Conservation planning in a fire-prone Mediterranean region: threats and opportunities for bird species

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Abstract

In response to the processes threatening biodiversity such as habitat loss, effective selection of priority conservation areas is required. However, reserve selection methods usually ignore the drivers of future habitat changes, thus compromising the effectiveness of conservation. In this work, we formulated an approach to explicitly quantify the impact of fire on conservation areas, considering such disturbance as a driver of land-cover changes. The estimated fire impact was integrated as a constraint in the reserve selection process to tackle the likely threats or opportunities that fire disturbance might cause to the targeted species depending on their habitat requirements. In this way, we selected conservation areas in a fire-prone Mediterranean region for two bird assemblages: forest and open-habitat species. Differences in conservation areas selected before and after integrating the impact of fire in the reserve selection process were assessed. Integration of fire impact for forest species moved preferences towards areas that were less prone to burn. However, a larger area was required to achieve the same conservation goals. Conversely, integration of fire impacts for open-habitat species shifted preferences towards conservation areas in locations where the persistence of their required habitat is more likely (i.e. shrublands). In other words, we prioritized the conservation of not only the current distribution of open-habitat birds, but also the disturbance process (i.e. fire) that favours their preferred habitat and distributions in the long term. Finally, this work emphasizes the need to consider the opposing potential impacts of wildfires on species for an effective conservation planning.

Keywords: wildfires; land-cover changes; priority areas; fire impact; bird assemblage, Marxan, spatial planning

Introduction

Over the past few decades, habitat loss and degradation arising from land-cover changes have been identified as a prevailing threat to species persistence (Tucker et al 1994; Wilcove et al 1998). In the light of the high rate at which habitats and landscapes are being transformed, areas identified as most valuable for the species persistence may be prioritized and managed for conservation actions to ensure the long-term persistence of their required habitats (Margules et al 2002).

The spatial selection of priority areas for conservation is usually performed using static information on habitats and species distributions (Moilanen et al 2009). However, landscapes and species distributions are naturally dynamic both in space and time (Pressey et al 2007; Drechsler et al 2009). Consequently, adequacy of conservation areas matching current landscape conditions and species distributions is not guaranteed in the future after the habitat mosaic has been transformed (Hermoso et al 2011). Hence, conservation decisions that ignore processes driving these changes can be relatively ineffective in promoting the persistence of biodiversity in the long term (Pressey et al 2007). This may be especially important in a context of global change, where climate change, interacting with land-cover shifts and modification of disturbance regimes, could drive the targeted species for conservation out of the reserves (Cabeza and Moilanen 2001; Santos et al 2008).

In the Mediterranean Europe, processes inducing changes at the landscape scale such as land abandonment and wildfires are expected to be critical in determining future biodiversity patterns (Brotons et al 2005; Moreira and Russo 2007). The abandonment of the agricultural land and other traditional land-uses such as grazing and forest harvesting have led to widespread woodland expansion and landscape homogenization (Lloret et al 2002). Fuel (i.e. vegetation) accumulation produced after years of land abandonment leads to an increase of wildfires (Lloret et al 2002), which entails a shift from forests to open-shrub habitats

(Moreira et al 2001). In this context, the resulting landscape dynamics will have variable impacts on species distributions depending on the biological traits of the species involved (Devictor et al 2008).

To deal with uncertainties in future changes in species distributions derived from known drivers of landscape shifts, prioritization of conservation areas should explicitly consider the land-cover changes impacting on species distributions (Araujo et al 2002; Pressey et al 2007). For instance, the effectiveness of conservation practices for forest birds would be seriously compromised if prioritized forest habitats burnt in the future, as it has been shown in many protected areas dominated by forests (Kinnaird and O'Brien 1998; Rodrigo et al 2004). Accordingly, conservation of forest species in areas with high fire risk is likely to be strongly uncertain. However, those areas may constitute an opportunity for the conservation of open-habitat species given that fire will guarantee the availability of open habitats, even under scenarios of land abandonment (Brotons et al 2005; Moreira and Russo 2007).

Hence, to improve the performance of conservation areas in the long term, the future impact of land-cover changes needs to be explicitly considered in the reserve selection process (Lawler et al 2003; Drechsler et al 2009). In this study, we aimed to identify priority conservation areas for two bird assemblages with contrasting habitat requirements: forest and open-habitat species. We analysed separately both bird assemblages to spatially explicit assess the potential impact of land-cover changes on conservation areas. As main land-cover changes, we considered decreases in forest extent and increases in shrubland cover, given the important role of fire dynamics at inducing such changes in the study area (Diaz-Delgado et al 2004). Since the studied bird assemblages have contrasting habitat requirements, we expect a variable impact of fire-induced changes on conservation areas creating a potential threat to forest species but conversely, entailing an opportunity to open-habitat birds.

To minimize future threats derived from land-cover changes for both bird assemblages, we included the potential impact of fire as a constraint to the selection of priority areas for conservation. Conservation areas selected before and after integrating fire impact in the conservation planning process were compared to assess differences between both conservation scenarios. Since zones affected by fire have been identified as an opportunity for the conservation of many open-habitat birds (Brotons et al 2004; Moreira and Russo 2007; Zozaya et al 2011), we also evaluated the role of burned areas in relation to the locations selected for the conservation of this bird assemblage.

Our final aim was to provide a feasible approach to integrate future known drivers of changes in key habitats into the reserve selection process to explicitly account for uncertainties in future species distributions derived from landscape dynamics.

Methods

Study area and conservation goals

The study was carried out in Catalonia (ca. 31,930 km^2), which is located in the northeast of Spain (Figure 1). Catalonia features a typical Mediterranean climate, except in the Pyrenees (in the North). It comprises a range of different habitats; from mountain regions in the North to coastal areas in the East, along the Mediterranean see. According to the land-use map of Catalonia from 1998, available at www.gencat.cat (method described in Viñas and Baulies 1995), about 31% is covered with forest, 29% with shrubland and 33% with agricultural land.

Land-cover changes occurred during last decades in the study area are largely characterized by changes in forest and shrubland habitats. Although both land-covers have not changed significantly their overall extent between 1975 and 2000, their spatial location has shown important changes as consequence of fire impact and land abandonment (Vallecillo et al 2009).

In this context, we selected bird species, whose distributions are strongly affected by changes in forest and shrubland covers, as conservation goals for our study. We found a total of 39 species with higher preference for either forest (24 species) or shrub-like habitats and farmlands (15 species) than for other land-cover classes (Appendix 1). This classification was based on the habitat selectivity index from the Catalan Breeding Bird Atlas (CBBA; Estrada et al 2004, available at http://www.sioc.cat/atles.php) supported by the experts' criteria. The habitat selectivity index ranges from positive values indicating high habitat preference to negative values showing habitat avoidance. According to this classification, forest species (e.g. the Eurasian Jay) show the highest selectivity index for forest habitats, with avoidance of farmlands. Likewise, open-habitat species (e.g. the Ortolan Bunting) show the highest selectivity index for open, shrub-like habitats and farmlands but with negative index for forested habitats. For this last bird assemblage strictly farmland species were not considered.

We found a 4% of forest species included under some of the IUCN threat categories (critically endangered, endangered and vulnerable) defined at the study area level (Estrada et al 2004), while the proportion of open-habitat species currently threatened was significantly higher (40%; Appendix 1). Definition of threat categories at the study area level by Estrada et al (2004) strictly followed the IUCN threat categories and criteria (IUCN 2003).

Information on the distribution for each species was sourced from distribution maps developed in the CBBA by means of Generalized Linear Models (GLM). GLM were built using empirical presence/absence data for bird species recorded at 1 km^2. Predictor variables included in the models were climate, topography, extent of the land-use classes from the land-use map of Catalonia 1998 (Viñas and Baulies 1995) and other miscellaneous variables (see Estrada et al 2004 and Brotons et al 2007 for further details). GLM were evaluated by means of the Area Under the Curve (AUC) indicating very high predictive power of the presence/absence data (Appendix 1). The distribution maps represent the variation in the probability of species occurrence across the whole study area, with a total of 32,003 grid-squares of 1 km^2. All these 1 km^2 squares were used as planning units to select priority areas for conservation.

Reserve selection algorithm

We identified priority areas for conservation using the simulated annealing algorithm in the software Marxan (Ball et al 2009). Marxan tries to find a minimum set of planning units where all the target species can be represented at the required level, using a complementarity-based approach (Kirkpatrick 1983).

We set different proportions of species distributions as conservation targets according to the conservation status of each species defined at the study area level (Estrada et al 2004). Similarly to Pearce et al (2008), conservation targets were: 20% of the distribution for least concern species, increasing up to 40% for vulnerable species and 60% for endangered species. Since we are using probability values of species occurrence (i.e. derived from GLM), a conservation target of 20% would translate into the selection of planning units that represent 20% of the total sum of probability values across the study area.

In Marxan, the optimal solution is sought by minimizing an objective function where penalties for not fully representing the conservation features at the desired targeted level and costs trade-offs are considered (Possingham et al 2000; see also Appendix 2). Moreover, the spatial aggregation in the planning units shaping the conservation areas (i.e. structural connectivity) can be adjusted with a boundary length modifier (BLM). The BLM is a weight applied to the connectivity penalty in the objective function that Marxan optimises. Priority areas will tend to be more spatially clustered when using high BLM values. However the increase in internal connectivity is normally achieved at expenses of a higher area needed. We calibrated the BLM testing six different values (0, 0.005, 0.01, 0.05, 0.1, and 1) to find the optimal BLM that provides a reasonable perimeter/area ratio (Possingham et al 2000).

For each bird assemblage, we ran Marxan 100 times to produce 100 near-optimal solutions to achieve the conservation goals while minimizing the objective function. Multiple runs allow estimating the frequency of selection for each planning unit, which is a measure of the likelihood that an area will be required to meet a given set of targets. Selection frequency in the 100 near-optimal solutions was here used as a surrogate for the conservation value of an area (Cowling et al 1999). According to the selection frequency, we defined as priority conservation areas those selected in more than 50% of the near-optimal solutions (Ardron et al 2008) and as core conservation areas those selected in more than 75% of solutions.

Conservation scenarios

We used two different scenarios to prioritize conservation areas: (a) Reference scenario in which the achievement of conservation targets aimed to minimize the area selected for conservation under the current conditions of species distributions – this is what most conservation planners have done in the past (Moilanen et al 2009) and (b) Fire-impact scenario, in which we included in the objective function the potential impact of fire as a penalty (i.e. cost in Marxan terminology) for the selection of planning units (Appendix 2). In this conservation scenario fire risk was explicitly considered as a proxy of the landscape dynamics. Future fire events would mainly lead to a decrease in forest extent and increase in shrublands (Diaz-Delgado et al 2004) having a variable impact on the conservation areas of the studied bird assemblages. Since the impact of disturbances, such as fire, on biodiversity has been shown to be heavily scale-dependent (Hamer and Hill 2000), we calculated the fire impact on conservation areas (Equation 1) at a given site at the same spatial scale as the conservation planning (i.e. 1 km^2).

Fire impact = fire risk x $\text{vulnerability}_{(\text{forest})}$ + fire risk x $\text{vulnerability}_{(\text{shrubland})}$ (Equation 1)

Where fire risk at each specific location was obtained from the static map of fire risk, provided by the Catalan Government (available at www.gencat.cat). This map shows ten categories with increasing fire risk (i.e. from 0 to 9), both in frequency and intensity; and was elaborated using data from past fire regime, flammability and fuel models derived from the Ecological and Forest Inventory of Catalonia, topography and climate data (Fig. 1).

#Figure 1 approximately here#

Vulnerability was estimated by calculating two different Pearson's correlation coefficients for each bird assemblage, one for forests and one for the shrubland cover, between the conservation value in the reference scenario (i.e. selection frequency of each planning unit) and the proportion of each land-cover within the 1 km^2 planning units. Information on forest and shrubland covers was obtained from the land-use map of Catalonia from 1998 (Viñas and Baulies 1995). Hence, coefficients of vulnerability are a measure of the degree to which the conservation value at a given location is related to forest and shrubland covers (similarly to Chan et al 2006). Large positive values of the correlation coefficient indicate that areas with high conservation value are favoured by a large extent of the land-cover class, either forest or shrubland. If changes occur in the extent of the respective land-cover class, conservation value of a given area will be affected suggesting higher vulnerability to future land-cover changes. The coefficients of vulnerability of each bird assemblage were used to weight the fire risk map and spatially explicit estimate the extent to which their conservation areas could be affected by fire in the future.

In this context, the reserve selection algorithm in the fire-impact scenario will achieve conservation targets at the minimum area, while accounting for the potential impact of wildfire on conservation areas. This means that areas with a positive fire impact will be positively selected, as expected for open-habitat birds, whereas those areas with an unfavourable effect of fire will be avoided in the selection of conservation areas for forest birds.

Including fire impact in the reserve selection algorithm as a penalty might result in a reduction in the contiguity of high quality areas and more fragmented reserves (Rayfield et al 2008) leading to undesirable effects on species persistence (Gaston et al 2002). Hence, for a sound comparison between the reference and the fire-impact scenario, we selected priority areas for conservation setting similar levels of aggregation (i.e. compactness) of the planning units selected in both conservation scenarios. Compactness accounted for differences in the spatial configuration of the reserves and was estimated by means of the inverse value of the ratio between the boundary length (perimeter of the reserve) and the circumference of a circle of the same area as the reserve (Possingham et al 2000) (Equation 2).

Compactness = 1 / [boundary length / (2√(pi x Area)] (Equation 2)

Reserves are more compact as compactness index approaches to 1, becoming close to 0 for highly fragmented reserves.

The compactness of conservation areas is closely related to the role of the BLM, which was previously determined by a calibration process (see the Reserve selection algorithm section). In the reference scenario, we found 0.005 to be the optimal BLM (i.e. reasonable area/perimeter ratio) for both bird assemblages. In the fire-impact scenario we obtained a BLM of 0.05 and 0.01, for forest and open-habitat species respectively, yielding conservation areas with comparable compactness to the conservation areas in the reference scenario (Table 1).

#Table 1 approximately here#

Then, we evaluated the differences between the conservation areas selected for both conservation scenarios, before and after integrating fire impact, by analysing: (1) Total conservation area required for the targeted species, estimated as the average of the number of

1 km^2 planning units selected in the 100 independent Marxan runs. (2) Efficiency estimated as the inverse of the conservation area required per species (i.e. averaged across 100 solutions). The smaller the area per species needed to meet the conservation goals, the more efficient the reserve is (Pressey and Nicholls 1989) (Equation 3).

Efficiency = [1 / (area/species)] x 100 (Equation 3)

(3) Core area was considered as the number of planning units selected in more than 75% of the near-optimal solutions. (4) Mean fire risk in conservation areas was estimated within all 100 near-optimal solutions using the fire risk map described above.

Finally, we also evaluated to what extent burned areas were selected as priority conservation areas for open-habitat birds. With this purpose, we calculated the overlap of the priority areas (i.e. those selected in more than 50% of the near-optimal solutions) for open-habitat birds with the areas burned between 1980 and 1999. Information on fire occurrence was provided by the Centre for Ecological Research and Forestry Applications and the Catalan Government (Fig. 2). Note that the forest assemblage was not considered here since there was small overlap between burned areas and their priority conservation areas.

#Figure 2 approximately here#

Results

Conservation requirements

Comparison between conservation areas selected in both the reference and the fire-impact scenarios for two bird assemblages showed that open-habitat species needed larger area to achieve the conservation goals than forest species (Table 2).

#Table 2 approximately here#

Furthermore, conservation areas for open-habitat species showed lower efficiency than for forest species. That is, the open-habitat bird assemblage, in spite of having a smaller number of species than the forest assemblage, required more than twice the extent of the conservation area per species than the forest ones (Table 2). Moreover, larger core areas (i.e. those selected in more than 75% of near-optimal solutions) for open-habitat species than for forest birds showed smaller flexibility to achieve conservation goals for this bird assemblage compared to forest species (Table 2; Fig. 3).

#Figure 3 approximately here#

Vulnerability of conservation areas

Coefficients of vulnerability to changes in the forest cover were larger than for the shrubland ones, for both forest and open-habitat bird assemblages (Table 3). This indicates that changes in the extent of forest cover have larger influence on the conservation value of a given area than changes in the shrubland extent. As expected, forest species showed to be favoured by increases in forest cover, whereas open-habitat species resulted disadvantaged, as shown by the negative sign of the correlation coefficient (Table 3).

#Table 3 approximately here#

Conversely, the low coefficients of vulnerability to changes in the shrubland extent showed smaller dependence between the conservation value of a given area and the shrubland extent compared to forest cover. Furthermore the positive sign for both bird assemblages revealed that conservation value of a given area can be favoured by certain extent of shrubland cover, for both forest and open-habitat birds. But open-habitat species resulted favoured at larger extent by increases in the shrubland cover than forest species (Table 3).

Fire impact in conservation planning

Integrating fire impact led to larger and less efficient conservation areas for both bird assemblages. Forest species resulted more negatively affected by considering the impact of fire than open-habitat birds as conservation areas for forest species underwent a larger increase in area and decrease in efficiency than open-habitat birds (Table 2). However, integration of fire impact for the forest assemblage yielded a reduction of its core area (Table 2; Fig. 3), leading to higher flexibility for the achievement of conservation targets.

Importantly, we demonstrated how to integrate the estimated fire impact as a constraint in the reserve selection algorithm at the required level to produce significant changes of fire risk in conservation areas (Table 2). Conservation areas for forest species were selected in zones with lower fire risk than in the reference scenario, whereas areas prone to be affected by fire were chosen for open-habitat birds.

Finally, from about 4,800 planning units affected by fire between 1980 and 1999, 21% were selected as priority conservation areas for open-habitat birds in the reference scenario, increasing to 49% after integrating fire impact in the conservation planning (see Fig. 2 and 3 for a graphical comparison). In this last scenario, burned areas constituted the 51% of the priority areas (i.e. selected in more than 50% of the near-optimal solutions).

Discussion

We have described a reasonable straightforward method for the integration of potential impacts of future land-cover changes into the selection of priority conservation areas with clear benefits for conservation and land use planners. This method is one of the first attempts to explicitly quantify the impact of future land-cover changes and implementing this in a static conservation planning approach. Methods applied until now have assumed that species are equally affected by the threatening processes (Araujo et al 2002), or have dealt with catastrophic events negatively affecting all the species (Game et al 2008), which is not always the case for fire-disturbance processes. More complex methods have been also applied including dynamic models of landscape predictions (Rayfield et al 2008; Drechsler et al 2009); however such models are very demanding in terms of required information and implementation, and are difficult to apply for large number of species.

Comparison of conservation areas for forest and open-habitat birds

Priority conservation areas (i.e. those selected in more than 50% of the solutions) for forest birds were located in the northern mountainous regions of Catalonia, at about 1,780 m a.s.l. Conversely, priority conservation areas for open-habitat species were situated at roughly 450 m a.s.l., mostly in the centre of Catalonia (Figure 3).

Definition of conservation areas in Catalonia for bird species with contrasting habitat requirements suggests that open-habitat birds require special conservation attention. First, this assemblage hosts a larger proportion of threatened species than the forest ones in the study area (Appendix 1). Furthermore conservation targets for open-habitat birds may be more difficult to achieve since their conservation areas showed smaller efficiency than forest birds and hence, larger conservation area per species will be required (Table 2). This small efficiency in the conservation areas selected may arise from the small overlap of species distributions (Howard et al 1998), as it has been suggested for open-habitat bird communities (Herrando et al 2003). Moreover, open-habitat birds showed larger core conservation area than forest birds making the achievement of the conservation goals less flexible. This suggests that environmental conditions required by open-habitat species are more limiting than those for forest birds because of the dominance of land abandonment, yielding forest expansion during the last decades (Moreira and Russo 2007; Gil-Tena et al 2009).

The vulnerability to land-cover changes estimated for both bird assemblages confirmed the variable impact of fire depending on the targeted bird assemblage. This is, the large vulnerability of the conservation areas to changes in the forest cover confirmed the key role of forest extent in conservation at 1 km^2 scale, with a positive effect on forest birds (Gil-Tena et al 2007) and negative on open-habitat birds (Vallecillo et al 2008). Conversely, we found that increases in the shrubland cover, as those expected after large fires in the study area (Diaz-Delgado et al 2004), appear to have a positive effect on conservation areas for both forest and open-habitat birds (i.e. positive sign of the coefficients of vulnerability, Table 3). This result was not really expected for forest species, suggesting that their conservation in the study area is favoured by a given shrubland extent. This may be the case of forest birds in Mediterranean regions, which have shown to use forest patches embedded in a shrub matrix provided that enough extent of forest is available (Brotons et al 2004).

Finally, the coefficients of vulnerability estimated are ecologically sound; proving as a useful approach to emphasize the need to consider both positive and negative species responses to fire disturbance (Devictor et al 2008), which is usually overlooked when taking conservation and planning decisions.

The influence of fire on conservation planning

By considering fire impact as a penalty in the identification of priority areas for conservation, we accounted for processes driving changes in land-covers (i.e. fire disturbance) and how they might affect priority areas for species conservation. The occurrence of this disturbance will determine the probability of species persistence, and therefore the efficiency of conservation areas. Consideration of processes driving changes has been shown to be crucial for the long-term maintenance of biodiversity (Cowling et al 1999; Pressey et al 2007) and to reduce the costs of conservation management actions (Wilcove and Chen 1998).

Including the impact of fire on the conservation problem yielded larger and less efficient reserves than in the reference scenario (Table 2), showing a trade-off between efficiency of conservation areas and the planning for threats and opportunities arising from fire disturbance.

However, despite the reduction of 13% in efficiency for forest birds after integrating fire impact, the fraction of highly selected planning units (i.e. core areas) also decreased (Table 2) which provides more flexibility in meeting conservation targets. This suggests that locations with suitable conditions for the conservation of forest birds, but unlikely to be affected by fire, are not especially restricted in the landscape.

The achievement of conservation targets for open-habitat birds in the fire-impact scenario did not markedly increase the required area for conservation (about 5%) and produced a smaller decrease in efficiency than for forest birds (Table 2). However, accounting for the impact of fires yielded larger core areas reducing flexibility to achieve conservation goals. This may happen because concurrence of areas with high fire risk but also suitable for the species conservation are more limited in the landscape. In this sense, this work confirms the significant role of burned areas as priorities for conservation of open-habitat birds (Brotons et al 2004; Moreira and Russo 2007; Zozaya et al 2011), constituting about 50% of the selected conservation areas. Large burned areas located in the centre of Catalonia (Fig. 2 and 3) where direct Black Pine (*Pinus nigra*) regeneration failed, giving rise to a heterogeneous habitat landscape (Rodrigo et al 2004, Zozaya et al 2011), are of high conservation value.

Furthermore, by integrating fire impact for the open-habitat assemblage we are also indirectly conserving the ecological process favouring their preferred habitat and their distributions at large spatial scales (Vallecillo et al 2009). In this way, potential threats of land-cover changes are minimized in conservation areas selected in the fire-impact scenario. Accordingly, areas with large fire risk will be more likely to present suitable habitat for open-habitat birds, even under scenarios of land abandonment where fire will act as an opposing force to woodland spread (Pausas et al 2008). In addition, constraining conservation areas to locations with large fire risk we are partially driving those areas out from intensive cultivated regions (i.e. large areas showing fire risk of zero in Fig. 1). Although a future scenario of farmland abandonment in predominantly cultivated areas is not likely to occur, we would also minimize other likely threats arising from agricultural intensification (Fuller et al 1995).

Management implications

We selected priority areas for conservation separately for the two bird assemblages to identify conservation areas requiring contrasting management: conservation of forested habitats vs. conservation of a mosaic with low and open shrublands and farmlands. Consequently, priority conservation areas here selected are not intended to indicate places for new reserves, but to guide spatially explicit on land-uses that ensure the persistence of species with contrasting habitat and management requirements.

Since fires have a widespread impact on Mediterranean ecosystems, which is likely to continue or even increase in the future (Pausas et al 2008), we suggest using it as a management tool for conservation. Fire maintains open habitats as traditionally this disturbance has been doing at sustaining the function of ecosystems (Rundel et al 1998). Hence, given that fires will inevitably occur at some point in future years, they offer the opportunity to reduce management efforts at maintaining early successional habitats and provide “for free” new and adequate areas for the conservation of species with these habitat requirements.

Importantly, favouring the maintenance of open habitats and reducing fuel (i.e. vegetation) precisely in the locations proposed in Figure 3b for open-habitat birds, not only supports the conservation of these species, but also may contribute to reduce the catastrophic character of fires in these areas. Therefore management practices such as grazing, prescribed fire and reforestation avoidance in the conservation areas for open-habitat birds here proposed are highly desirable for both the conservation of these species and the reduction of the catastrophic character of fires, increasingly occurring during the second half of the 20th century (Miller et al 2007; Pausas et al 2008).

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Tables

Table 1. Description of conservation areas for two bird assemblages selected after integrating fire impact in the reserve selection process (Fire-impact scenario) with increasing levels of spatial aggregation of reserves according to the Boundary Length Modifier (BLM). Values of area, perimeter and compactness of reserves were averaged for 100 near-optimal solutions. Compactness was compared with that obtained before integrating fire impact (Reference scenario) at the optimal BLM (0.005) to choose the BLM at which compactness between both scenarios was analogous (values in bold)

Bird assemblages	Fire-impact scenario				Compactness in reference scenario	Change in compactness (%)
	BLM	Area (km^2)	Perimeter (km)	Compactness[a]		
Forest	0	4895	14944	0.017		-77
	0.005	4646	5622	0.043		-41
	0.01	4838	4567	0.054	0.073	-26
	0.05	**5892**	**3385**	**0.080**		**10**
	0.1	6270	3167	0.089		22
	1	6241	2434	0.115		58
Open-habitat	0	7590	16969	0.018		-72
	0.005	7830	5647	0.056		-13
	0.01	**8683**	**5380**	**0.061**	0.064	**-4**
	0.05	10522	4867	0.075		16
	0.1	10979	4616	0.080		25
	1	11447	4059	0.093		46

[a]Compactness index closer to 1 indicates more compact reserves

Table 2. Comparison between priority conservation areas for two bird assemblages selected under two conservation scenarios: (1) Reference scenario in which the achievement of conservation goals aims to minimize the area selected for conservation under the current conditions of species distributions and (2) Fire-impact scenario in which the reserve selection process includes the potential impact of fire, separately estimated for the two bird assemblages, as a penalty for the selection of planning units

Bird assemblages	Area[a] (km^2)			Efficiency[b]			Core area[c] (km^2)			Mean fire risk[d]		
	Reference	Fire Impact	Change (%)	Reference	Fire Impact	Change (%)	Reference	Fire Impact	Change (%)	Reference	Fire Impact	Change (%)
Forest	5150 ± 110	5923 ± 201	15.01***	0.47	0.41	-12.60***	22	3	-86.36	3.21 ± 0.08	2.75 ± 0.10	-14.41***
Open-habitat	8253 ± 218	8696 ± 207	5.37***	0.18	0.17	-4.95***	312	403	29.17	2.64 ± 0.09	3.15 ± 0.07	19.63***

[a]Area: total conservation area required for the targeted species (mean ± sd from 100 near-optimal solutions)

[b]Efficiency: the inverse of the conservation area (i.e. averaged for 100 near-optimal solutions) required per species, multiplied per 100. Larger values indicate smaller conservation area required per species and therefore more efficiency

[c]Core area: number of planning units (1 km^2) selected in more than 75% of the near-optimal conservation solutions

[d]Mean fire risk in conservation areas (mean ± sd from 100 near-optimal solutions)

***P-value < 0.001 – Evaluation of significant differences by the paired samples t-test

Table 3. Vulnerability of areas with high conservation value to increases in the extent of forest and shrubland covers for two bird assemblages. Vulnerability was estimated as the Pearson's correlation coefficient between selection frequency in the 100 near-optimal conservation solutions and the proportion of each land-cover class within the planning units

Bird assemblages	Vulnerability***	
	Forest	Shrubland
Forest	0.56	0.05
Open-habitat	-0.49	0.18

***With a significance level < 0.001

Figure captions

Figure 1. Fire risk map of the study area (Catalonia, northeast of Spain) showing ten categories with increasing probability of fire occurrence (from 0 to 9)

Figure 2. Burned areas from 1980 to 1999 in the study area (Catalonia)

Figure 3. Selection frequency of the planning units in 100 near-optimal conservation solutions for forest and open-habitat birds in (a) Reference scenario and (b) Fire-impact scenario in which fire impact was integrated in the reserve selection process. Those areas selected in more than 50% of the near-optimal solutions were considered as priority conservation areas for the achievement of the conservation goals, while those selected in more than 75% of solutions were considered in terms of core conservation areas

Figure 1

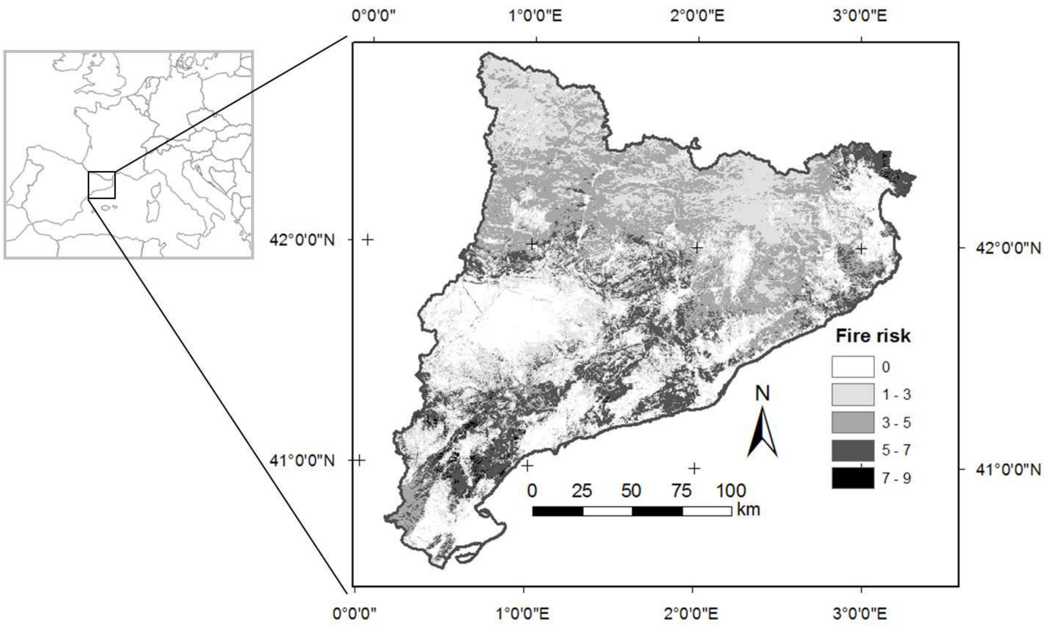

0°0'0"
1°0'0"E
2°0'0"E
3°0'0"E
42°0'0"N
41°0'0"N
Fire risk
0
1 - 3
3 - 5
5 - 7
7 - 9
N
0 25 50 75 100
km

Figure 2

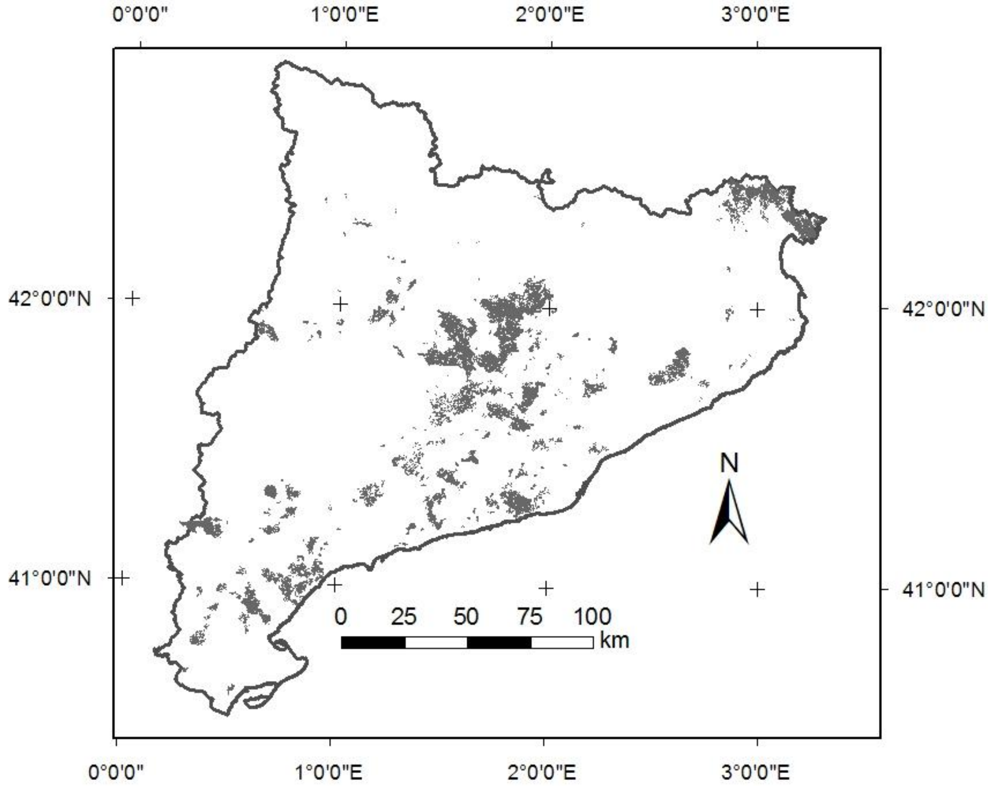
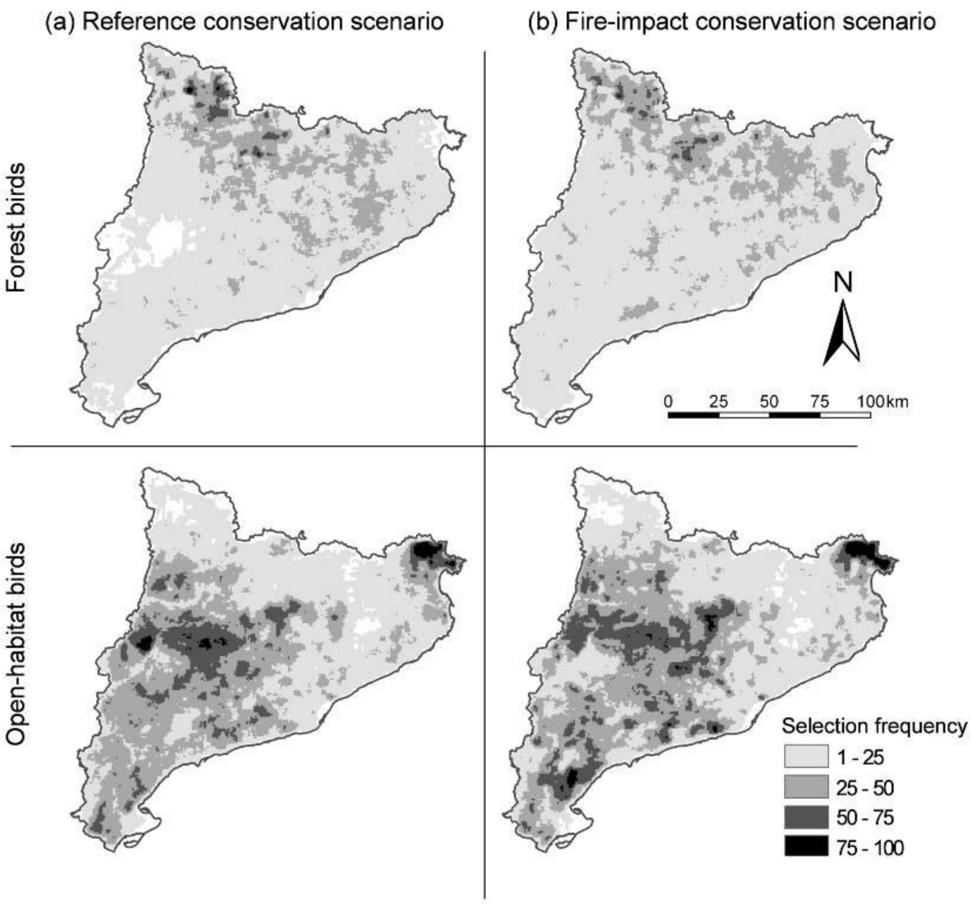

0°0'0"
1°0'0"E
2°0'0"E
3°0'0"E
42°0'0"N
42°0'0"N
41°0'0"N
41°0'0"N
N
0 25 50 75 100
km
0°0'0"
1°0'0"E
2°0'0"E
3°0'0"E

Figure 3



(a) Reference conservation scenario
(b) Fire-impact conservation scenario
Forest birds
Open-habitat birds
N
0 25 50 75 100km
Selection frequency
1 - 25
25 - 50
50 - 75
75 - 100

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Appendices

Appendix 1. List of species of two bird assemblages and their respective IUCN threat categories defined at the study area level in the Catalan Breeding Bird Atlas (Estrada et al 2004; available at http://www.sioc.cat/atles.php). IUCN threat categories defined at the global level are also shown in parentheses when different from those designated at the study area level. Since selection of conservation areas was based on species distribution maps derived from generalized linear models, model accuracy based on the AUC is shown (Fielding and Bell 1997; Estrada et al 2004).

Scientific name*	**Common name***	**IUCN category at the study area level**	**AUC**
	Forest bird assemblage		
Accipiter gentilis	Northern Goshawk	least concern	0.71
Accipiter nisus	Eurasian Sparrowhawk	least concern	0.72
Aegithalos caudatus	Long-tailed Tit	least concern	0.82
Carduelis spinus	Eurasian Siskin	least concern	0.94
Certhia brachydactyla	Short-toed Treecreeper	least concern	0.83
Certhia familiaris	Eurasian Treecreeper	least concern	0.94
Coccothraustes coccothraustes	Hawfinch	least concern	0.99

Dendrocopos major	Great Spotted Woodpecker	least concern	0.84
Dendrocopos minor	Lesser Spotted Woodpecker	least concern	0.91
Dryocopus martius	Black Woodpecker	least concern	0.92
Erithacus rubecula	European Robin	least concern	0.92
Fringilla coelebs	Eurasian Chaffinch	least concern	0.94
Garrulus glandarius	Eurasian Jay	least concern	0.86
Loxia curvirostra	Red Crossbill	least concern	0.89
Parus ater	Coal Tit	least concern	0.91
Parus caeruleus	Blue Tit	least concern	0.86
Parus cristatus	Crested Tit	least concern	0.84
Parus palustris	Marsh Tit	least concern	0.94
Phylloscopus collybita	Common Chiffchaff	least concern	0.88
Regulus ignicapilla	Firecrest	least concern	0.88
Regulus regulus	Goldcrest	least concern	0.98
Sitta europaea	Wood Nuthatch	least concern	0.90

Tetrao urogallus	Western Capercaillie	vulnerable (least concern)	0.99
Turdus philomelos	Song Thrush	least concern	0.84
Open-habitat bird assemblage			
Alauda arvensis	Eurasian Skylark	least concern	0.88
Alectoris rufa	Red-legged Partridge	vulnerable (least concern)	0.79
Anthus campestris	Tawny Pipit	least concern	0.82
Carduelis cannabina	Eurasian Linnet	least concern	0.84
Emberiza hortulana	Ortolan Bunting	least concern	0.74
Falco naumanni	Lesser Kestrel	endangered (least concern)	0.88
Galerida theklae	Thekla Lark	least concern	0.82
Lanius excubitor	Great Grey Shrike	vulnerable (least concern)	0.83
Lanius senator	Woodchat Shrike	vulnerable (least concern)	0.90
Miliaria calandra	Corn Bunting	least concern	0.83
Oenanthe hispanica	Black-eared Wheatear	vulnerable (least concern)	0.93
Oenanthe leucura	Black Wheatear	least concern	0.93

Sylvia conspicillata	Spectacled Warbler	vulnerable (least concern)	0.81
Sylvia hortensis	Orphean Warbler	least concern	0.82
Sylvia undata	Dartford Warbler	least concern (near threatened)	0.86

*BirdLife International (2012) The BirdLife checklist of the birds of the world, with conservation status and taxonomic sources. Version 5. Downloaded from http://www.birdlife.info/im/species/checklist.zip

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Appendix 2. Description of the objective function used by Marxan (Possingham et al 2000; Ball et al 2009)

The final aim of Marxan is to adequately represent a set of species at the required level by selecting as few planning units as possible. However to find an optimal reserve Marxan tries to minimize an objective function where penalties, spatial design and cost trade-offs are considered. After creating a random initial reserve system, planning units are added or discarded from the reserve system in an attempt to minimise the objective function:

Objective function = ∑Cost + ∑ SPFxSpecies penalty + BLM∑Perimeter + Fire Penalty

In its simplest form, the Marxan objective function is a combination of the total cost (∑Cost) of the reserve system and a penalty for any of the ecological targets that are not met (∑ SPFxSpecies penalty).

The total cost (∑Cost) of the reserve in our case was the number of 1 km^2 planning units (i.e. total area selected). Because the final solution proposed by Marxan might fail to meet adequate conservation objectives (i.e. species distributions) at the required level, there is the species penalty factor (∑ SPFxSpecies penalty). In this work the SPF for not fully representing all the species at the targeted level was set up to 10.

However, Marxan also allows taking into account the fragmentation of the reserve system, so that it will generally be desirable for a reserve system not to be too fragmented. More fragmented reserves will have a greater overall boundary length. Thus this boundary length, plus a weighting on its importance were included in the objective function (BLM ∑ Perimeter). The BLM was calibrated in order to find the optimal solution where the area/perimeter ratio was minimized.

Finally, Marxan allows including a last term as a penalty (i.e. cost in Marxan terminology), which was only included in the fire impact scenario. Thus the Fire Penalty was integrated in the objective function as a penalty in the selection of planning units accounting for fire impact (see Conservation scenarios section in Methods for further details).

Figure 1
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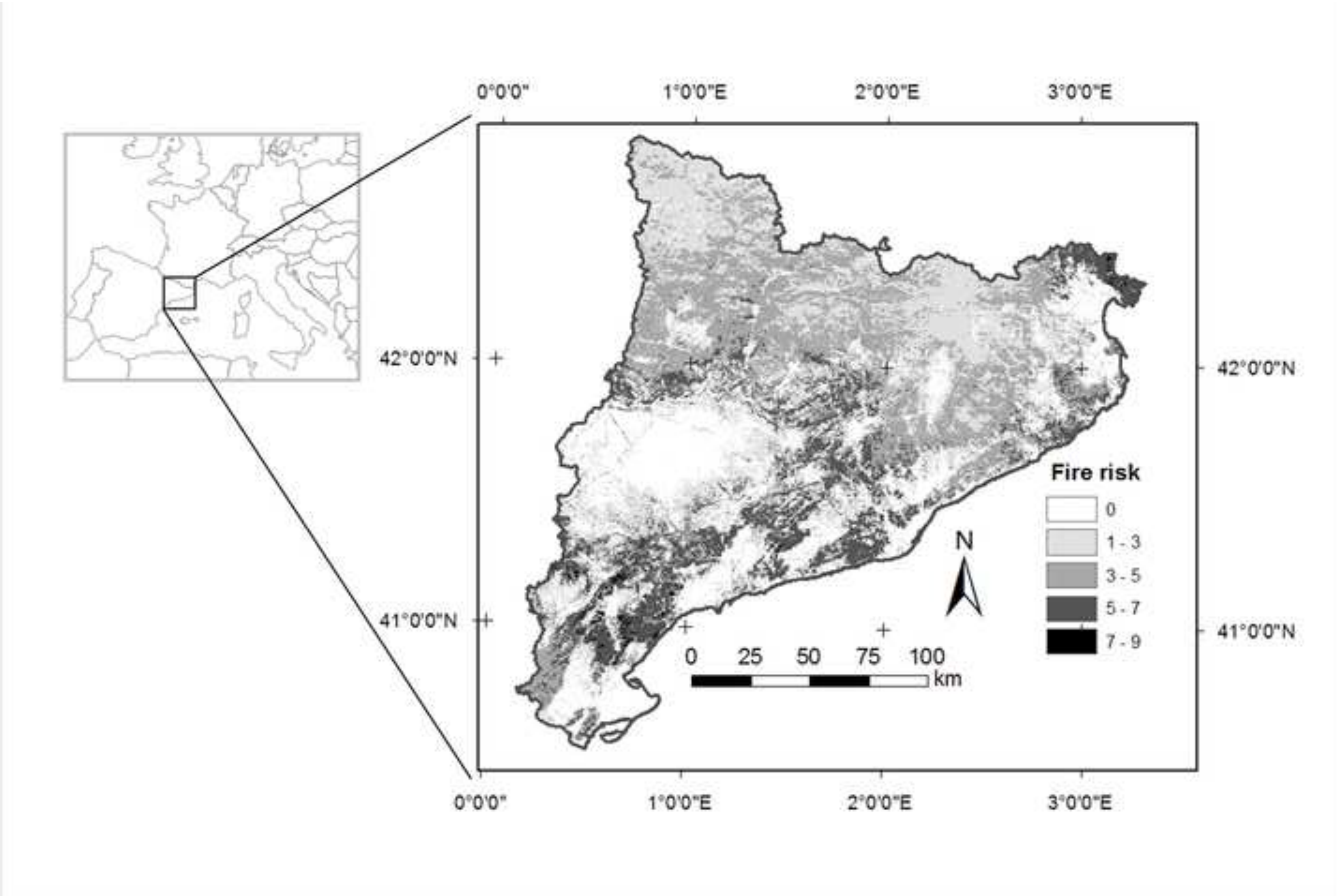

Figure 2
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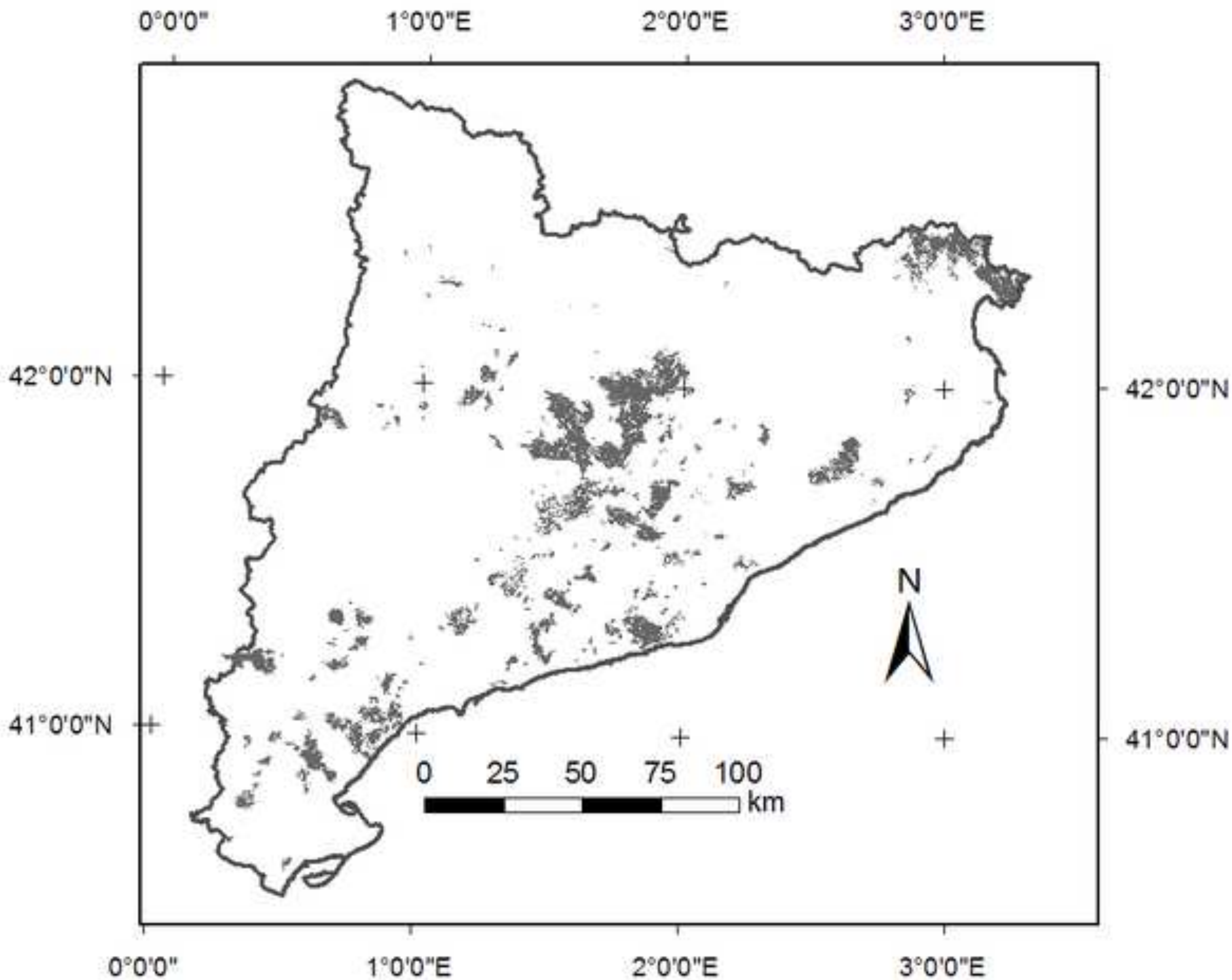

Figure 3
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