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Using multi-scale spatial prioritization criteria to optimize non-natural mortality mitigation of target species

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ABSTRACT

Non-natural mortality is a major threat to animal conservation worldwide. Its origins are extremely diverse and include infrastructures that cause animal casualties. Its effects are widely felt and so prioritization criteria are necessary when implementing mitigation actions. Most of the threats causing non-natural mortality have in common the fact that they are distributed unevenly across several spatial scales. Thus, here we present a protocol for prioritizing conservation measures in: (i) population fractions suffering from high levels of non-natural mortality whose demographic effects are the most serious, and in (ii) areas with the highest risk of casualties due to heterogeneities in both spatial use by individuals and the inherent hazards of the infrastructures causing mortality. To do so, the protocol consist of 5 steps: 1) to identify sink populations over large geographical areas; 2) to identify sink areas of high mortality within target populations; 3) to identify areas intensively used by individuals in target areas; 4) to identify spatial points or individual infrastructures showing high mortality risk; and 5) using direct evidence of casualties to complete information on high-risk sites and infrastructures. To show the potential of this protocol, we use as an example the mitigation of mortality due to electrocution in Bonelli's eagle in SW Europe, where this species is of conservation concern. Thanks to the retrofitting of dangerous pylons, we demonstrate that our protocol can help restore Bonelli's eagle territories to levels that will ensure the persistence of the studied population. In addition, we show that our criteria enhance the optimization of resource investment in mortality mitigation as our criteria identify the pylons with the most devastating effects on the population. To summarize, we provide the basis for a framework applicable to many different species and scenarios whose costs in terms of mitigation actions and benefits in terms of population viability prospects can be explicitly calculated.

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1. Introduction

Human-caused or non-natural mortality is a major threat to animal species conservation worldwide (Bennett, 2017; Dwyer et al., 2018). The causes of non-natural mortality are extremely diverse and they include both mortality directly and indirectly caused by humans. Humans are directly responsible for a substantial proportion of wildlife mortality including infrastructures that cause animal casualties and the deliberate killing of individuals either for harvesting or as a product of human-wildlife conflicts (Hill et al., 2019). Usually, the effects of non-natural mortality are felt over large areas and their overall short-term elimination is unfeasible. Consequently, criteria are needed to prioritize the areas in which mitigation measures should to be implemented (Polak et al., 2014; Hernández-Lambraño et al., 2018).

Environmental spatial heterogeneity acts as an important driver of demographic processes at a number of spatial scales ranging from local differences that determine survival and the reproduction prospects of individuals within a population (Bolnick et al., 2003; Stover et al., 2012; Dall et al., 2012) to regional variations that determine the contribution made by local populations to the species' overall trends (Bonnot et al., 2011; Hernández-Matías et al., 2013). In addition, human-induced impacts have dramatically increased demographic spatial heterogeneity in animal populations, which means that some populations or local areas within populations perform more poorly due to the effect of non-natural stressors such as sources of non-natural mortality (Hernández-Matías et al., 2015). Accordingly, studies addressing the occurrence and magnitude of non-natural causes of death (e.g. vehicle collisions, poisoning and power line casualties) have shown that these causes of mortality have a strong spatial heterogeneity (Mañosa, 2001; Dwyer et al., 2014; Malo et al., 2004; Guil et al., 2015). Consequently, spatial heterogeneity can be used as a tool to rank the priority areas in which conservation actions should be focused and where corrective effects will have greater impact (Wilson et al., 2009; Rappaport et al., 2015; Dwyer et al., 2020).

At the individual level, animals tend to disproportionally use some areas more than others according to resource availability, individual preferences or the specific behaviors they perform there (Gastón et al., 2016; Real et al., 2016). For instance, most migratory species use well-defined migratory routes to reach their wintering or breeding grounds and so threats to their survival along these intensively used routes may have a disproportionately more devastating effect on their populations (Shillinger et al., 2008). Hence, fine-level spatial heterogeneity in individuals' use of space offers an opportunity for prioritizing conservation actions (Vasudev and Fletcher, 2015; Martín et al., 2018). Furthermore, within these intensively used areas, not all infrastructures susceptible to cause casualties are equally dangerous; rather, both their intrinsic traits (e.g. design of pylons or curves in roads) and the local environmental characteristics of the site (e.g. open habitat) will determine their true dangerousness (Grilo et al., 2009; Mañosa, 2001; Tintó et al., 2010; Dwyer et al., 2014).

All the levels of spatial heterogeneity described above have been previously used to some extent to define conservation priorities. However, as far as we know, the integration of all the levels of spatial heterogeneity described above into a single framework for non-natural mortality mitigation has never been attempted. Additionally, studies addressing mortality mitigation aimed at detecting the areas or infrastructures of greatest concern have generally focused on all species negatively affected by the threat in question (Bevanger, 1998; Lehman et al., 2007; Loss et al., 2014, 2015; Bernardino et al., 2018). This approach may be adequate for reducing the problem as a whole, or may allow the use of common species for the identification of critical areas or points with high casualty rates, where more scarce or endangered species, for which data are difficult to obtain, can also be killed (Pérez-García et al., 2016; Sebastián-González et al., 2018). However, this approach may potentially bias results towards regions or infrastructure characteristics that are more relevant to the most abundant species and it may not be sufficient to protect other less abundant and more endangered species (Mañosa, 2001; Eberhardt et al., 2013). To tackle this problem, certain recent analyses have incorporated the presence of target species in the geographic area of concern (Pérez-García et al., 2017; Bedrosian et al., 2020). However, not all areas where target species are present are equally relevant in terms of population persistence and in fact the potential demographic effect on target species of conducting actions of non-natural mitigation in prioritized areas has been scarcely tackled by previous studies.

In this study, we propose a protocol that integrates heterogeneities in demographic performance, habitat use and casualty risk occurring at several spatial scales, from regional to very local, to define spatial prioritization criteria for the mitigation of non-natural mortality directly caused by humans in target species. We consider that it is advisable to focus first on target species that are under greater risk from the threat in question to ensure that the prioritized areas will provide the greatest effective protection. In addition, legal requirements may compel the prioritization of certain species and so managers need suitable tools to mitigate threats to these particular species within the constraints of their budgets. In our approach, we use as an example the mitigation of electrocution by power lines in Bonelli's eagle *Aquila fasciata*, a territorial bird predator with a poor conservation status in part of its European range (Hernández-Matías et al., 2013). We describe the implementation of several conservation actions envisaged under this protocol and study their effectiveness in improving survival in one population of the study species. Using population viability analysis (PVA) we estimate the expected demographic effect of the actions that were implemented. Finally, we use data on the risk posed by pylons and this eagle's habitat use over an extensive area to illustrate how our protocol will contribute to selecting and prioritizing the most dangerous pylons. We also aim to understand whether focusing only on the pylons known to have caused mortality events is sufficient for solving this problem. Our overall aim is to illustrate the importance of incorporating multi-scale information on demographic and behavioral processes into prioritization procedures aimed at mitigating non-natural mortality.

2. Materials and methods

2.1. Mortality mitigation protocol

The proposed protocol for mortality mitigation consists of 5 steps considering several spatial scales from large geographical areas to particular spatial points or infrastructures (see Fig. 1 and Table S1 in supplementary data). Although the procedure was employed here to mitigate electrocution in a large territorial raptor, all the steps included therein are applicable to all types of non-natural mortality associated with any spatial location for any vertebrate species. The distribution of the target species must be known; if not, the use of species distribution models can be used as a starting point. In the text, we describe general aspects of the protocol to facilitate its application to other systems.

2.1.1. Step 1: Identify sink populations over large geographical areas

Many species show marked spatial variation in the demographic performance of local populations over large areas (e.g. regional variation in vital rates), though the demographic consequences of this source of heterogeneity are not well understood for most populations, either because the required demographic data to do so is not available or because proper demographic analyses have not been applied. Nevertheless, current evidence indicates that spatial variation in the demographic performance of local populations is an important driver of overall population dynamics (Bonnot et al., 2011; Hernández-Matías et al., 2013). Additionally, certain stages of both the annual and life cycle of a migratory species may represent sensitive bottlenecks for survival (Sergio et al., 2019). To identify local populations that behave as sinks, that is, those populations or areas where mortality exceed productivity (Pulliam, 1988), population models should incorporate all relevant aspects determining the dynamics of the population including the dispersal and migratory processes and the spatial structure of the population. Even though very detailed models covering large spatial scales are often unfeasible (i.e. because demographic data is not available), it is possible to implement well-suited demographic models even using only monitoring data (e.g. Bonnot et al., 2011). In all cases, models should reliably incorporate both emigration and immigration processes between local populations to determine source and sink populations. Once these sink populations have been identified, the populations that perform poorly due to unacceptably high levels of the non-natural mortality to be mitigated must be targeted.

2.1.2. Step 2: Identify sink areas of high mortality within target populations

Demographic heterogeneity caused by fine level spatial variation in vital rates may occur within local populations and may have a serious impact on population dynamics (Lescroël et al., 2009). Depending on the cause of mortality addressed, the target species and the vital stage on which we are aiming to act, the most convenient scale for operating will vary. In long-lived territorial predators in which the population growth rate is highly sensitive to adult survival, and in which territorial individuals usually establish large home ranges that are spatially consistent over fairly broad temporal scales, the areas used by territorial pairs may be suitable for identifying the territories that are responsible for the majority of deaths in the population (e.g. step 2 in Fig. 1). In other species subject to stronger temporal variation in territorial occupation or in their contribution to population growth rate (e.g. territorial passerines, e.g. Paradis et al., 2000), it may be more useful to identify patches with the highest levels of mortality. In colonial species, the targeted local areas at this spatial scale should be those used by sink colonies or sub-colonies within local populations. When targeting non-breeding life stages, such as non-adult, wintering or floating individuals, the application of this step is more problematical —but still possible— since mortality risks may differ greatly between areas used by these fractions of the population.

2.1.3. Step 3: Identify areas intensively used by individuals in target areas

In general, intensively used areas of home ranges are those where the presence of a threat implies a greater mortality risk and so mitigation actions should be prioritized in these areas. Some types of threat may be linked to specific behavior or activity by individuals (e.g. foraging grounds located in humanized areas); thus, priority areas for mitigation should be selected on the basis of the place where that specific behavior or activity is performed. Currently, the combination of novel tracking technologies with statistical spatial methods allows us to fully appreciate spatial use by the individuals of a wide range of species. Therefore, we advocate for using these methods to identify those areas where individuals may be more susceptible to suffering non-natural mortality. Indeed, procedures based on these methods have been used to define both terrestrial and marine reserves and protected areas (Arcos et al., 2012). For some species, it may be logistically possible to obtain the information for all the individuals that inhabit in a target area (as we did here). But more often, species distribution models need to be applied to infer the degree of spatial use by individuals. Researchers and managers should also be aware of the temporal dynamics of the system they are studying.

2.1.4. Step 4: Identify spatial points showing high mortality risk

Mortality risk is very unevenly distributed among potentially dangerous infrastructure (Mañosa, 2001; Malo et al., 2004; Rollan et al., 2010). Mortality risk in infrastructure is driven by the combination of the effects of both infrastructure hazard and wildlife exposure (Tintó et al., 2010; Guil et al., 2011; Dwyer et al., 2016). The first one depends on the physical traits of the infrastructures (e.g. fences along a road) and the second one depends on the species behaviour and local environmental characteristics of the site they are placed in. The penultimate step consists in identifying spatial points or individual

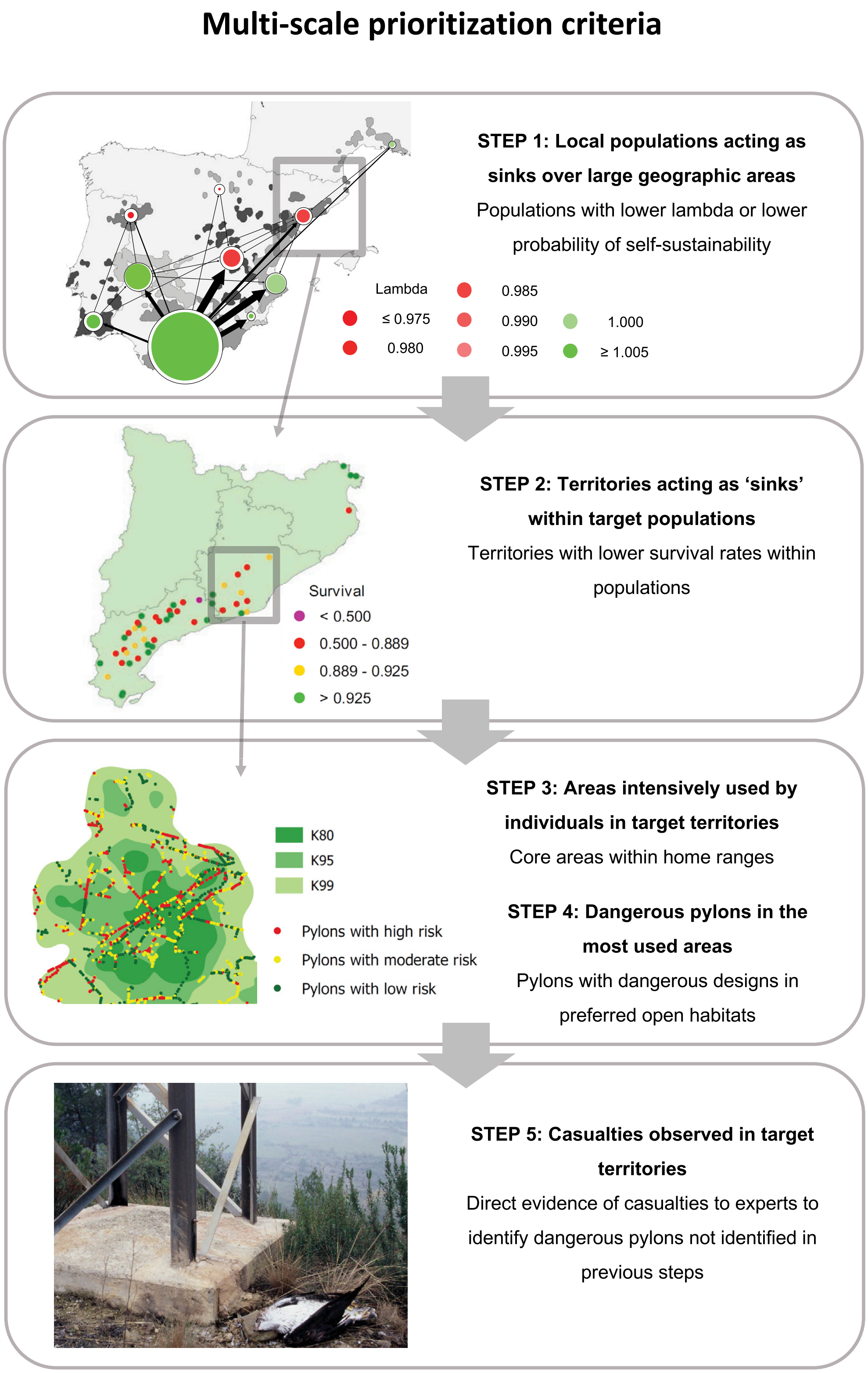

Fig. 1. Graphical representation of the multi-scale prioritization criteria described in the proposed protocol. Population acting as sinks were those with lambda values below 1 and territories acting as sinks were those with survival values below 0.925.

infrastructures that have the highest casualty risks. We encourage the use of predictor models that can assess the degree of dangerousness of the threat in question. Alternatively, it would be necessary to design and implement *ad hoc* monitoring to detect the presence of dead individuals and then use these data to construct models.

2.1.5. Step 5: Using direct evidence of casualties to complete information

Finally, we recommend gathering systematically all available information on dead individuals as a means of identifying dangerous infrastructures. This information may be obtained from the authorities responsible for wildlife conservation, from companies operating a given infrastructure, or from even from citizen-science monitoring schemes. In addition, local experts may be able to help identify dangerous infrastructures not identified in the previous steps (see Pérez-García et al., 2017). It is worth to mention that steps 4 and 5 can be developed in parallel if they are suitably planned and applied. For example, the information of dead individuals recorded systematically can be used to develop predictor models to assess the degree of dangerousness of the threat in question. Once the models are developed, the new information of dead individuals can be used to validate the predictor model, to assess the effectiveness of corrections and to redefine priority areas after the implementation of corrections (see Discussion section).

2.2. Our example

2.2.1. Study species

Electrocution on overhead power lines is a serious threat to a wide range of birds. Bonelli's eagle is a species of conservation concern in Europe seriously threatened by non-natural mortality and specifically by electrocution (Real et al., 2001; Hernández-Matías et al., 2015). The European Bonelli's Eagle population is estimated at 920–1100 pairs, of which ca. 80% are found in the Iberian Peninsula. This species has undergone a dramatic decline in numbers and range in recent decades and was listed as an endangered species (BirdLife International, 2004). Although more recently its populations appear to have stabilized, it still warrants its classification as Near Threatened within Europe (BirdLife International, 2015). Legally, Bonelli's eagle is included in Annex I of the Birds Directive (2009/147/EC) and it is listed as endangered in Spain.

2.2.2. Identifying target areas and priority pylons

Actions designed to mitigate electrocution were put in place in an area within the range of the local population of Bonelli's eagle in Catalonia (NE Spain).

Step 1: we focused our mitigation actions on the population of this eagle in Catalonia as it acts as a demographic sink on a larger scale (Hernández-Matías et al., 2013) and its viability is threatened by electrocution (Hernández-Matías et al., 2015). One concerning area of this population is found in the Barcelona province, since most of the 12 territories occurring in this area show survival rates below the median of the population in Catalonia.

Step 2: this population has marked heterogeneity in survival within territories (Rollan et al., 2016), a key vital rate driving the population growth rate. We studied 10 territories located in Barcelona province that showed low survival; three of these territories were used to perform conservation actions and to assess their effects on survival and population viability, and the remaining seven territories were used to illustrate the benefits of the correction effort used as a result of our prioritization criteria. These seven territories were selected because they were located in an area where we had additional information on the total numbers of birds known to have been killed by electrocution in recent years.

Step 3: we used radiotracking and kernel methods to identify the most used areas by territorial pairs. Detailed information on capture and tagging can be found in Bosch et al. (2010). 7 territorial individuals from 3 territories were captured in 2002–2006 and tagged with a backpack transmitter. Overlapping between individuals from the same territory was high, so we used locations of both individuals to construct the home range. We used Hawth's Analysis Tools module for ARGIS to analyze the 80, 95 and 99% kernels (thereafter K80, K95 and K99, respectively) as isolines with the smoothing factor (see Bosch et al., 2010 for details).

Step 4: the overall area covered by the home ranges of the three pairs considered for conservation actions covered 423.33 km^2 (K99). This corresponds to a sub-area of a large-scale project of electrocution mitigation that implied the mapping and characterization of 15,323 pylons, and the implementation of correction measures in 813 in 2001–2007. Some results of this project are given by Tintó et al. (2010), who report a reduction in the electrocution risk for all bird species from 13.1 to 0 killed birds/100 pylons, respectively, before and after corrections made to a sample of 222 pylons. Following Tintó et al. (2010), pylons in our study area were considered to be of correction priority if they were classified in either the 'very high' and 'high' categories of electrocution risk according to the probability of electrocution described in the cited study. This probability of electrocution was estimated as a function of conductivity (e.g. unearthed, earthed), the type of conductors and insulators (e.g. suspended, exposed), the presence of technical elements (e.g. only insulators, connector wires, devices), the configuration of the pole (e.g. flat or cross, alternate) and environmental variables (e.g. habitat, vegetation cover, topography, presence of rabbit). Within eagles' home ranges, we detected 3258 pylons. Of these, 977 pylons were considered of priority correction.

Step 5: all dangerous pylons known to have caused electrocution casualties of any bird species within the home range of all the studied territorial pairs were also prioritized for correction. This information came from opportunistic data recorded by rangers and power line companies, as well as a specific survey we did of a random sample of 3869 pylons in this area (1999–2006).

2.2.3. Implementing conservation actions

Corrective measures were implemented thanks to an agreement between three power companies (FECSA-ENDESA, Estabanell y Paysa S.A., and Electra Caldense S.A), local administrations (Diputació de Barcelona) and the University of Barcelona; so the on-the-ground implementation of measures was done by technicians of power companies supervised by researchers of the University. Corrective measures implemented by the companies involved 1) substitution of the pylon with a new one based on alternate cross-arms designs; 2) substitution of exposed jumpers and pin-type insulators with suspended jumpers and insulators; 3) isolation of the conductive parts of the cross-arms, principally in vault cross-arm pylons; and 4) substitution of the central exposed jumper and pin-type insulator with a suspended insulator, along with isolation of the jumper and conductor wires as a supplementary measure (see Tintó et al., 2010 and Real et al., 2015). Technical issues during the mitigation process implied that both priority and non-priority pylons were corrected and that some pylons were corrected with unsuitable measures; however, the suitability of the corrections was also assessed for all corrected pylons. We considered unsuitable measures when any of the criteria defined above was not achieved.

Out of 977 priority pylons within eagles' home ranges, 308 were corrected (31.5%), 236 with suitable measures (24.2%). In the territories of the three pairs considered for conservation actions, 86 (37.2%), 64 (21.5%) and 86 (19.2%) priority pylons were corrected with suitable measures.

2.2.4. Assessment of the effectiveness of corrections

First, the effectiveness of the corrections was assessed as the response in terms of survival and reproduction rates to the implementation of the corrections in the 3 focal territories. Monitoring data (1990–2016) consisted of repeated visits during the breeding season (January–July) to the studied territories. This allowed us to obtain the identity of individuals (if marked), the plumage-age and sex of territorial birds, and the number of fledged chicks in each territory. We classified territorial birds according to their plumages as juvenile (first year), immature (second year), subadult (third year), or adult (fourth year or older). Productivity was estimated as the number of fledglings per pair and year, while survival was estimated using turnover rates of territorial individuals as described in Hernández-Matías et al. (2011). We used general linear models to assess the effect of period (before and after corrections) on vital rates. The period before corrections was 1990–2001 in two territories and 1990–2004 for a third territory, and the period after corrections was 2002–2015 for two territories and 2005–2015 for a third territory. We considered either the number of fledglings (productivity) or whether the territorial individual survived or not (survival) as the response variable, territory and year as random factors, and period as a fixed factor. Link functions were log for productivity and logit for survival. The null model contained the intercept and the two random factors. The effect of mitigation actions was assessed based on the Akaike weights (w_i) of the model containing the effect of period in relation to the null model.

Second, we performed a PVA of Bonelli's eagles found in Barcelona province to assess whether or not the levels of survival attained due to corrections were demographically meaningful. We assessed viability under 3 scenarios considering: A) adult survival and reproduction rates in Barcelona province in 1990–2001; B) adult survival and reproduction rates of Barcelona province in 2002–2015; C) similar to B but considered only adult survival of the three focal territories in 2002–2015. Demographic models were based on Hernández-Matías et al. (2013) and accounted for demographic and environmental stochasticity; nonetheless, the population was assumed to be closed and not regulated by density-dependence to facilitate the interpretation of the effect of the corrections. Vital rates of non-adults were those considered in Hernández-Matías et al. (2013). The initial population was 12 pairs. The viability metric considered was the predicted population growth rate over the next 50 years.

2.2.5. Optimization of resource investment

In this section, we defined a study area containing seven home ranges of the territorial Bonelli's eagle based on the 10x10-km UTM grid. We had information from rangers regarding all birds known to have been killed by electrocution in 1997–2017. These territories are located in an area of 1604 km^2 (defined by UTM 10 × 10 km, see Supporting Information). All distribution power lines in this area were identified and their pylons geolocated using GIS data provided by power-line companies. 10 territorial individuals from 7 territories were captured in 2002–2006 and tagged with a backpack transmitter. We estimated the area corresponding to the K99, K95 and K80 of home ranges following the same methods described in section 2.2.2, step 3. All pylons within the kernels were characterized and their electrocution risk assessed based on Tintó et al. (2010). Using the estimated value of the electrocution risk, the pylons were classified into one of three categories: (i) very high and high (pylons considered to be of priority correction), (ii) moderate or (iii) low electrocution risks.

To illustrate the benefits in terms of the correction effort we analysed pylons within the overall study area K99, K95 and K80 according to their electrocution risk. In addition, to assess whether or not basing the identification of dangerous pylons exclusively on the detection of dead individuals provides comparable results to the method proposed in step 4 of the protocol, we also calculated the number of pylons where electrocution events were known to have occurred (for any bird species).

3. Results

3.1. Assessment of the effectiveness of corrections

In terms of survival of territorial individuals in the 3 focal territories, the model containing the effect of mitigation actions performed slightly better than the null model (w_i of 0.58 vs. 0.42): survival increased from 0.888 (CI 95% = 0.790–0.943; n = 56 individual-years of observations in 12 years) to 0.939 (CI 95% = 0.885–0.969; n = 84 in 14 years) in these territories (Fig. 2), which, as we discuss below, is demographically highly meaningful. In Barcelona province considering all the territories, survival showed fairly similar values to the 3 focal territories in 1990–2001 (0.899, CI 95% = 0.831–0.942, n = 229), but it worsened in the period after corrections due to high mortality levels in territories where corrections had not been performed (0.857, CI 95% = 0.802–0.898, n = 281). In terms of reproductive performance, we did not detect any effect of the mitigation actions in the 3 focal territories (w_i of null model 0.62 vs. 0.38) and productivity values remained similar during both periods (1990–2001: 1.31, CI 95% = 1.13–1.48, n = 30 territory-years of observations in 12 years; 2002–2015: 1.21, CI 95% = 1.09–1.34, n = 42 in 14 years). In the Barcelona province considering all the territories, adult productivity worsened notably in the latter years (1990–2001: 1.44, CI 95% = 1.31–1.57, n = 108; 2002–2015: 0.94, CI 95% = 0.82–1.07, n = 156).

The population viability analysis revealed that the Bonelli's Eagle population in Barcelona province was not self-sustaining in the period 1990–2001 and is still not at present (Fig. 3A and B: λ = 0.985 (CI 95% = 0.909–1.019) and λ = 0.905 (CI 95% = 0.780–0.983), respectively), but that they could achieve self-sustainability if adult survival reached the values achieved in the 3 focal territories after corrections, even with the low observed levels of productivity (Fig. 3C: λ = 1.002; CI 95% = 0.963–1.027).

3.2. Optimization of resource investment in the mitigation of electrocution

The number of pylons in the whole study area was very high (15,428 pylons, with a density of 9.61 pylon/km2), but fell drastically to just 219 pylons (1.4%) if we only include the priority pylons (dangerous and very dangerous) in the most used areas where eagles spend 80% of their time (Fig. 4A). The area within the 99% kernel of the 7 territories contains 1402 priority pylons, of which, by contrast, only 47 pylons have been ever reported to have caused the death of any bird (Fig. 4B). Only five Bonelli's eagles are known to have been killed in this area: two in K80, one in K95 and two in K99, although at least one of these latter two eagles was a non-territorial individual (Fig. 4C). The number of priority pylons within the 99% kernel of each of the seven territories, varied from 35 to 496 (average = 203.7; n = 7), corresponding to the 4.5–28.6% of pylons (average = 17.4; n = 7). Pylons known to have caused bird casualties varied in number from 0 to 15 in each territory.

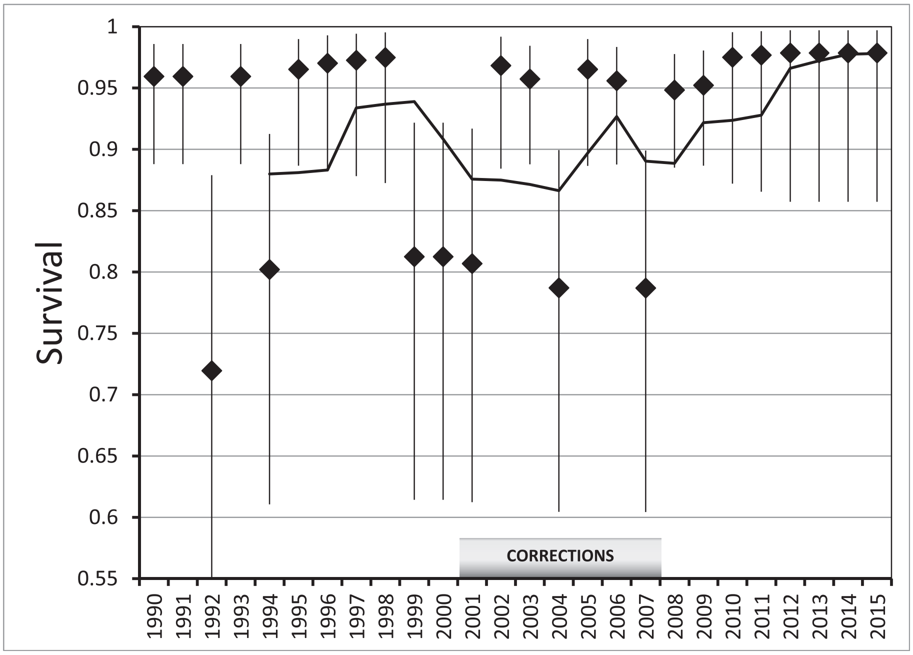

Fig. 2. Observed temporal variation of survival within territories in three focal territories of Bonelli's Eagle where corrections were carried out in 2001–2007. The estimated values (solid diamonds) and their CI 95% as per Hernández-Matías et al. (2011) are shown. The solid line shows the variation over time of the geometric mean of survival rates in the five previous years.

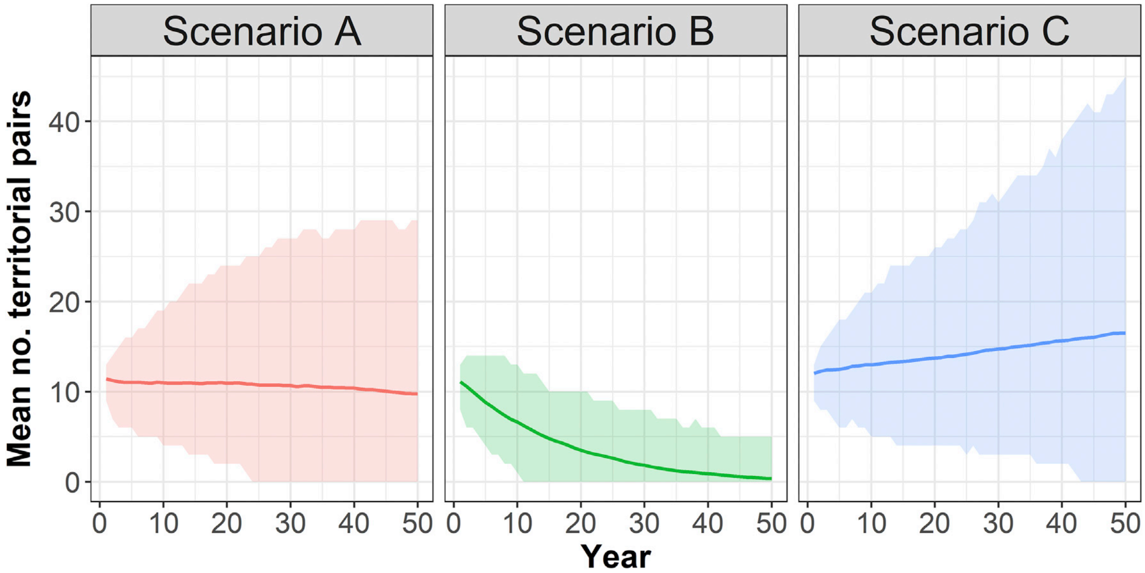

Fig. 3. Predicted trend of the local population of Bonelli's Eagle in Barcelona province for the next 50 years. A: adult survival and productivity in Barcelona province in 1990–2001. B: adult survival and productivity in Barcelona province in 2002–2015. C: productivity in Barcelona province and survival of the three focal territories in 2002–2015. Plots show the mean (solid line) and percentile 95% confidence intervals (dashed lines) for 5000 population trajectories.

4. Discussion

The causes of non-natural mortality are usually widespread over regions inhabited by target species of conservation concern and full mitigation is impractical in the short-term for economic and logistical reasons. We present here a protocol for prioritizing mitigation actions that takes into account (i) the fractions of the population suffering from high levels of non-natural mortality that have the greatest demographic effect, and (ii) the areas with the highest risk of casualties due to the heterogeneities of both the spatial use by individuals and the dangerousness of the infrastructures causing mortality. To show the potential benefits of this protocol, we used as an example the mitigation of deaths by electrocution in the Bonelli's eagle in SW Europe, a region in which this species show a concerning conservation status, precisely due in part to electrocution (Real et al., 2001; Hernández-Matías et al., 2013, 2015). We demonstrate that survival rates can be restored up to values that ensure the persistence of the studied population. In addition, we show that our criteria help optimize investment as they identify the pylons that have the most devastating effects on the population. Finally, our monospecific study provides further evidence that the retrofitting of pylons known to have caused electrocution is not sufficient to prevent accidents, as has been shown in certain multispecies studies (Janss and Ferrer, 1999; Mañosa, 2001).

Previous protocols for non-natural mortality mitigation have generally focused on one single cause of mortality. Here, we attempt to provide a single unified protocol for the mitigation of non-natural mortality. Although our empirical approach only considers mortality caused by electrocution, we stress the idea that most sources of non-natural mortality are distributed heterogeneously on several scales (Malo et al., 2004; Grilo et al., 2009; Guil et al., 2015; Martín et al., 2018) and therefore we believe that our protocol is applicable to many other types of non-natural mortality. Certain previous studies have focused on the presence, abundance and frequency of a given threat (Dwyer et al., 2016;Bennett, 2017). However, these approaches may not be effective if the presence of the target species is unevenly distributed in relation to the infrastructures in question (Pérez-García et al., 2017; Bedrosian et al., 2020). In addition, the most dangerous infrastructures may not be homogeneously distributed throughout the overall network of the infrastructure in question (van Langevelde et al., 2009). A better identification of priority areas can be obtained using risk prediction models built with a representative sample of casualties and taking into account the relevant environmental variables and technical characteristics of infrastructures (Mañosa, 2001; Tintó et al., 2010; Dwyer et al., 2014; Hernández-Lambraño et al., 2018). However, currently available models tend to consider the overall threat and all species affected by this threat are usually treated equally. This type of model may thus be valid for identifying the infrastructures and/or areas that are most relevant for the commonest species. It may also allow the use of common species for the identification of critical areas where endangered species, for which data is usually scarce, can also be killed (Pérez-García et al., 2016; Sebastián-González et al., 2018). Yet, the most important areas for particular groups or species will vary (Eberhardt et al., 2013; Santos et al., 2016) and thus some models will not be effective in the mitigation of mortality in the rarest and most endangered species. To solve this weakness, two recent studies combined spatial risk models with species distribution maps to identify areas of concern for electrocution in which a number of target species are present (Pérez-García et al., 2017; Bedrosian et al., 2020). We incorporate here the demographic contribution of local populations or territories as a means of identifying the top-priority areas. In our study species, local populations contribute very differently to the

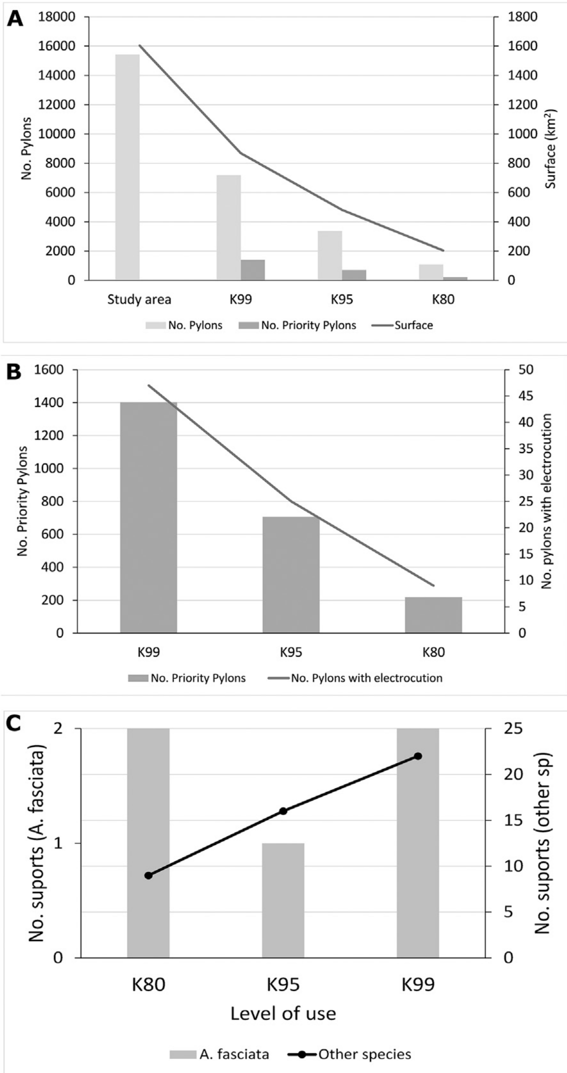

Fig. 4. A: Surface area and the number of pylons (total and priority) in the study area of 7 Bonelli's eagle territories according to level of use by Bonelli's eagles (K99, K95 and K80: 99%, 80% and 50% kernels, respectively). The number of priority pylons in the overall study area was not estimated. B: number of priority pylons and reported electrocutions of all bird species in relation to the level of use by territorial Bonelli's eagles. C: number of reported electrocutions of Bonelli's eagle (labelled as "*A. fasciata*") and other species (labelled as "Other species") according to the level of use by territorial Bonelli's eagles. In A and B larger kernel categories include smaller ones.

overall population dynamics of the species in western Europe. In addition, within-population demographic heterogeneity is important and survival rates at territory level range from 0.27 to 1, a much wider range than that observed in our local populations (0.86–0.94, Hernández-Matías et al., 2013). Consequently, concentrating mitigation efforts on areas with the lowest survival rates may have the greatest positive impact on populations. Besides demographic heterogeneity, we also explicitly incorporate the behavioral determinants that drive differential spatial use by individuals; this clearly determines the exposition of individuals to a given threat, an aspect rarely considered in previous mitigation protocols.

Non-natural mortality is a major threat for animal species conservation worldwide (IUCN/SSC, 2008, Birdlife, 2015) and strategic planning commonly includes non-natural mortality as a relevant threat to be taken into account in species' action plans. Furthermore, a growing number of conservation strategies now address specific far-reaching threats from a multi-species perspective; examples of this include action plans for reducing incidental catches of seabirds and cetaceans in fishing gear (European Commission, 2012) and for reducing the non-natural mortality of migratory birds and vultures (https://www.birdlife.org/europe-and-central-asia/protecting-migratory-birds-all-projects). Prioritization tools are crucial for allocating financial resources efficiently over large areas; nevertheless, detailed information regarding how these resources should be prioritized is rarely made explicit. For example, the pylons prioritized for retrofitting are usually those known to have caused electrocution, which, although a seemingly reasonable criterion, is largely insufficient as shown in this study. Our results from seven Bonelli's eagle territories illustrate that only 3.3% of 1402 dangerous pylons are known to have caused electrocution of any bird species (0.6% of total pylons), comparable to the 1.7% pylons of 18,610 potentially dangerous pylons identified by Hernández-Lambraño et al. (2018) known to have caused casualties in Central Spain. These percentages of dangerous pylons where corpses have been found are much lower than those we corrected in three territories in Barcelona province (between 19.2 and 37.2%), an intervention that resulted in an improvement of survival, while productivity was not affected. Although we cannot exclude that other environmental factors contributed to these changes, the fact that survival and productivity decreased over this period in other territories of the Barcelona province suggest that the observed improvement in survival was caused by our intervention. Importantly, the values of survival achieved guarantee the self-sustainability of this local population, at least until some new threat becomes population limiting. Similarly, retrofitting of power lines implemented on a regional level resulted in a positive shift of survival and demographic trends in other populations of Bonelli's eagle (Chevallier et al., 2015) as well as in other species, such as the endangered Spanish Imperial Eagle (López-López et al., 2011). In turn, our protocol highlights the importance of a multiple spatial scale approach and so can be used to objectively prioritize conservation actions. To date, the spatial prioritization methods that have been developed to prioritize areas for protection are usually based on biodiversity features but also incorporate financial costs, socio-political factors and threatening processes (Wilson et al., 2009). Prioritization methods have also been extended to incorporate a broader range of conservation actions such as restoration or the mitigation of threats. Our framework offers a hierarchical protocol in which costs in terms of mitigation actions and benefits in terms of population viability prospects can be explicitly accounted for, and in which optimization algorithms can be potentially implemented to improve decision making (Polak et al., 2014).

Although our protocol is designed to be applied to a wide range of species and scenarios, several constraints must be born in mind. The protocol focuses in non-natural mortality directly caused by humans, but its application can be difficult in other causes of mortality indirectly caused by humans, such as the introduction of invasive species and habitat loss (Loss et al., 2013). The protocol is very well suited for mortality caused by infrastructures, which show a fixed location. Its application may be more difficult for more scattered threats such as persecution or harvest, which are likely to show more spatial and temporal variation in nature. Even so, deaths caused by these threats are more likely to occur in specific areas (e.g. corridors and breeding sites; Mateo-Tomás et al., 2012) and, therefore, many aspects of the protocol can be still applied. In some cases, demographic and behavioral knowledge of target species may be poor, but the protocol can still be used as a guideline for the main steps needed to achieve the maximum positive impact on the target species conservation. Modern population quantitative methods offer a wide range of tools for identifying the principal demographic drivers and meaningful local areas for the overall population dynamics, and we advocate for incorporating this type of information into the prioritization process. If demographic data is not available, information on the distribution area of the target species should be sought (Pérez-García et al., 2017). Species distribution models may provide helpful information when direct empirical data on the distribution area is lacking. Analogously, the characteristics that determine the dangerousness of the considered threat factors may be unknown and so, we propose conducting quantitative analyses to identify them, for example, obtaining a representative sample of casualties to be able to determine which features make this particular threat factor most dangerous. Ideally, a model that can be used to predict the dangerousness of threat factors that were not sampled should be obtained. If this is not possible, expert opinion and common sense based on previous knowledge may be beneficial. A major constraint is that data on dead animals is usually recorded in a very heterogeneous fashion and rarely at large spatial scales. Consequently, baseline values of species mortality due to a given threat are not available. This means that it may be difficult to detect areas hampered by a given cause of mortality and, furthermore, the impact of mitigation actions are difficult to estimate. The estimation of the impact of a given cause of mortality is always challenging. The most common situation is of a target population mostly composed of non-tagged individuals, with no tagging scheme. Under this scenario, the only source of information comes from the encountering and reporting of dead individuals that, in most cases, will be untagged. Protocols should be designed to ensure that all the relevant information is gathered and that the effort in detecting mortality events is constant over time or, at least, that if the effort changes, it will be reported and taken into account when conducting the analyses. In addition, the cause of death should be determined by necropsy performed by a specialist (e.g. veterinary in a rehabilitation centre). In recent years, conservation organizations and administrations have begun to make more efforts to obtain information that is comparable on a regional basis; as well, citizen science may come to play an important role in the future (e.g. mortality modules on popular wildlife internet portals) if relevant information is recorded systematically. Even so, mortality caused by a given cause is usually estimated as a raw proportion, which ignores the fact that different causes of death may have distinct encounter probabilities leading to biases in the estimates of mortality caused by the threat in question (Naef-Daenzer et al., 2017). Long-term tagging schemes offer the opportunity to obtain an unbiased estimate of the fraction of mortality caused by any given cause if suitable analysis are implemented (Schaub and Pradel, 2004; Hernández-Matías et al., 2015). Tracking studies are also a valuable tool to estimate accurately the fraction of mortality caused by any given cause. The main constraint of these type of data is the difficulty to achieve a representative number of tagged individuals and that the lifespan of transmitters is usually short compared to the lifespan of the studied individuals. In turn, they provide much greater opportunities to know the fate of tagged animals. Even so, it is important to state that it is important to apply suitable analytical methods accounting for the probability of encountering the individuals (e.g. considering animals of unknown fate), the lifespan of transmitters and the time since tagging (Tavecchia et al., 2012).

It is worth to highlight that our protocol focuses on the process of prioritization. Once priority areas or infrastructures are identified, it is critical to implement suitable mitigation measures that must be permanent or at least long term and durable.

For example, in the case of electrocution, the substitution of dangerous pylons or cross-arm designs by safer ones may be preferable to insulation, which is not permanent and needs regular monitoring and repair (Tintó et al., 2010; Guil et al., 2011). After the mitigation actions, it is also critical to carry out an assessment of the effectiveness of mitigation actions at two levels. Firstly, comparing mortality rates in areas or infrastructures where mitigation actions were done with control areas or infrastructures using suitable study designs (e.g. Tintó et al., 2010). In this sense, managers should record systematically the information both of dead individuals and the characteristics of the mitigation actions already implemented. This data may allow both validating the predictor models used to assess the dangerousness of infrastructures, and assessing the effectiveness of conservation actions. In addition, the information of dead individuals may be also important to redefine priority areas. Secondly, comparing the survival of the focal territories or sink areas between the periods before and after mitigation actions as we did in this study. In this regard, population viability analysis must be used to assess whether the conservation actions allowed restoring the values of vital rates that would guarantee the persistence of the population. All in all, the assessment of the effectiveness of mitigation actions should be considered as the link between the implementation of corrections and the prioritization protocol we described in this study, so the overall cyclical process may greatly improve our ability to identify priority areas and to perform mitigation actions efficiently in an adaptive management fashion.

5. Conclusions

Our study highlights the fact that multi-scale prioritization criteria based on fine knowledge of species biology, demographic heterogeneity, and spatial use by individuals greatly improves the efficiency of any investment in conservation actions designed to mitigate non-natural mortality. We highlight that most populations are highly heterogeneous in terms of demographic performance both between- and within-local populations. Frequently, the observed heterogeneity is partly shaped by the effect of non-natural mortality, so focusing in the fractions of the population that are most seriously impacted by the threat in question may greatly improve the efficiency of mitigation actions. Similarly, we highlight that mitigation actions should be prioritized in those areas more intensively used by individuals, which greatly improves the efficacy of the conservation efforts. Our results also stress that focusing only on the specific infrastructures (e.g. pylons) known to have caused mortality events is not sufficient for solving this problem, even taking into account all species negatively affected by the threat in question. Finally, our example of pylon retrofitting in Bonelli's eagle territories demonstrates that our protocol can reduce mortality to levels that guarantee the long-term persistence of populations, an ultimate goal of species conservation practice.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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