INTRODUCTION

Analyses of the relationships between species and their habitats are essential for establishing appropriate conservation management plans (Morrison et al. 1998, Jones 2001). During the last decade, a high number of statistical procedures for modeling the distribution of species have been developed (e.g. Guisan & Zimmermann 2000, Rodríguez et al. 2007). They provide a means to model habitat suitability for a certain species over an extended area using a limited number of observations, and with the help of a number of auxiliary environmental variables. Although this approach has significant limitations (Seoane & Bustamante 2001, Rushton et al. 2004, Guisan & Zimmermann 2000, Rodríguez et al. 2007, Tapia et al. 2007b), modeling studies of the distribution of raptors and other endangered species have become more common in recent years, given their utility as management tools (see e.g. Sánchez-Zapata & Calvo 1999, Naves et al. 2003, Bustamante & Seoane 2004, López-López et al. 2007, Tapia et al. 2007a, Tapia et al. 2009a, Sarasola et al. 2008). The existing spatial prediction models for habitat suitability range from logistic regression techniques, where the presence and absence of a species is related to a number of auxiliary variables through a logit link function, to models like DOMAIN (Carpenter et al. 1993) and ENFA (Hirzel et al. 2002) that use pattern analysis techniques to understand the relationships between the presence of the species and some environmental variables. The use of these techniques has been facilitated in recent years by the high quantity of environmental information freely available via numerous web sites, and by the implementation of such models using Open-Source software (Rodríguez et al. 2007).

The Golden eagle (Aquila chrysaetos) is a cosmopolitan large raptor species, distributed throughout the Northern hemisphere (Del Hoyo et al. 1994, Watson 2010). This top predator, typical of open or lightly wooden landscapes (Watson 2010), is considered scarce and declining in most European countries (Haller & Sackl 1997, Watson 2010, Sergio et al. 2006, Whitfield et al. 2004a, Tapia et al. 2007a).
In Spain, Golden eagle is currently considered a near threatened species (Madroño et al. 2004). Its population declined in the 1970s but at present seems to be stable or even increased in some regions (Arroyo 2003, Del Moral 2009), and indeed these populations are among the most important in the Western Palearctic (Del Hoyo et al. 1994, Birdlife International 2004). Galicia constitutes the northwestern border of its distribution range in the Iberian peninsula. The species in this region is considered very threatened, with a population of 11 confirmed breeding pairs (Gil & Tapia 2009), and other 9 confirmed breeding pairs in the neighboring regions of Castilla-León, Asturias and the north of Portugal. Individuals outside these breeding areas are generally in post-breeding dispersion. The main conservation problems of the species in Galicia are associated with habitat limitations such as inadequate food-supply, poor availability of nesting sites, human disturbance in breeding areas and changes in land use (Madroño et al. 2004, Tapia et al. 2007a). Moreover, this small population inhabits a transitional ecological area relatively isolated from other nuclei in the Iberian Peninsula (Tapia et al. 2007a, Gil & Tapia 2009), and an increase in mortality, in a species with such low reproductive rates, can have a major impact on its population (Whitfield et al. 2004a, b). Recent studies have been conducted to determine the main aspects of habitat suitability for Golden eagle in different areas in Europe. Studies in Scotland aimed to provide a scientifically sound framework for the protection of the species in that country (Whitfield et al. 2004a, b; Whitfield et al. 2006). Sergio et al. (2006) used stepwise logistic regression to model the habitat suitability for Golden eagle in a region of the Alps. López-López et al. (2007) used a Generalized Linear Model (GLM) to determine suitable nesting areas, at three spatial scales in a representative Mediterranean area in the southeast of the Iberian Peninsula, with topographic, climatic and land use parameters as explanatory variables. In the province of Ourense (northwestern Spain), Tapia et al. (2007a) analyzed both the historical and present situation of Golden eagle and used logistic regression to generate maps of the potential distribution at 10 x 10 km cells.

Remote sensing technology provides information at high spatial and temporal resolution (Turner et al. 2003). The combination of remotely sensed and field survey data within modeling algorithms makes possible to map species habitat and monitor their temporal changes over large areas (Sarasaola et al. 2008, Franklin & Miller 2009, Tuanmu et al. 2011). The goal of the present study is to identify the suitable breeding habitats for a threatened population of Golden eagle in a transitional ecological area in northwestern Spain and to investigate the advantages of using remote sensing information versus the use of traditional categorical land use maps in modeling habitat suitability for this raptor in this area, where nesting site availability is an important natural factor limiting its breeding density.

MATERIALS AND METHODS

The study area: Even if the natural distribution of Golden eagle in the NW of Spain includes Galicia and the neighboring regions of Castilla-León and the north of Portugal, there is a lack of auxiliary data beyond the administrative boundaries of Galicia. This implies that our study area has been restricted to the SE of the Autonomous Region of Galicia according to its current nesting distribution (Fig. 1).

This is a transitional area of 13500 km² between Atlantic and Mediterranean climates. Average annual rainfall ranges between 700 and 1900 mm, and annual mean temperature between 6.3 and 14.5 °C (Martínez & Pérez 1999). Maximum altitudes (up to 2071 m.a.s.l.) are located east, with minimum altitudes (29 m.a.s.l.) in the river valleys. The natural vegetation is essentially Eurosiberian in the central and western mountains and Mediterranean in the remaining area (Izco 1987). Natural woodland is composed by deciduous forests, mainly Quercus pyrenaica, Quercus robur and Castanea sativa. A large part of the territory is dedicated to timber production, mainly Pinus pinaster and Pinus sylvestris. In the Atlantic region the dominant shrub-land vegetation is gorse (Ulex sp.) and Calluna vulgaris, while in the areas with a Mediterranean influence, Erica australis, Pterospartum tridentatum and Cistus ladanifer are the most representative species. In mountainous areas, Cytisus sp. and Genista sp. dominate. Although gradually abandoned, extensive livestock and agriculture are common traditional land uses over a large part of this area, and the territory is being recolonized by natural vegetation.

Nesting sites: From 1997 to 2010 sampling campaigns, on areas with suitable habitat for the nesting of Golden Eagle, have been conducted in order to detect the presence of breeding territories (see Tapia et al. 2007a, Gil & Tapia 2009, Tapia et al. 2009b for details on the field survey). An inventory of the former breeding territories (well-know nesting areas in the 1960s

Fig. 1. – Location of the study area (gray) over the map of the Iberian Peninsula.
and 1970s) has been also conducted by compiling bibliographic information (López & Guíñán 1983, Guíñán et al. 1991, Romero 1995, SGHN 1995, Arroyo 2003, Martínez et al. 2003, Tapia et al. 2007a, Tapia et al. 2009b), as well as field data provided by biologists, ecologists and technical personnel. We assumed that the distribution of the Golden Eagle in the study area is fully known, and that the rate of pseudo-absences (Hirzel et al. 2002, Bustamante & Seoane 2004) is low. The final dataset includes 60 different current and past breeding territories in Galicia and the neighboring regions of Castilla-León, Asturias and the north of Portugal (< 10 km from the Galician border), which avoids pseudoreplication. However, the information of the auxiliary variables is not completely available outside the Galician region and only the 48 territories within the Galician border have been considered. Some pairs changed their nests during the study period inside the same territory. In these cases, we selected the most frequently used nest as the reference location for the calculations. Finally, we randomly split our data set into a calibration set containing 80 % (n = 38) of the data points, and a validation set containing the remaining 20 % (n = 10) of the nest locations to check the accuracy of our predictions.

Methodology: The classification method used in this paper follows the DOMAIN algorithm developed by Carpenter et al. (1993) and implemented in the statistical environment R V2.11.1 (http://www.r-project.org/) through the package adehabitat (Calenge 2006). The DOMAIN algorithm determines habitat suitability using a point-to-point similarity metric between the environmental conditions at observed nesting areas and those at candidate locations. The most suitable areas for nesting correspond to those candidate points that present higher similarity values, in the hyperspace of environmental variables, in relation to the observations (Carpenter et al. 1993).

The distance d between a candidate point A and an observation B in a p-dimensional space is:

\[ d_{AB} = \frac{1}{p} \sum_{i=1}^{p} \left| \frac{A_i - B_i}{\text{range}_i} \right| \]  

The complementary similarity is defined as:

\[ R_{AB} = 1 - d_{AB} \]  

We can calculate, for each candidate point A in the grid, the maximum value of similarity in relation to the overall group of observations Tm:

\[ S_A = \max_{j=1}^{m} R_{TA} \]

Finally, a user-defined environmental threshold will only select as suitable those points with a maximum similarity equal 70 or higher than this threshold.

Auxiliary information: A total of 24 raster maps were used as predictor variables within a Geographic Information System (GIS). Each raster map has the following grid definition: Xmin = 2819000, Ymin = 2245000, Xmax = 2954000, Ymax = 2345000 and grid size of 250 m, encompassing an area of 13500 km². All the maps were projected to the Lambert Azimuthal Equal Area projection (European Terrestrial Reference System 1989) following the recommendations of INSPIRE (Annoni, 2005). The spatial resolution of the available remote sensing information limits the spatial resolution of the analysis to 250 m. Water bodies (rivers and dams) were masked out using the information on the CORINE land cover map (http://dataservice.eea.europa.eu/)

Topographic variables: A 90 m Digital Elevation Model (DEM) from the SRTM90 V4 dataset was obtained from the Consortium for Spatial Information (CGIAR-CSI) (http://srtm.csi.cgiar.org/). This DEM was used to derive the following topographic maps: slope, annual solar radiation and insolation, plan curvature and profile curvature. These raster maps were then upsampled to 250 m to have the same spatial definition as the remote sensing information.

Remote sensing information: A temporal series of Moderate Resolution Imaging Spectroradiometer images (MODIS) of the Enhanced Vegetation Index (EVI) at 250 m resolution for the period 01/01/2004 to 31/12/2006 was also used. These data were obtained from the MODIS EOS-Terra imagery at the Earth Observing System Data Gateway (http://eospso.gsfc.nasa.gov/). The EVI is an index designed to enhance vegetation patterns. Sixty four blocks covering the whole study area were reprojected to the Lambert Azimuthal Equal Area (ETRS89) projection. Multicollinearity in the temporal series of remote sensing images is a common phenomenon which causes over-fitting of the estimates. PCA transformation of temporal remote sensing has been proved as an effective method to enhance vegetation changes in multi-temporal data sets while avoiding multicollinearity in the data (Lasaponara 2006). In our study, the original MODIS images have been transformed to Principal Components and only the first 10 principal components have been used for modeling.

Land use: Land use was determined according to the vector vegetation maps from the Regional Environmental Council, at 1:100 000 scale. This map was rasterized and generalized to a 250 m grid. A total of 12 land use classes are present in this area. The most prevalent land use classes are heathland, pastures and deciduous forests. Arable agricultural land has a relatively high presence in the SW of the study area. In general, the area is mostly covered by natural vegetation.

Climatic Variables: Monthly mean temperatures were obtained from the Climatic Atlas of the Iberian peninsula (Ninyerola et al. 2005) and upsampled to 250 m resolution. A map of extreme temperature differences was created using the mean temperature maps for January and July.

Landscape fragmentation and diversity: Landscape Fragmentation, Relative Richness, Simpson’s Index (D) and Simple diversity index (S) were calculated using the Spatial.CalcDiversity script and the Texture Analysis and Neighborhood Statistics
extension (http://arcscripts.esri.com/) within ArcView GIS 3.2, using the land use map as input data.

Distance to villages and roads: The maps of distances to both villages and roads were calculated using the distance operation in ArcGIS 9.2 and the layers of roads and populated sites from the Territorial Information System of Galicia (http://sitga.xunta.es) within a buffer of 2 km.

RESULTS

Correspondence between land use classes and the remote sensing information

Fig. 2 shows the histograms for each land use class and the EVI-PCA values (only relationships for the three main Components of EVI have been presented). We observe a correspondence in the patterns between land use classes and values of EVI-PCAs. Coniferous forests show high frequencies in the higher range of PCA3 values, while deciduous forests tend to be more frequent in the lower
ranges of this PCA. Mines also show high frequencies in PCA3, but they can be differentiated since they tend to present low values on PCA1. These patterns, analyzed over the whole 10 EVI-PCAs, allow the discrimination of different land use classes. However, there is an overlapping of different land use classes over the same values in EVI-PCA. As reasons for this overlapping we can cite i) generalizations made in the land use classification of transitional areas that leads to an unsatisfactory land use classification; ii) Errors due to the upscaling of the vector database up to 250 m rasters, with the consequent loss of information and iii) the generalization in the MODIS data, that averages the EVI values within each pixel. In any case we consider that these Principal Components can be properly used in this kind of study since they provide more precise information about vegetation variability than the 250 m information coming from the rasterized vector maps of land use. In addition, they also capture spatial differences, related to vegetation dynamics, climatic influence and changes in land use, not recorded in land use vector maps.

**Spatial pattern of nesting sites**

As shown in Fig. 3, the selection of nesting locations by the species is preferentially influenced by topograph-

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Fig. 3. – Histograms of the observations (gray) over the environmental variables (white).
ic and human pressure variables. There is a clear trend to find nesting areas at medium-high altitudes on steep slopes, low insolation and radiation and low anthropic disturbances (avoiding human settlements and roads) and low values of EVI-PCA1. The nests clearly shows a spatially aggregated clustered pattern. The species range for nesting is restricted to specific areas within the region, with 77.1% of nests presenting a nest neighbor within 1 km distance.

**Map of the suitable locations for nesting**

The final map of the suitable locations for nesting obtained through similarity metrics of environmental conditions is shown in Fig. 4. An optimal environmental threshold of 0.96 has been used to calibrate the algorithm according to the model performance obtained from a receiver operating characteristic curve (ROC), which has been calculated upon presence data from the validation dataset and an equal number of randomly distributed pseudo-absence locations. The total area suitable for nesting is estimated to encompass 510 km² and is mainly located in areas along the ridges formed by the main canyon rivers, with medium elevation ranges, steep slopes and low human influence. Only 14.6% of the territories appear completely isolated at distances higher than 5 km from the closest nest.

**Model Validation**

We performed the validation of the model using a randomly selected 20% subset of the total nesting sites database. Since we only have true nest locations, we only can check true positives vs. false negatives. The validation shows an overall agreement for 78% of the observations.

**DISCUSSION**

The results obtained in this study are in agreement with the nesting habitat requirements of the species in different regions of the Iberian Peninsula and Europe (Sánchez-Zapata & Calvo 1999, López-López et al. 2007, Carrete et al. 2000, Watson 2010) and, interpreted from a biological point of view, congruent with a previous habitat selection study in a sub-region of the same area with similar auxiliary variables but considering a different spatial scale and a different modeling algorithm (Tapia et al. 2007a). The areas identified with highest suitability correspond to the historical presence of nesting sites for the species (Tapia et al. 2007a, Tapia et al. 2009b). The distribution of suitable habitat for Golden eagle is mainly controlled by topographic variables, climate and human pressure independently of the spatial scale. River canyons and steep slopes are the preferred locations for nesting. We relate
the low values of radiation and insolation, at these sites, to an effect due to topography. In this study, EVI-PCA1 values, which correspond to the areas of Mediterranean climate (Martínez & Pérez 1999). The comparison with previous studies (Tapia et al. 2007a) shows that the use of temporal MODIS-EVI satellite images presents some advantages in relation to the use of traditional land use classification maps. These latter maps provide land use information as ordinal classes that can only be included in quantitative analyses after transformation to dummy variables. These maps are often old and present information on a mid-lag period of about 5-10 years. MODIS-EVI information provides directly quantitative information on the vegetation differences that can be interpreted as different types of vegetation cover. In addition, they provide the temporal component of variation that can be used to differentiate patterns of vegetation linked to seasonality (evergreen vs. broad-leaved forests, crop alternation in the same area, etc), land use changes (afforestation, reforestation, forest fires, etc) and climate. This information can be readily included in quantitative modeling without any transformation. However, in this study we decided to simplify this information through Principal Component Analysis to avoid redundancy while accounting for the maximum variability in the data.

We finally created a nesting suitability map using the land use classes as an input instead of the remote sensing information in the EVI-PCAs. The land use classes map was previously transformed to dummy maps. This map (Fig. 5) shows more widespread potential suitability for nesting than that obtained in the previous analysis and shows clear disagreements with the known distribution for the species in the area (Arroyo 2003).

The overall percentage of agreement between predicted and observed locations is high (78 %). This can be partly due to the aggregation effect of this species in the selection of their breeding territories. This clustering effect makes that most of the points used for validation fall within the neighborhood of a nest used for calibrating the model, over estimating the model accuracy. Some of the inaccuracies that can be found in our final model of nesting suitability may be explained because of the different spatial resolutions of the original data. Our model was built mixing information at field scale with 250 m raster information. In addition, some of the 250 m grids come from vectorial information or from information at higher spatial resolution. This generalization of the data is necessary but we are aware that this can constitute an important source of uncertainty in the final results.

**Fig. 5.** Predicted locations suitable for nesting using land use classes instead of EVI as auxiliary information.
The framework presented here has a number of important advantages over other previous studies. It allows the use of a variety of different types of information without considerations of multicollinearity. In fact, the method is not based in a probabilistic measure but a classification of similarities. It also allows an in-depth analysis of the processes governing the distribution of nesting sites over the area, so that conservation policies can be implemented appropriately. The advantage of this technique lies in the possibility of integrating various environmental factors that would otherwise be ignored, especially related to vegetation types. It is clear that there are some spatial features like topography, human pressure and land cover that highly influence the location of future breeding areas. Such environmental patterns must be taken into account by policy makers in order to preserve this endangered species in the region. The R script we developed is fully automated so that selecting suitable observations, retrieving environmental information for the observations, suitability mapping, validation, projection and export to a GIS environment is done with little human intervention. A great advantage of the automation is that the input maps (points and rasters) can be updated when new auxiliary variables at higher spatial extent or resolution, or new nest observations, become available.

This study of habitat suitability constitutes a basic tool for the implementation of conservation policies for this threatened species in the transitional ecological region considered. It would be important to increase future cooperation with the regional agencies in the neighboring territories of Castilla-León and the north of Portugal to improve the knowledge of the Golden eagle population in northwestern Iberia. Golden eagle is considered as an indicator of high biodiversity (Sergio et al. 2005), thus its conservation should be a priority and it is urgent to get an integral strategic conservation plan to preserve the natural heritage in this region.

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