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Short communication

Using network analysis to identify indicator species and reduce collision fatalities at wind farms

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ABSTRACT

The adverse effects of wind farms on wildlife, mainly the mortality of flying animals at turbines, should be carefully studied to reconcile renewable energy production and biodiversity conservation. The growing consensus about the aggregated pattern of this mortality at particular turbines suggests that the identification of high-mortality turbines can decisively aid in the implementation of effective management actions. Here, taking advantage of a long-term monitoring program of animal mortality at wind farms (10,017 fatalities of 170 bird and bat species between 1993 and 2016) in two Spanish regions, we demonstrate the utility of network analysis in identifying species indicative of high-risk turbines whose stoppage could significantly reduce the mortality of other species. Our protocol can be easily applied to any region with available data on animal mortality to help managers reduce the negative impacts of wind farms.

1. Introduction

The negative impacts of greenhouse gases produced by traditional energy sources have led to the development of renewable energy alternatives (e.g. Sims, 2004), which may have substantial environmental impacts of their own (Sánchez-Zapata et al., 2016). Especially alarming is the number of fatalities due to the collision of flying animals (birds and bats) with rotating turbine rotor blades (hereafter, turbines; Smallwood, 2007) at wind farms. In the United States alone, wind turbines cause an estimated annual mortality of 140,000–328,000 birds (Loss et al., 2013) and 500,000–1.6 million bats (Arnett and Baerwald, 2013). Thus, it is urgent to find solutions that make green energy production compatible with wildlife conservation.

A generalized pattern observed in studies of avian mortality at wind farms is that the spatial distribution of *mortalities* is not uniform at large (among wind farms) or at small scales (among *turbines),* but rather is concentrated at some specific wind farms and *turbines* that show the highest *mortality* rates (e.g. Osborn et al., 2000; Carrete et al., 2012). Although there are factors such as topography or proximity to colonies of sensitive species that relate to mortality rates at turbines (Barrios and Rodriguez, 2004; Carrete et al., 2012), much variance remains unexplained and more work is needed to fully understand it. Meanwhile, actions to reduce the hazard level of these points are urgently required, and a first step is to detect those turbines that are the most dangerous. In this scenario, the use of indicator species (i.e. estimators of the status of other species or environmental conditions of interest, Caro and O'Doherty, 1999) can greatly contribute to the identification of hazardous wind turbines, and help managers focus management efforts.

Here, we use a network analysis approach to easily identify species indicators of wind farm fatalities. Network analysis has proven useful to select indicator species within schemes of infrastructure impact monitoring, especially in complex or understudied communities, in part because it does not require detailed species-specific information (Pérez-García et al., 2016). Our study focuses on peninsular Spain, one of the areas of the world with the largest numbers of wind farms (> 1080 wind farms producing 23,026 MW of generating capacity in 2018; http://www.aeeolica.es). At the same time, Spain is vastly important to wildlife, with population strongholds of many threatened European avian (Birdlife International, 2000) and bat species (Ibáñez et al., 2006). These characteristics make this a good model to study the interactions between wildlife and wind energy.

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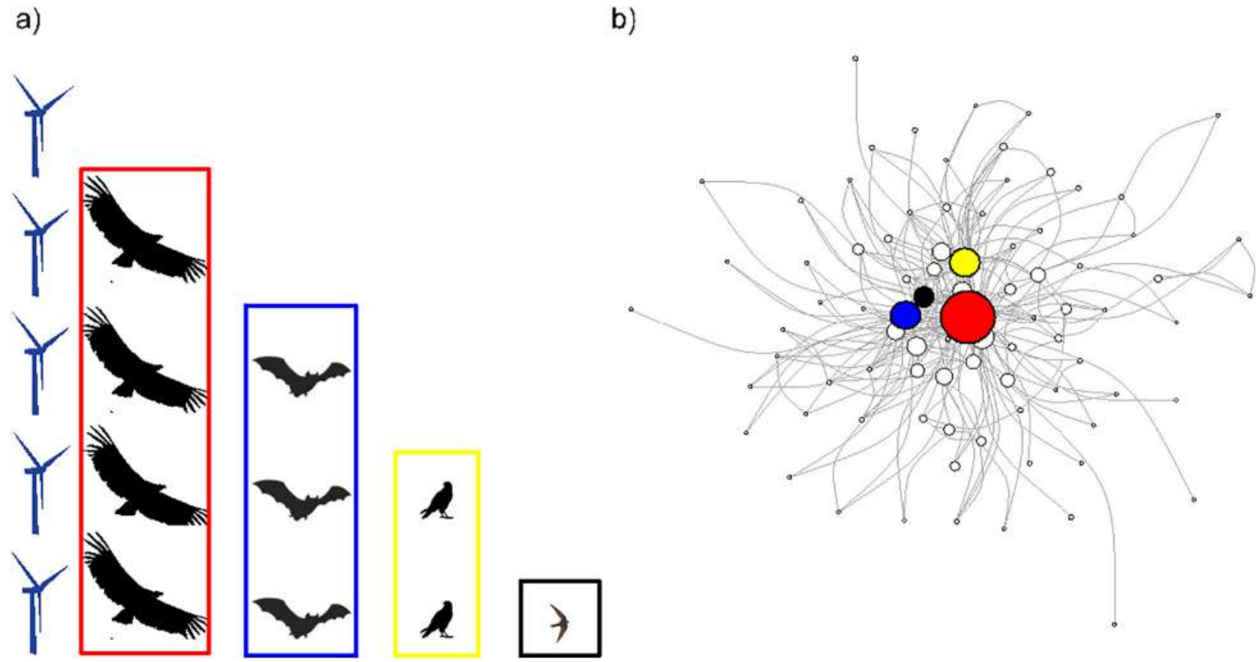

Fig. 1. a) A conceptual representation of how stopping high-risk turbines identified by using an indicator species (red: griffon vulture) can reduce the mortality rate of other species (blue: *Pipistrellus* spp.; yellow: common kestrel; black: common swift). b): Network describing the co-occurrence of wildlife fatalities at one of the study sites. Each circle represents a species and each line links species that co-occur at a turbine. The size of the circles represents the (log) number of fatalities per species and colors match those of a). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. Methods

2.1. Study areas and mortality data

We included information from two areas located in the provinces of Cádiz (southern Spain) and Castellón (eastern Spain). Both are areas dominated by Mediterranean landscapes with a mixture of *Quercus* woodlands, scrublands and pastures in hilly areas and agricultural lands in plains. Moreover, Cádiz's wind farms are located near the Strait of Gibraltar, one of the main migratory routes for Palearctic birds. More information on these study areas can be found in Carrete et al. (2012) and Martínez-Abraín et al. (2012).

From the moment of their construction, power companies and local governments have regularly monitored wind farm mortality. We used information on 27 and 12 wind farms (totalling 869 and 320 wind turbines) located in Cádiz and Castellón and built between 1992 and 2009 and 2006–2011, respectively. We included mortality fatalities from December 1993 to March 2016 for Cádiz (although the monitoring was more systematic after 2008) and from October 2006 to June 2015 for Castellón. For each mortality case, monitoring programs recorded the species, date, and turbine. If the exact turbine where the collision occurred was not identified, data were excluded from our analysis.

Species identification was difficult for some groups (e.g. bats from the *Pipistrellus* genus), so their mortality records were pooled for subsequent analyses. Because the surveys were conducted twice per week (at maximum) and were not standardized among wind farms, some of the carcasses may have disappeared before detection (mainly small-sized species; Ponce et al., 2010). Thus, our results are conservative, indicating minimum mortality rates (see Carrete et al., 2012 for a more detailed explanation on monitoring).

2.2. Indicator species identification

Our procedure had three main steps, namely: 1) First, we tested whether data are organized under a nested pattern. Our reasoning is that if the distribution of dead animals in a wind farm is quantitatively nested at turbines, the most commonly affected species (i.e. the species killed at more turbines and in the largest numbers) can be used as indicators of dangerous turbines because the rest of the species will also die in these points (Fig. 1a). If the assemblage is nested, we then 2) identified the species contributing the most to this nestedness as a candidate for an indicator species. Finally, 3) we considered whether the biological characteristics of the species are appropriate for its use as an indicator. Note that indicator species should point to the presence of other, more evasive/elusive (difficult to detect) species, so we were particularly interested in large species that can be easily detected during the standard monitoring programs performed at wind farms to correctly estimate its presence (i.e. mortality).

We identified if mortality data were quantitatively nested using the metric WNODF (Weighted Nestedness Of Decreasing Fill), ranging from zero to 100 (100 corresponding to a perfectly nested matrix and medium values to random ones). Since the variation in the number of fatalities could influence the degree of nestedness, we compared our observed value of nestedness to values obtained in 1000 matrices constructed following a null model where species-specific probabilities are proportional to the relative number of fatalities per species (Vázquez et al., 2007). We then calculated the contribution of each species to the nestedness as a proxy of how accurate the mortality of each species in a turbine is in predicting the mortality of the other species (positive or negative values for species with a high or low contribution to nestedness, respectively). In our case, indicator species are those with the largest positive values. Species with the lowest contribution to the pattern should also be identified as their mortality will go unnoticed when using the indicator species. WNODF and contribution to nestedness were obtained using the *bipartite* package (Dormann et al., 2009) in R (R Development Core Team, 2015).

3. Results

A total of 10,017 carcasses from 170 species were recorded in the two studied areas (9014 individuals from 151 spp. in Cádiz, and 1014 from 78 spp. in Castellón) (Table S1). Bird fatalities were more common than mammal fatalities (88% and 22%, respectively), with this rate higher in Castellón than in Cádiz (Fig. 2). Mortality distribution across

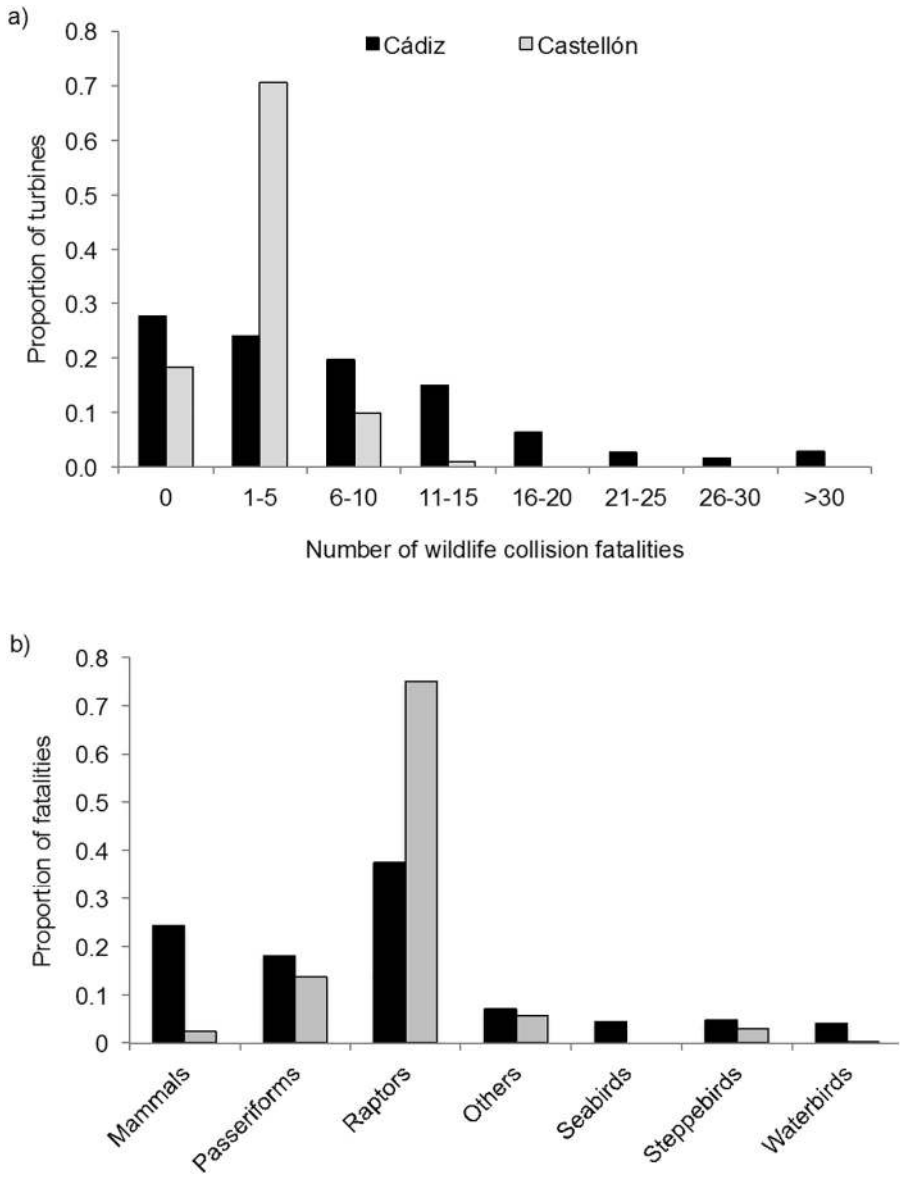

Fig. 2. Wildlife fatalities in wind turbines in both study areas. a) Number of wildlife collision fatalities per turbine. b) Proportion of fatalities from different animal groups.

Table 1
Reduction in the number of avian and bat fatalities in a scenario of turbine stoppage using the griffon vulture as an indicator species. We show the percentage (%) and number (N) of turbines with more than one and more than two vulture fatalities, and the percentage of fatalities (% fatalities) detected at those turbines from the total number of fatalities detected in each study area, both including (V) and excluding (NV) vulture mortality.

	% turbines (N)	Vulture fatalities > 0		% turbines (N)	Vulture fatalities > 1	
		% fatalities (V)	% fatalities (NV)		% fatalities (V)	% fatalities (NV)
Cádiz	52.5 (632)	78.8	73.6	32.4 (390)	52.8	47.5
Castellón	66.8 (255)	91.6	75.2	43.4 (166)	74.8	51.6

turbines was highly heterogeneous, with no fatality records in 28% and 18% of the turbines and some turbines reaching a maximum of 101 and 14 fatalities (data for Cádiz and Castellón, respectively). Species-specific patterns of mortality were also highly heterogeneous. The griffon vulture (*Gyps fulvus*) was the most affected species (1772 fatalities in Cadiz and 672 in Castellón), while the second most affected groups were bats (genus *Pipistrellus*, 1504 fatalities) in Cádiz and swifts (common swift *Apus apus*; 36 fatalities) in Castellón. Thirty percent of the species were anecdotally detected (i.e. only appeared at one turbine; Table S1).

The species mortality pattern was significantly nested in both Cádiz (WNODF = 13.97, $p < 0.001$) and Castellón (WNODF = 15.25, $p < 0.001$, Fig. 1). The griffon vulture was, by far, the species that most contributed to this pattern in both study areas, showing its role as an indicator of dangerous turbines (Fig. 1, Table S2). Indeed, in Cádiz, stopping or changing the location of turbines with records of griffon vulture mortality (66.8% of all turbines) would have reduced global fatalities at wind farms by > 90% and mortalities of species other than vultures by 73%. With a threshold of mortality greater than one individual (43.4% of all turbines), total mortality would be reduced by 74.8% and mortality of other species by 47.5% (Table 1). We also identified some species with a low contribution to nestedness such as the Eurasian eagle-owl (*Bubo bubo*) in Cádiz and the common blackbird

(*Turdus merula*) in Castellón (Table S2). These species have singular mortality patterns and should be considered separately.

4. Discussion

In this note, we demonstrate the usefulness of network analysis and the indicator species concept in helping managers to rapidly identify high-risk turbines for wildlife to implement targeted conservation actions (Pérez-García et al., 2016). Although it would be desirable to understand the underlying factors causing the high variability in turbine hazard, this approach represents an opportunity to reduce the high mortality numbers at the most dangerous wind farms in the meantime.

Our results show that the griffon vulture, the species with the highest mortality records in the two study regions, is a perfect candidate to use as an indicator species due to its high contribution to the observed mortality nestedness and its large body size (mean body weight of griffon vultures: 8.82 kg ($N = 101$), authors' own data). Moreover, as griffon vultures are widely distributed not only across Spain (Martí and Del Moral, 2003) but also Eurasia (del Hoyo et al., 2018), it is very likely that this species could be used as an indicator of risky turbines in other regions. However, it should be taken into account that indicator species would change depending on the characteristics of the study community. Thus, our straightforward protocol should be applied in other regions to obtain realistic results.

Different procedures have been used to reduce mortality at wind farms. For example, the temporary stoppage of particular turbines has been effective in reducing griffon vulture mortality at some wind farms in southern Spain (de Lucas et al., 2012). However, the necessity of constant vigilance and its dependence on visual contact with flying animals may restrict its use to large groups of soaring birds or large species. Other management actions, such as halting operation during peak migration periods or under climatic conditions of high collision risk (Barrios and Rodriguez, 2004), have not been shown to be safe for species other than the target species. Our approach, on the contrary, is straightforward and effective, as we propose the use of indicator species to reduce wildlife mortality at wind farms by stopping (or dismounting) those turbines with the highest numbers of fatalities of that indicator species. In our case, by removing turbines with more than one record of vulture fatality, not only will the mortality of this species be reduced, as observed in other studies (Martínez-Abraín et al., 2012), but so will that of other avian and bat species, some of which are highly threatened such as the Egyptian vulture (*Neophron percnopterus*; Carrete et al., 2009).

It is worth noting that the stoppage or removal of a low percentage of turbines with high mortality records would have no significant economic costs for the wind power industries, as previously shown (de Lucas et al., 2012). Although this approach could be very effective for most species found dead at wind farms, it is important to note that the mortality of some other species may not be effectively predicted by the indicator species. In these cases, specific monitoring programs and conservation measures are required, especially when dealing with threatened species and/or species with high rates of mortality (Carrete et al., 2009).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2018.06.003.

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