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Measuring the Insecurity Index of species in networks of protected areas using species distribution modeling and fuzzy logic: The case of raptors in Andalusia

D.L. Díaz-Gómez[a,*], A.G. Toxopeus[a], T.A. Groen[a], A.R. Muñoz[b], A.K. Skidmore[a], R. Real[c]

[a] Faculty of GeoInformation Science and Earth Observation (ITC), University of Twente, PO Box 217, 7500 AE Enschede, The Netherlands
[b] Fundación Migres, Huerta Grance, CN'340 Km. 96 (Pelayo), 11390 Alegeciras, Cadiz, Spain
[c] Faculty of Science, University of Malaga, E29071 Malaga, Spain

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ABSTRACT

Networks of protected areas often fail to include favorable areas for all species, even when they cover a considerable percentage of a territory. To assess the effectiveness of protected areas, harsh thresholds are commonly used (e.g. minimum 20% of the cell must be covered by a protected area to define it as protected). Setting a threshold implies a transformation of continuous data into binary data which frequently results in information loss and in outcomes changing sharply depending on the threshold set. To avoid uncertainty and information loss when evaluating the effectiveness of protected areas, we developed the "Insecurity Index" based on species distribution modeling and fuzzy logic. The Insecurity Index (0–1) of a species represents how much of the fuzzy set of favorable areas for the species is not included in the protected areas. The larger the extent of favorable areas of a species that is not covered by protected areas, the higher the Insecurity Index. We applied this approach to Andalusia, in the south of Spain, which sustains 22 out of the 40 raptor species present in Europe, and has about 30% of its territory covered by regional and Natura 2000 protected areas. By measuring and mapping the Insecurity Index of raptors in Andalusia we assessed the extent to which protected areas exclude favorable sites for forest, cliff and steppe nesting raptors, identified species with a high Insecurity Index and mapped high priority areas for implementing conservation actions. The Insecurity Index was significantly higher for steppe nesting raptors (mean Insecurity Index = 0.81) compared to forest (mean Insecurity Index = 0.62) and cliff nesting raptors (mean Insecurity Index = 0.59). We propose areas of high insecurity for steppe nesting raptors, as potential sites for implementing actions aimed at providing nesting habitat for these species. As demonstrated here for raptors in Andalusia, the Insecurity Index can be used to assess and compare the extent to which species' favorable areas are left unprotected by reserves while avoiding uncertainty and information loss due to the use of thresholds.

1. Introduction

Networks of protected areas are fundamental conservation measures for the persistence of species (Chape et al., 2008), but in many cases even if they cover a considerable percentage of a territory they may fail to support adequately all groups of species (Rodrigues et al., 2004; Watson et al., 2011). Given the limited financial resources available for conservation, evaluating species protection within current networks of protected areas and prioritizing sites for the establishment of new ones or for the implementation of management action are crucial steps for biodiversity conservation.

The basic information required to evaluate a species' protection within a network of protected areas is the geographical distribution of the species and of the protected areas (Jennings, 2000). Predefined thresholds are often used to derive such information. For example, when the distribution of a species is inferred from a species distribution model, a threshold is frequently used to transform probability of occurrence into discrete categories (present/absent or suitable/unsuitable) (de Pous et al., 2011; López-López et al., 2011; Martinez et al., 2006). This transformation entails a loss of information on the location of areas of very high probability of occurrence (e.g. probability of occurrence >0.9). Adittionally, depending on the method used to derive a probability threshold, models with different levels of accuracy can be obtained (Jiménez-Valverde and Lobo, 2007).

Information on protected areas often comes in vector format whilst information on species often comes in raster format.

* Corresponding author. Present address: Carrera 66 N. 76 – 26 Unidad 7 Apartamento 203, Postal code 111211, Bogota, Colombia. Tel.: +57 1 2251421; mobile: +57 3202262571.

E-mail addresses: diazgomez24161@itc.nl (D.L. Díaz-Gómez), toxopeus@itc.nl (A.G. Toxopeus), groen@itc.nl (T.A. Groen), roman@fundacionmigres.org (A.R. Muñoz), skidmore@itc.nl (A.K. Skidmore), rrgimenez@uma.es (R. Real).

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Thresholds are also used to match the spatial scale of the protected areas' data with the spatial scale of the species data (Estrada et al., 2008; Sanchez-Fernandez et al., 2008; Traba et al., 2007). For example, in order for a 10 km × 10 km cell to be considered protected, it has to be covered at least in a 25% by a protected area. The protected area threshold chosen affects the estimated representation of species in the network (Araújo, 2004). The use of both thresholds, probability and protected area thresholds, implies that the perceived protection status of the species can change sharply depending on the thresholds set (Alagador et al., 2011).

Fuzzy logic deals with sets that have a degree of membership to a category (i.e. fuzzy sets) (Zadeh, 1965). Within the framework of fuzzy logic a statement can be half true instead of being either false or true. Previously, fuzzy logic was used to derive fuzzy indices of richness, rarity, vulnerability and endemicity (Estrada, 2008; Real et al., 2006b). These fuzzy diversity indices are calculated from favorability values (Estrada, 2008). To obtain favorability values, the probability of occurrence of a species predicted by a logistic regression model is transformed with the favorability function (Real et al., 2006a) (Eq. (1)). Because favorability values are comparable between species with different prevalence (i.e. ratio of the number of presences to the total number of sample points), they can be used to calculate diversity indices without a threshold transformation into species' presence and absence (Real et al., 2006a). These fuzzy diversity indices address the problem of information loss, resultant from using a harsh probability threshold, and as such allow the characterization of areas with varying degree of favorability for the species (Estrada et al., 2008).

$$F_{ij} = \frac{P_{ij}/(1 - P_{ij})}{n_1/n_0 + P_{ij}/(1 - P_{ij})} \qquad (1)$$

The favorability function by Real et al. (2006a). F_{ij} is the favorability of the species i in the cell j. P_{ij} is the predicted probability of the species i in the cell j, n_1 is the number of presences and n_0 is the number of absences.

We propose the "Insecurity Index" as a new approach to evaluating species protection. This index is built as a fuzzy logic equation involving two fuzzy sets: extent of a cell covered by a protected area and predicted favorability. The Insecurity Index represents how much of the fuzzy set of favorable areas for the species is not included in the fuzzy set of protected areas. We focused on an "Insecurity Index" rather than a "Security Index" because it provides the same essential information and it facilitates mapping of important areas for the implementation of conservation or management action. This index is comparable between species with different prevalence because it is calculated from predicted values of favorability instead of predicted values of probability. Since the index is constructed from fuzzy instead of binary sets it avoids the uncertainty and information loss arising from the use of thresholds.

We exemplify the use of the Insecurity Index and its advantages over threshold approaches with raptors in Andalusia (Southern Spain). We obtained favorability models for all raptors breeding in Andalusia and used them to calculate the Insecurity Index for each species. We compared the Insecurity Index of steppe, cliff and forest nesting raptors under two scenarios of protection. For one of the species we compare the results obtained from a threshold approach to the results obtained from using the Insecurity Index. Subsequently, we demonstrate how the Insecurity Index can be used to identify areas of conservation importance by mapping the Insecurity Index for raptor species in Andalusia.

2. Data and methods

2.1. Study area

Andalusia (87,600 km^2) is an autonomous region of Spain located in the Southern part of the Iberian Peninsula. The climate is typically Mediterranean and presents a strong gradient of rainfall, of 170–1800 mm from east to west (Font, 2000). The altitude varies from sea level up to 3500 m and the mean annual temperature ranges from 9.8 °C to 19.4 °C (Font, 2000). The Pennibaetic and Subbaetic mountain ranges are located in the south and east, the Sierra Morena Mountains in the north and the Guadalquivir valley in the west. In the mountain ranges the Mediterranean forest is the most characteristic vegetation; in the lowlands olive and cereal crops predominate.

2.2. Data

2.2.1. Species data

The autonomous region of Andalusia sustains 22 raptor species breeding within its territory, representing half of the raptor species present in Europe (Martí and Moral, 2003). Raptors in Andalusia can be classified into forest, cliff or steppe raptors according to their nesting habitat. Data on the presence and absence of breeding territories of all the breeding raptors in Andalusia were obtained from the Atlas of breeding birds of Spain (Martí and Moral, 2003). The data on the atlas was the result of fieldwork campaigns that took place between 1998 and 2001 by a network of volunteers and professionals and it is originally represented in a vector UTM projected grid that covers Andalusia with 975 polygons of 10 km × 10 km. The UTM projected grid was converted to a series of rasters, one for each species presence/absence data. Two species were not included in the modeling. The Western Osprey (*Pandion haliaetus*) was not included because it is considered to be extinct (and is under reintroduction) (Consejería de Medio Ambiente, 2001; Muriel et al., 2010) and the European Honey Buzzard (*Pernis apivorus*) because it has very occasional reproduction in Andalusia (Martí and Moral, 2003). In total we modeled 20 raptor species (Appendix A).

2.2.2. Protected areas' data

We evaluated separately two scenarios of protection: the network of protected areas of Andalusia (RENPA from the Spanish "Red de áreas protegidas de Andalucía") and the RENPA plus the Natura 2000 sites (from here on called Natura 2000). The Natura 2000 network in Andalusia includes all areas protected under RENPA, plus areas that have been declared "site of community interest" but have not yet been officially incorporated into RENPA. The RENPA and the Natura 2000 networks cover 19% and 29% of Andalusia, respectively (Consejería de Medio Ambiente, 2006).

Shapefiles of the protected areas were downloaded from the webpage of the Andalusia's Board (Junta de Andalucía, n.d.) The vector data on protected areas was intersected with the vector UTM projected grid of Andalusia. For each polygon of the UTM projected grid, the intersected areas were used to calculate the proportion of the polygon covered by protected areas (P_j). P_j ranges between 0 and 1, with a polygon receiving a value of 1 when is completely covered by protected areas. The vector UTM projected grid was converted to a raster with P_j as values. By calculating P_j before the vector to raster conversion, the information on the smallest protected areas was not lost.

2.2.3. Predictor variables for species distribution models

The potential predictor variables used in the species distribution models were chosen from a set of 46 environmental variables from various sources (Appendix B). To generate a geometrically consistent data set, all environmental variables were set to the coordinate