bio-geo-physical systems.

As expected, the environmental model obtained from LCD24 shows that land-cover diversity is directly related to spatial variability in climate and lithological diversity. This pattern is typical of mountain systems throughout the world, which generally comprise many different types of vegetation, land use and morpho-climatic belts as a consequence of the control of altitude on temperature. In the Pyrenean case, lithological diversity (granite, limestone, sandstone, flysch, slate and schist) produces areas of strongly contrasting topography (with contrasting slopes and soil depth and therefore variable exposure to solar radiation) that control water availability. This indicates different potentialities for different areas in terms of supporting natural vegetation and the exploitation of land use. In terms of the effect of the number of land-cover classes on diversity analysis, the proposed approach shows a poor

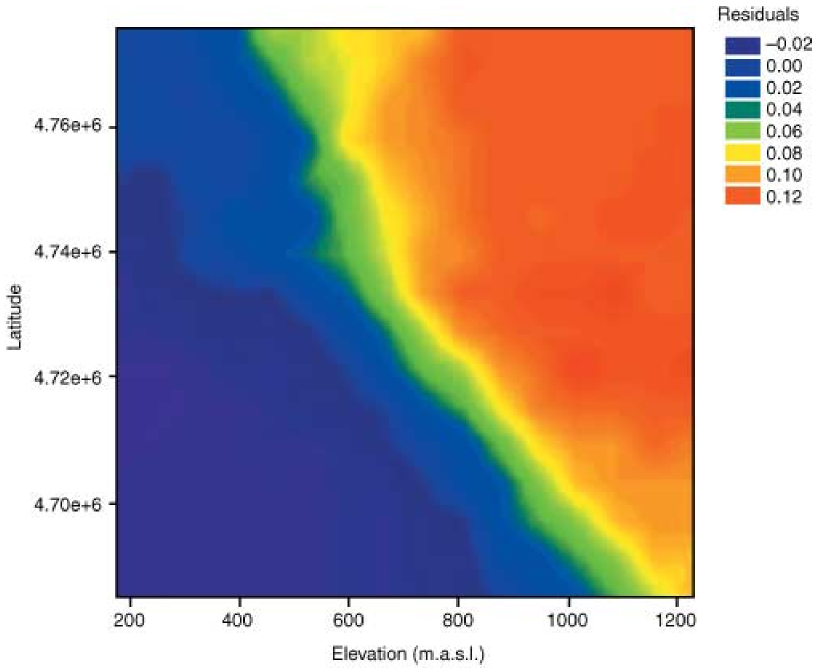

Figure 5 Standardized residuals of environmental multivariate model plotted against elevation and latitude. There is a clear spatial pattern from the highlands, mainly located in the north part of the study area, and the cropland systems located in the lowlands. This pattern suggests that human management has altered land-cover diversity in different ways: diversification in the mountains and homogenization in lowland areas

robustness when the number of land-cover classes is changed. The explained variance of LCD220 by physical factors is low (23%). In our case, this could be a consequence of the type of land-cover map used in the analysis. The map was generated from an agronomical perspective, and areas of cropland classes were very detailed. Thus, the map differentiates, for example, many types of fruit trees (olive, peach, apple, etc.; irrigated and non-irrigated) as well as croplands cultivated during the year compared to those left fallow. Consequently, lowland areas devoted to cropping present high levels of land-cover diversity when the original map is used in the analysis. The uncertainty that different classification rules of thematic values introduces into the results must be assessed in specific studies.

The methodological approach used in this study can also be applied to other areas to interpret the nature of diversity in regional-scale land-cover dynamics in relation to social and economic trends where temporal data on changes in land cover are unavailable. Land-cover diversity can be transformed bi-directionally by anthropogenic forces: diversification–homogenization. In the present study area, the residuals (obtained from an environmental model with 24 classes) are positive in areas around the Pyrenees that are traditionally devoted to forestry and grazing (Figure 4), suggesting that traditional socio-economic and cultural frameworks enable the Potential Diversity (H_P) derived from environmental factors (Garcia-Ruiz 1990).

It is important to question why land-management practices have resulted in increased landscape diversity in mountainous areas within Navarra. Pyrenean landscapes, as with other European mountain landscapes, are the result of a long history of human management and feature high levels of spatial heterogeneity (Di Pasquale *et al.* 2004). European mountains have been transformed by two different management models: over-exploitation based on traditional management with a global and intense use of resources, and a sub-exploitation model that features intensive use of productive areas and the abandonment of other areas. During the traditional management period, the environmental diversity and high levels of population that this area supported for decades led to a complex spatial organization. In short, the process of past landscape diversification in many European ranges may well be explained as follows. Initially, pastures, forestry and agriculture formed the basis of economic activity. These activities resulted in a mosaic of land-cover types characterized by summer pastures, forests, cultivated land, abandoned fields and brushland. Specifically in terms of Navarra, previous authors (Loidi and Bascones 1995) have suggested that potential forests such as those of beech (*Fagus sylvatica*) or oak (*Quercus petraea*) were partially transformed and dominated by more productive species such as *Pinus sylvestris*. Some forests were cleared and transformed into meadows or cultivated terrace fields in the lower parts of Pyrenean valleys. These changes in potential vegetation resulted from the adaptation of anthropogenic economic production to the potentiality of each landscape unit, and it implied a transformation of the potential distribution of land cover. Finally, the boundary between forest and alpine pastures was transformed to obtain supplementary sources of fodder. This situation, a common one for many European mountains, was dynamic because of fluctuations in population densities and grazing livestock and it supported an increment in spatial complexity.

Over the past 40 years in the Iberian ranges and other mountainous regions in Europe, the above scenario has changed because of the transformation of demographic structures. This transformation has thus reversed the dynamics from diversification to homogenization (Floristán and Lizarraga 1990; Fernández-Guillén and Jogman 1994; Torta 2004). Montane landscapes have accelerated toward unstable states because of radical changes associated with emigration to urban areas and improved accessibility to mountain regions. Consequently, grazing pressure has decreased and cultivated slopes have been abandoned (García-Ruiz and Lasanta 1990 1993). New spatial trends such as reforestation and land-cover homogenization have emerged (Beguería *et al.* 2003; Metailié and Paegelow 2004), resulting in a decrease in landscape diversity within the Pyrenees (Taillefumier and Piégay 2003; Lasanta-Martinez *et al.* 2005). For example, the abandonment of crop areas in the Navarra region from 1960 to 1990 has led to an increase in the area of forested land of 100 000 ha (Gobierno de Navarra 2000). Nevertheless, the spatial signals of recent land-cover homogenization are not yet extensive, and Current Diversity (H_C) is higher than Potential Diversity (H_P). Thus, residuals are positive in mountainous areas devoted to grazing and forestry. This positive trend is a consequence of the vegetation recovery process and its different stages in relation to: (i) the soils, climate and topography of each area; (ii) the type and intensity of human disturbance; and (iii) the year of abandonment. Following abandonment, a process of plant succession occurs at varying rates and results in a dense shrub cover after 25–30 years and forest cover after 70 years (García-Ruiz *et al.* 1996; Molinillo *et al.* 1997). Some abandoned areas, such as cultivated terraces developed within the lower reaches of forests, contain recovering vegetation such as scrublands; these areas belong to the first succession stage. Other areas have been transformed to sparse or dense forest. Thus, as these areas have not changed directly and uniformly to dense forest, land-cover diversity remains high. In contrast to mountainous areas, we identified homogenization related to human management in areas further from the Pyrenees; however, some of the residuals located in areas of Mediterranean agriculture in Navarra show positive values, perhaps as a consequence of local characteristics (Figure 4). Those areas that are geographically located in the Mediterranean part of Navarra but that contain montane forests in addition to the surrounding land covers, such as areas with mountain ranges, show higher levels of land-cover diversity than areas that are strictly located in regions with little relief. Negative residuals indicate that these areas of low-lying land present lower Current Diversity (H_C) values than those of Potential Diversity (H_P). Traditionally, these areas have been characterized by a mosaic of natural land cover, being mainly *Quercus coccifera* and *Quercus ilex*, croplands following the traditional Mediterranean system (wheat, grape vines and olives) and smaller areas devoted to irrigated vegetables and fruit crops. Thus, there has been a high level of diversity and complexity in land cover; however, the twentieth century saw a change in this pattern. In short, the driving forces of these changes during different periods included technical advances such as mechanization, changes in tenure and production regimes, and finally, macro-economic changes related to globalization and the specialization of particular regions in specific types of agricultural production. These forces have created new land-cover patterns, and cereal production has led to a new homogenized landscape in southern Navarra and other Mediterranean landscapes. The satisfactory description that our numerical model provides of well-documented changes in the diversity of the landscapes in the present study area (as described above) suggests that the model may well be able to detect the past influence of socio-economic driver forces on current land-cover diversity. Accordingly, the model is likely to be useful in detecting the state of many other European landscapes within the context of diversification–homogenization drift.

Having a clear insight into the effects of driver forces on landscape changes and the specific magnitude of biological impacts on these changes is of utmost importance at both local and regional scales because of the future environmental and social consequences of changes in land management within European landscapes. In terms of biodiversity, numerous studies have reported a link between species richness and the diversity of land use or land cover (e.g. Nogués-Bravo and Martínez-Rica 2004). Landscape diversity indicates higher levels of resource variability, and consequently a greater capacity to support species (Faith 2003). With this issue in mind, and the abandonment of agricultural land documented in many different areas of Europe since the Second World War (for a review of agricultural abandonment in Europe, see MacDonald *et al.* 2000), the future vulnerability of European biodiversity to trends in landscape homogenization should to be taken into account. In light of current concerns over processes of agro-ecosystem homogenization and climate change, further reductions in biodiversity are likely. Thuiller *et al.* (2005) discuss the vulnerability of plant species in Europe related to climate change, while Farina (1997) describes a reduction in the species richness of birds in a sub-Mediterranean agro-ecosystem resulting from landscape homogenization. In terms of Navarra, the projected transformation of land uses and climate change may well result in important losses of vertebrates. The most vulnerable species are likely to be those related to Eurosiberian and alpine biogeographic provinces (changes in their geographical ranges outside Navarra or local extinctions within alpine belts; for an overview of factors that control vertebrate species-richness in Navarra, see Nogués-Bravo and Martínez-Rica 2004). The abandonment of agricultural land also provides opportunities for the purchase and management of land with the aim of enhancing biodiversity (Rounsevell *et al.* 2006). For example, one of the most endangered birds in Navarra, Dupont's Lark (*Chersophilus duponti*), is under pressure because of changes in the composition and structure of steppic landscapes resulting from agricultural activity (Nogués-Bravo and Agirre 2006). Further abandonment of croplands is likely to reduce anthropogenic pressures on steppic habitats and on Dunpont's Lark. In any event, future impacts on biodiversity are likely to be complex. Araújo *et al.* (under review) assessed human–biodiversity conflicts in Europe for the twenty-first century. Their results challenge the idea that no single set of decisions should necessarily maximize benefits for all aspects of biodiversity in every region.

In summary, the present study proposed a methodological approach that is suitable for use at regional scales and has been used to detect a robust signal supporting the hypothesis proposed by previous authors (García-Ruiz and Lasanta 1990) from a descriptive perspective without any numerical verification: traditional management in European mountains, especially in Mediterranean mountains, has resulted in an increased diversity of land cover, although new homogenization trends have emerged. Results obtained herein also show that land-cover diversity is the final result of synergies among environmental and anthropogenic factors, but that the effect of human management on landscape trends (diversification–homogenization) differs in relation to geographical context. The availability of the data used herein for many European countries supports the applicability of this approach to other landscapes in order to gain a better regional-scale insight into diversification–homogenization trends where detailed information on land-cover changes based on aerial photographs or remote-sensing images is unavailable. It is important to emphasize that the results contain a degree of uncertainty. I have assessed only two environmental variables (climatic variability and lithological diversity) to explain land-cover diversity. These variables were chosen because they synthesize most of the abiotic factors that comprise the landscape system, although other variables such as soils or geomorphology could also be used in this model. Nevertheless, these kinds of data are not usually available at a regional scale and the applicability of the model would then be reduced.

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