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Using species distribution modelling to predict bat fatality risk at wind farms

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ABSTRACT

Bats are often killed in large numbers at wind farms over a wide geographical range. We aimed to predict which areas conferred higher fatality risks to bats at wind farms. In an innovative approach, we combined species distribution modelling with mortality data and the ecological conditions at wind farms located in Portugal. We then generated predictive models to determine areas of probable mortality and which environmental factors were promoting it. Mortality data for four bat species, *Hypsugo savii*, *Nyctalus leisleri*, *Pipistrellus kuhlii* and *Pipistrellus pipistrellus*, were used. These experienced the highest levels of fatalities at wind farms in Portugal, comprising 290 of the 466 fatalities recorded from 2003 to 2011.

The mortality risk models showed robust performances. Wind farms sited at humid areas with mild temperatures, closer than 5 km to forested areas and within 600 m of steep slopes showed higher probabilities of mortality. High mortality risk areas also overlapped highly with the potential distribution of *N. leisleri* in Portugal, suggesting that populations of this species may be at high risk due to wind farm fatalities. Moreover, a large extent of the area predicted to be a hotspot for mortality (i.e. areas likely to confer high mortality risk for four species) overlaps with sites highly suitable for wind farm construction.

In summary, the approach used in this study could be paradigmatic for the development of important pre-emptive conservation measures for bat populations by identifying mortality risk in areas prior to wind farm installation and determining which conditions promote mortality.

1. Introduction

The increasing concern about the negative effects caused by climate change phenomena and the depletion of the traditional energy sources has promoted high investment in the renewable energy sector (McLeish, 2002; Pasqualetti et al., 2004). Consequently, wind energy is an increasingly explored alternative energy source.

Despite its clear benefits for the reduction of the emission of green-house gases, the impacts of wind farms on biodiversity need to be considered. It was only recently discovered that bat populations might be affected by these facilities, when in 2003 considerable numbers of bat fatalities were estimated at a wind farm in West Virginia, USA (Kerns and Kerlinger, 2004). More recently, substantial and geographically widespread fatalities have been documented in the USA (Arnett et al., 2008), Canada (Baerwald and Barclay, 2009) and in Europe (Rydell et al., 2010; EUROBATS, 2011).

Besides the mortality risk, wind turbines present other potential negative effects on bat populations such as degradation and destruction of foraging habitats, commuting corridors and roosts (Rodrigues et al., 2008).

It is still unclear why bat mortality rates vary across wind farms. Some studies have hypothesized that the ecological features and conditions surrounding wind farms are associated with mortality rates. Arnett et al. (2008) state that, although there are very few studies on this subject, understanding the relationship between landscape characteristics and bat fatalities may help develop mitigation strategies. In Europe the highest mortality rates appeared on top of forested hills and wetlands, while the lowest rates occurred at flatlands and farmlands, suggesting that habitat surrounding wind farms influences mortality risk (Rydell et al., 2010). Baerwald and Barclay (2009) suggest that mountain ridges are important guiding structures for bats during migration, as mortality risk at wind farms is higher near such landscape features. Periods of high bat mortality overlap with most bats' migration period especially during autumn, between August and October (Arnett et al., 2008; Rydell et al., 2010).

Monitoring programs for bat fatalities at wind farms have not been implemented in all European countries and can differ in the methods used for fatality surveys and in sampling effort across sites. Nevertheless, there are records of bat fatalities in more than

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13 European countries, mainly in Germany, Spain, France and Portugal (EUROBATS, 2011). In Europe there are records of 3545 bat fatalities (EUROBATS, 2011), 466 of them in Portugal, where 11 of the 25 mainland Portuguese bat species are known to be affected, most notably *Pipistrellus pipistrellus* Schreber, 1774, *Nyctalus leisleri* Kuhl, 1817, *Hypsugo savii* Bonaparte, 1837, *Pipistrellus pygmaeus* Leach, 1825 and *Pipistrellus kuhlii* Kuhl, 1817 (EUROBATS, 2011). Although the conservation status of the pipistrelle bats is of ''Least Concern'', *N. leisleri* and *H. savii* are labelled as ''Data Deficient'' in the Portuguese Red List, and are therefore considered of high priority for studies focusing on their conservation (Cabral et al., 2006). Most casualties in Europe involve tree and crevice roosting bats (Jones et al., 2009; Rydell et al., 2010; EUROBATS, 2011), yet little is known about the population sizes and dynamics of these species. Nevertheless, the potential impacts of wind farms on some species such as *N. leisleri* may have population-level consequences (Jones et al., 2009).

Currently, the main priorities identified for research on bat mortality at wind farms include the development of adequate mitigation measures (e.g. Szewczak and Arnett, 2008; Baerwald et al., 2009; Arnett et al., 2011), determining whether fatality rates at wind farms have an impact on populations and assessing the risks presented by wind farms prior to construction (BWEC, 2008). This study aims to make a relevant contribution for the last priority area by employing a new approach using species distribution models (SDMs).

SDMs are empirical models that relate field observations to environmental predictors, based on response surfaces derived from statistical or theoretical calculations (Guisan and Zimmermann, 2000). Predictive modelling of species' distributions offers a possible solution to this challenge, by combining occurrence data with environmental variables (such as temperature, precipitation, altitude or land cover) considered to influence the presence of the species studied. The production of a model of the species' requirements given the variables selected provides insights into environmental tolerances and habitat preferences (Anderson et al., 2003), i.e., its ecological niche. SDMs imply that species occurrence is influenced by certain ecological conditions but, as stated before, there is evidence that bat mortality at wind farms is also influenced by ecological conditions. As mortality rates differ among wind farms, then consequently the occurrence of fatalities should be related to a range of values within a set of environmental variables associated with the location of the wind farms – the 'mortality niche'. Fatality data can therefore paradoxically be used as a proxy for presence data and environmental predictors related to mortality can be determined. We present a pro-active approach where it will be possible to predict mortality risk for bats prior to wind farm instalment, hence providing a method that could potentially be used in other countries and for other taxa.

In this study we predicted areas in which the construction of wind farms might cause higher mortality in bat populations and we identify which environmental conditions promote that mortality. Four species with highest mortality recorded at Portuguese wind farms were selected for study: *P. pipistrellus*, *N. leisleri*, *H. savii* and *P. kuhlii*, with 136, 104, 33 and 17 fatalities respectively, altogether comprising 290 of the 466 fatalities recorded. These fatality records do not represent the full extent of fatalities: there may be strong biases resulting from different survey methodologies used and variation in search effort and among observers. However our presence-only modelling approach attempts to overcome these caveats.

Therefore, the main questions addressed in this study are: (a) where are the areas of potentially high mortality risk for bats if wind farms are constructed?; (b) which ecological variables promote bat mortality in wind farms?; (c) what is the range of values for these variables that increase mortality risk? and (d) how do mortality predictions relate to the species' predicted distributions and also to proposed areas for the construction of wind farms?

2. Methods

2.1. Study area

The study was carried out in mainland Portugal, situated in the extreme southwest of Europe and bordered by the Atlantic Ocean to the west. Portugal has two distinct biogeographic regions: Eurosiberian and Mediterranean. The country's orography varies between the high altitudes in the north and central regions, in contrast to the plains in the south and coastal regions of the west (Fig. 1). Portugal offers high wind power potential in the central and northern areas of the country, due to the proximity of the ocean and the influence of the dominant northerly winds (Costa, 2004).

2.2. Bat mortality and distribution data

The fatality data used for the mortality risk modelling were obtained from governmental institutions ICNB (Portuguese Institute for the Conservation of Nature and Biodiversity) and APA (Portuguese Environmental Agency) where we consulted wind farms environmental impact assessment studies and monitoring reports, from 2003 up to 2011. Wind farm location data were supplied by DGEG (Portuguese Department of Energy and Geological Resources).

The species selected for this study had at least 10 geographically-specified fatality records, this number being considered the minimum of records necessary for robust analyses using SDM (Elith et al., 2006; Hernandez et al., 2006). This criterion was selected also considering that the ecological characteristics within

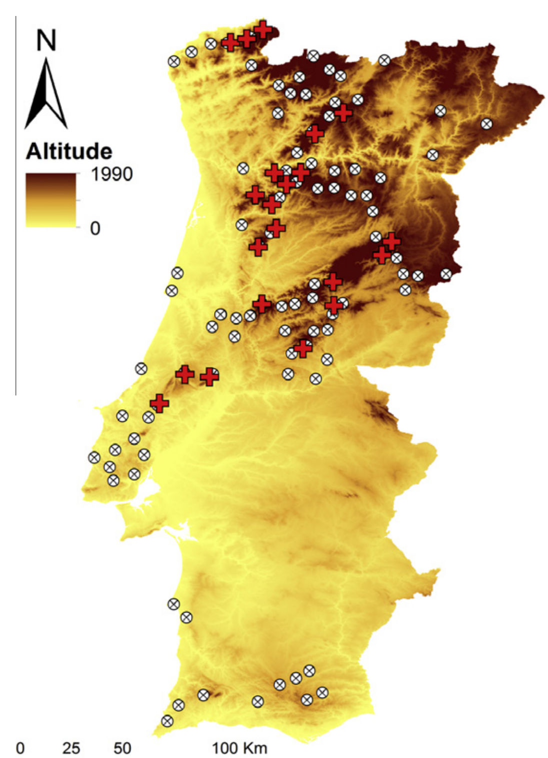

Fig. 1. Map with the location of the data used for the mortality risk models. White crossed circles indicate the location of wind farms and red crosses are the fatality records for *H. savii*, *N. leisleri*, *P. kuhlii* and *P. pipistrellus*. Each symbol may correspond to more than one location.

and surrounding wind farms can be very specific, forming a very narrow niche of conditions. Consequently, a small number of records was likely to be sufficient to cover the width of the entire mortality niche.

Mortality records were highly correlated spatially due to their highly aggregated distributions within wind farms. In order to guarantee independence, a minimum distance between records was calculated using a semi-variogram and Moran's I measure of spatial autocorrelation in the software package SAM v4.0 (Rangel et al., 2010). Consequently, records less than 3 km of each other were randomly eliminated from the fatality data sets for each species. Therefore, the number of records used in the mortality risk models were 34 for *P. pipistrellus*, 32 for *N. leisleri*, 18 for *H. savii* and 13 for *P. kuhlii*. Distribution records up to 2010 were supplied by ICNB and were 24, 71, 30 and 151 records for each species, respectively. Wind farms used in this study were mainly in areas of high elevation in the north and central regions of Portugal, although smaller numbers occurred in the most southern regions (Fig. 1).

2.3. Environmental variables

A set of independent ecogeographical variables (EGVs) was chosen taking into account the environmental characteristics that might influence bat mortality at wind farms (Arnett et al., 2008; Rydell et al., 2010) (Supplementary Material A, Table A.1): these were climate variables (mean, maximum and minimum temperature, temperature range and precipitation), obtained from WorldClim and calculated for the months April to October, when bat mortality at wind farms is known to occur in Portugal (ICNB, 2010); topographical variables (altitude, slopes higher than 10°, 15° and 20°, distance to slopes higher than 10°, 15° and 20° and north-south and east-west exposures), obtained from the United States Geological Survey (Shuttle Radar Topography Mission) and calculated in ArcGIS 9.2 (ESRI, 2006) and habitat variables represented by land cover, obtained from Global Land Cover 2006 (MEDIAS-FRANCE, 2006). Habitat variables were reclassified into 8 classes: agricultural fields (large arable fields, pastures, orchards and croplands), eucalyptus forests, pine forests, native woodland (temperate broadleaf and Mediterranean forests), scrubland, urban areas, bare areas (burnt areas, bare ground and rocks) and water (major water courses and still waters). Euclidian distances to eucalyptus forests, to native woodland and to water were calculated. These variables may represent distances to relevant roosting, feeding and drinking areas for Mediterranean bats (Russo and Jones, 2003).

The chosen set of EGVs also reflects the environmental factors related to bat occurrence, according to current knowledge. Climate conditions are highly relevant for bat physiology, energy demands and water availability (Racey et al., 1987; Webb et al., 1995; Adams and Hayes, 2008). Moreover, distances to land cover and slope are related to bat foraging areas and to the potential presence of roosts for tree and crevice-dwelling bats (Rainho and Palmeirim, 2011).

Wind direction and speed influence bat mortality at wind farms (Amorim, 2009; Rydell et al., 2010). However, it was impossible to establish a link between these wind values and the precise moment of the bat fatality, hence it was not possible to consider wind speed and direction in this study. Exposure variables (predominant orientation of cliffs, mountains or other topographic features) were chosen as surrogates for wind conditions. Both north-south and east-west exposures were determined by using the aspect (X) function derived from the altitude variable, using the formulae $\cos[(X\pi)/180]$ and $\sin[(X\pi)/180]$, for each direction respectively.

It is important to emphasise that distance variables were only used for the mortality risk models, reflecting the distance between wind turbines and areas where bats may occur, mainly at potential foraging areas or roosts (Rainho and Palmeirim, 2011).

After a preliminary analysis to understand which variables were most important for both types of modelling (mortality risk and distribution), altitude was removed from the analyses because results were consistently biased towards high altitudes, where wind farms are sited.

All data had a resolution of ca. 300 m, making the total area covered ca. 81000 km^2.

2.4. Modelling procedure

Maximum entropy (Maxent) was the technique chosen to develop the mortality risk models and the species distribution models. Maxent is one of the most widely used methods used in species distribution modelling because it does not need absence data and it seems robust to scarce and biased datasets (Elith et al., 2006; Hernandez et al., 2006; Rebelo and Jones, 2010). Moreover, Maxent's predictive performance outperforms other modelling methods (Elith et al., 2006; Hernandez et al., 2006; Wisz et al., 2008; Rebelo and Jones, 2010) and it has been used successfully in several species distribution and niche modelling studies (e.g. Pearson et al., 2007; Brito et al., 2009; Guisan and Zimmermann, 2000; Rebelo and Jones, 2010). Maxent estimates the area where a species is most likely to occur by determining the distribution of maximum entropy that is closest to the uniform, although subject to a restriction: the expected value of each environmental variable of this distribution must be equivalent to its empirical average (Phillips et al., 2006).

By using presence-only data the problem of unreliable absence records is overcome. Bats have limited detectability and identification in flight, due to their elusive and nocturnal behaviour (Ahlén and Baagøe, 1999). This factor could lead to the creation of "false absences", meaning that a species was not detected, although it was present (Elith et al., 2010). The same concept can be applied to fatality data, meaning that even if a wind farm does not present mortality records, it does not necessarily mean that no bats were killed there, especially considering that different observers and methodologies were employed in the fatality searches (Arnett et al., 2008; Jones et al., 2009).

Presence data and the respective EGV sets were imported into Maxent software 3.3.3e (http://www.cs.princeton.edu/~schapire/maxent/) and run in auto features with a regularization multiplier of 1. To test model outputs, 100 replicates were run with 25% of the dataset left to test the models. The Area Under Curve (AUC) of the Receiver Operating Characteristics (ROCs) plot was taken as a measure of the overall fit of the models (Fielding and Bell, 1997). The AUC ranges from 0 to 1, where the maximum score of 1 represents perfect discrimination and a medium score of 0.5 represents random predictive discrimination (Phillips et al., 2006).

The initial mortality risk models could have been predicting areas of possible fatalities in areas outside each species range of occurrence. In order to correct for this, the mortality models were filtered with the distribution models for each species (Supplementary Material B). Each model was reclassified into binary (presence/absence) format and then multiplied by the logistic output of the mortality risk models of each species. Reclassification was done using the 10 percentile training presence logistic threshold value (Rebelo and Jones, 2010). This criterion assumes that at least 10% of the presence data may suffer from some type of error such as misidentifications or incorrect geographical coordinates. In parallel, mortality risk models for all four species were also reclassified into binary models, although using the minimum training presence logistic threshold value instead of the 10 percentile training presence logistic threshold value used in the reclassification of the distribution models. This value was thought to be more adequate for the mortality risk models, in order to reduce omission errors though it is likely that commission errors may increase (Rebelo and Jones, 2010). From a conservation perspective, in an extreme scenario it is preferable to have reliable positive predictions (all predicted fatalities are "true") than the other way around, i.e., it is preferable to avoid errors type I (Rebelo and Jones, 2010).

Variable importance was measured using the percent contribution values and the jackknife values of regularized training gain (a measure of likelihood between species data and the variable) for each species. The percent contribution is calculated based on how much the variable contributed to the model depending on the path selected by Maxent for a particular model run. Gain values are obtained by creating different models. Each variable is excluded in turn, and Maxent generates a model with all the remaining variables, then using each variable in isolation to generate another model. Finally, a model is created using all variables.

Variable response curves are determined when Maxent creates a univariate model. These represent a limited range of values within a variable associated to the species presence or mortality.

2.5. Data analysis

A mortality hotspot map (i.e. areas likely to confer high mortality risk for four species) was built by summing the four binary

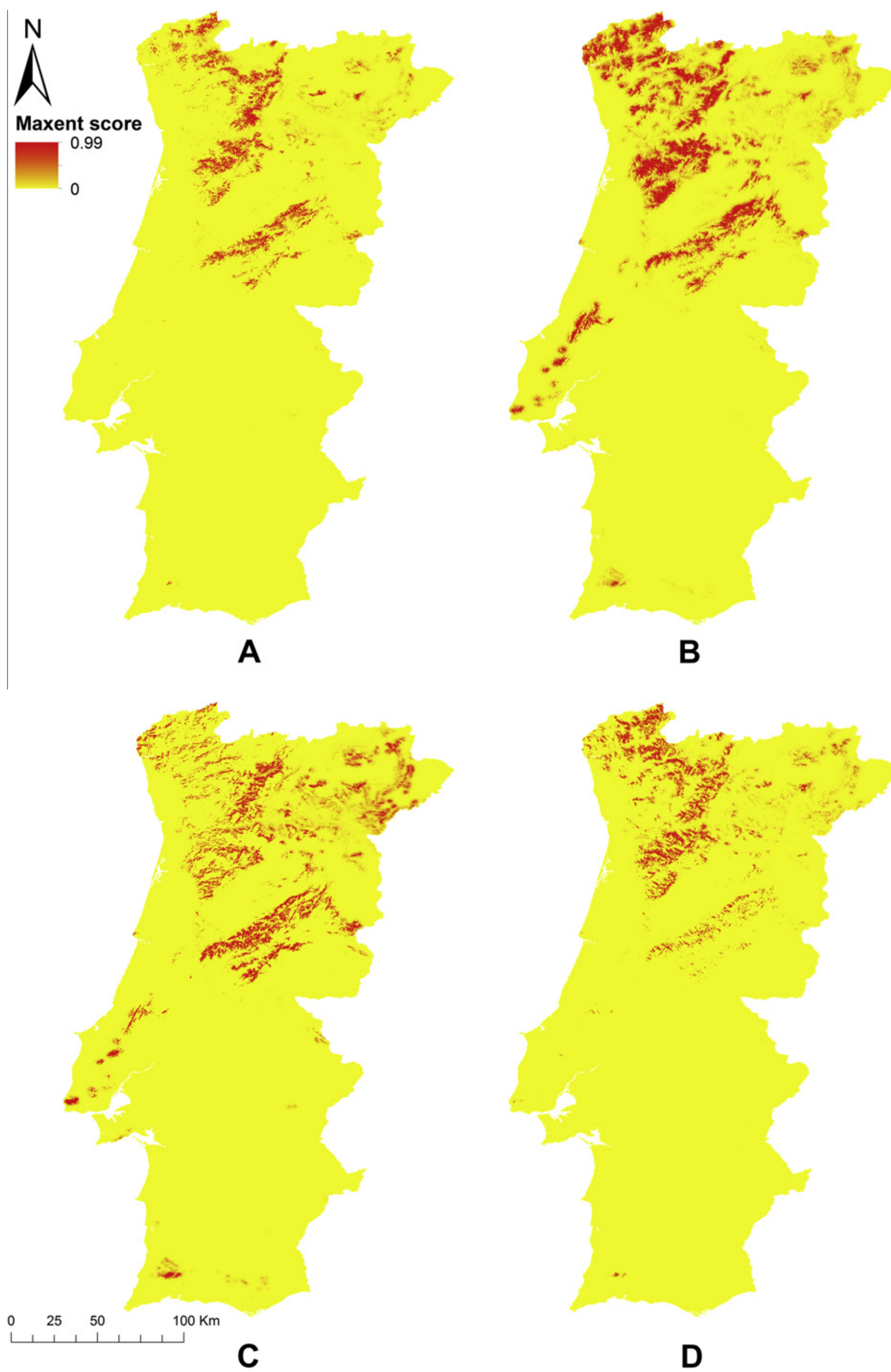

Fig. 2. Maps of the mortality risk models obtained for *H. savii* (A), *P. kuhlii* (B), *N. leisleri* (C) and *P. pipistrellus* (D). Maxent score indicates 0 for no probability of mortality and 0.99 for high probability of mortality.

mortality risk models of the studied species. All calculations were made in ArcGIS 9.2.

Furthermore, species distribution and mortality prevalence in the study area were calculated. This was accomplished by first determining the total distribution area, obtained using the number of pixels reclassified as "presence" in the binary distribution models and multiplying it with the pixel size. Afterwards, the prevalence in the study area was calculated by considering the total distribution area and dividing it with the total area of the country. The prevalence in mortality was determined using the number of pixels reclassified as "mortality" in the binary mortality risk models, after multiplying them with the pixel area and dividing this value with the total distribution area for each species.

We also determined the proportion of overlap between predicted mortality risk areas and different wind potential classes. These latter are used to select wind farm sites (where areas with average wind speeds higher than 5 ms^{-1} are preferred) and were reclassified into two classes: low and high potential for wind farm construction (Costa, 2004).

3. Results

3.1. Mortality risk models

Models for species distributions are not analysed in detail in this study and were only calculated to filter mortality risk models (see Methods). Therefore these results are available in Supplementary Material B. All mortality risk models exhibited ROC curves with high average AUCs, with all species presenting very similar values (*H. savii* AUC = 0.99 ± 0.005; *P. kuhlii* AUC = 0.99 ± 0.008; *N. leisleri* and *P. pipistrellus* had the same AUC = 0.99 ± 0.01).

Mortality models for the four species exhibit higher fatality probability in the central and northern regions of the study area, though also presenting likelihood of fatality in a small area in the southwest (Fig. 2). Moreover, when focusing on the central region of the study area, *N. leisleri* and *P. kuhlii* also demonstrated a possibility of fatality in the western part of the country.

The map of mortality hotspots (Fig. 3) showed that the central and north regions of the country, with a special focus on the northwestern sector, were the largest areas where fatalities can occur for the four species studied.

After the calculation of the models, new data from monitoring reports was published. These results, although preliminary, seem to validate our models' predictions (Supplementary Material C). Most notably, in a wind farm in the southwest of the country several fatalities were recorded for *N. leisleri*, *P. kuhlii* and *P. pipistrellus*. All were registered in locations where there were no previous records of fatalities for those species but, remarkably, mortality risk models predicted a high probability of fatality for those species for that location. We produced a preliminary model evaluation with the new presence/absence records, although only accomplishing this for *N. leisleri* and *P. kuhlii* because we did not have sufficient data for *H. savii* and *P. pipistrellus* (Supplementary Material C, Table C.1).

3.2. Importance of ecogeographic variables for species mortality and respective response curves

The variables that contributed most highly to the mortality models were distance to slope, distance to water, distance to eucalyptus forests, precipitation, mean temperature and maximum temperature (Fig. 4).

All four species appear to have high probability of fatality when eucalyptus forests are located less than 5 km from wind turbines, with *H. savii* and *N. leisleri* presenting a peak between 1 and 5 km of distance (Fig. 5). Additionally, areas with an average slope higher than 15° closer than 600 m from wind farms are also associated with an increased mortality risk for all species. Moreover, the higher the distance to water sources, the higher the likelihood of fatality occurrence, *N. leisleri* being an exception to this by presenting two peaks of probability of mortality at 15 and 28 km of distance to water.

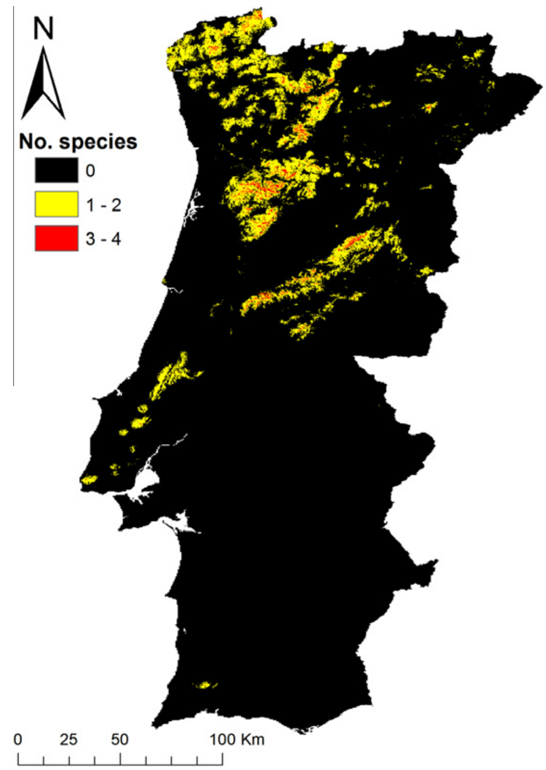

Fig. 3. Map representing the mortality hotspots divided in three classes: no species, one to two species or three to four species likely to suffer fatalities in wind farms.

Regarding climatic variables, all species present a peak between 550 and 600 mm of precipitation, with an exception for *P. kuhlii* which shows an increased probability of fatality in areas with higher precipitation (Fig. 5). This species is also an exception in terms of responses to the other climatic variables, presenting higher probability of fatality below 14 °C maximum temperature and below 10 °C mean temperature, whereas all the other species present a peak at 18 °C maximum temperature and at 14 °C mean temperature.

3.3. Mortality in the context of species distributions and wind farm construction areas

Species prevalence in the study area showed that *N. leisleri* had the widest potential distribution, covering almost 40% of the total country area. It is followed by *P. kuhlii* with ca. 33% and *P. pipistrellus* with little over 12%. *H. savii* showed the most confined predicted distribution, potentially appearing in only around 10% of the study area (Table 1).

Regarding the proportion of potential distribution of a species that overlaps with areas of high mortality risk (prevalence of mortality), *P. pipistrellus* is the most affected, being likely to occur in almost 20% of the area of high mortality risk estimated for that species. It is closely followed by *N. leisleri*, with 16%. *H. savii*'s distribution covers only 5% of the mortality areas obtained for that species and *P. kuhlii*'s only around 2%.

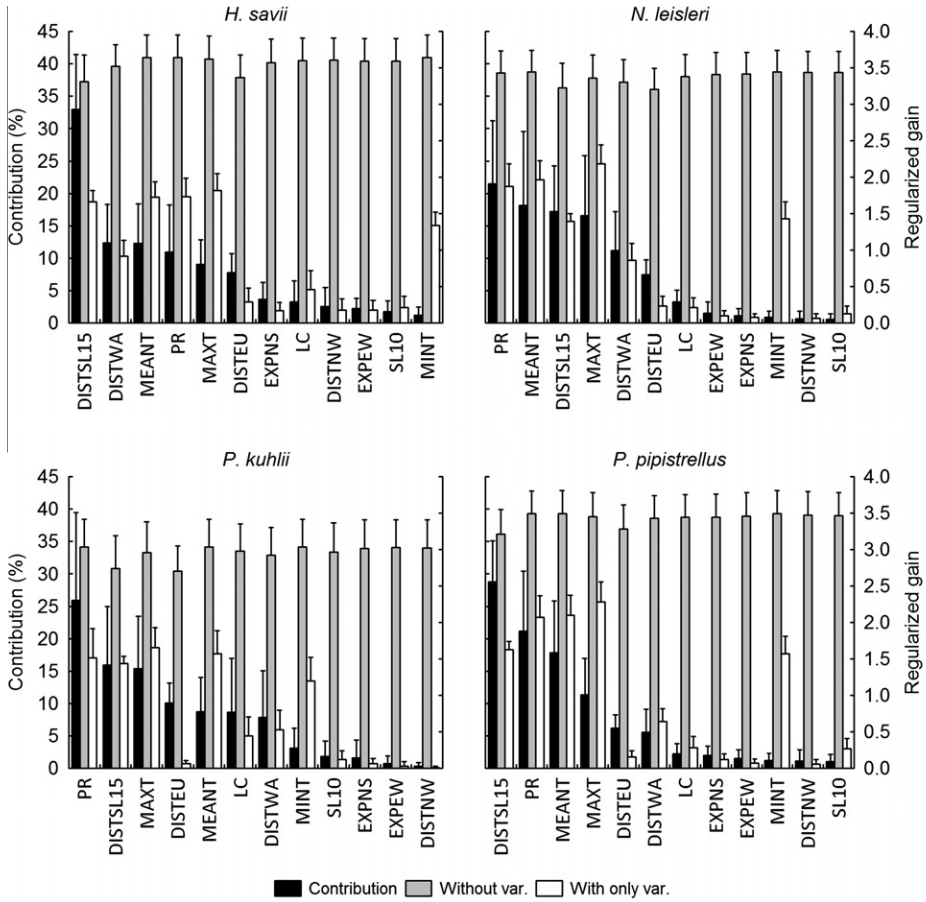

Fig. 4. Graphics representing variable importance of *H. savii*, *N. leisleri*, *P. kuhlii* and *P. pipistrellus* for the mortality risk models. The contribution, in percentage, of each variable is represented by the black bars, whose values can be read in the left axis of each plot. Grey bars represent the values of the jackknife results for models without the variable (without var.) and white bars represent the same results for models with only one variable (with only var.); these values can be read in the right axis of each plot. Variables are displayed from the highest to the lowest contribution for each species: ALT, altitude (m); DISTEU, distance to eucalyptus forest (m); DISTNW, distance to native woodland (m); DISTSL15, distance to slope (m); DISTWA, distance to water (m); EXPEW, exposure East-West; EXPNS, exposure North-South; LC, land cover; MAXT, maximum temperature from April to October (°C); MEANT, mean temperature from April to October (°C); MINT, minimum temperature from April to October (°C); PR, precipitation from April to October (mm); SL10, slope (°); TRANG, temperature range from April to October.

When considering areas with potential for wind farm construction, we calculated the proportion of overlap between mortality risk areas and the areas with low or high average wind speeds. With a total of 2652 wind turbines within the study area, as expected the majority (1937) are located within the areas of high wind potential. Moreover, a large extent (ca. 71%) of the area predicted to be a hotspot for mortality (between three to four species) overlaps with sites highly suitable for wind farm construction (Table 2).

4. Discussion

4.1. Identification of mortality risk and relevant variables

Our mortality risk models have identified areas where bat fatalities may occur in relation to the siting of wind farms. Substituting species occurrence records with species fatality records seemed to be successful in determining the mortality niche for bats at wind farms.

The variables that were most strongly associated with mortality risk show that wind farms closer than 5 km of forested areas and 600 m of slopes steeper than 15° are the most likely to display higher mortality. Also, wind farms sited in humid areas, with precipitation around 600 mm, with mild temperatures, maximum temperatures around 18 °C and mean temperatures around 14 °C, showed higher rates of mortality. Moreover, the further the distance to large water bodies, the higher the probability of mortality. This is likely to be because wind farms are usually sited on ridges, whereas large water bodies are located downhill in valleys.

Considering that forested areas offer roosting opportunities for tree-dwelling bats and feeding areas for several bat species (Russo and Jones, 2003), and that slopes provide cracks and crevices that serve as potential roosts for bats (Kunz and Lumsden, 2003), the distances to these areas is considered highly relevant for wind farm siting. This is supported by our models and by previous studies that state that ecological features surrounding wind farms are related to bat mortality at wind farms (Amorim, 2009; Rydell et al., 2010). Moreover, bats are known to follow landscape features, such as mountain ridges, during migration. Such landscape features also represent suitable sites for wind turbine instalment. Baerwald and Barclay (2009) found that fatality rates decreased with distance from mountain ridges and this supports our results that proximity to high slopes leads to increase mortality risk.

Even though all the mortality data available for Portugal were used, it is important to state that wind farms that show no mortality are not necessarily mortality-free sites, but that during the fatality survey period there were no bat corpses found. Consequently, false absences may occur. Also, many wind farms in Portugal have not undergone bat mortality survey studies, therefore many mortalities remain undocumented. Moreover, the survey

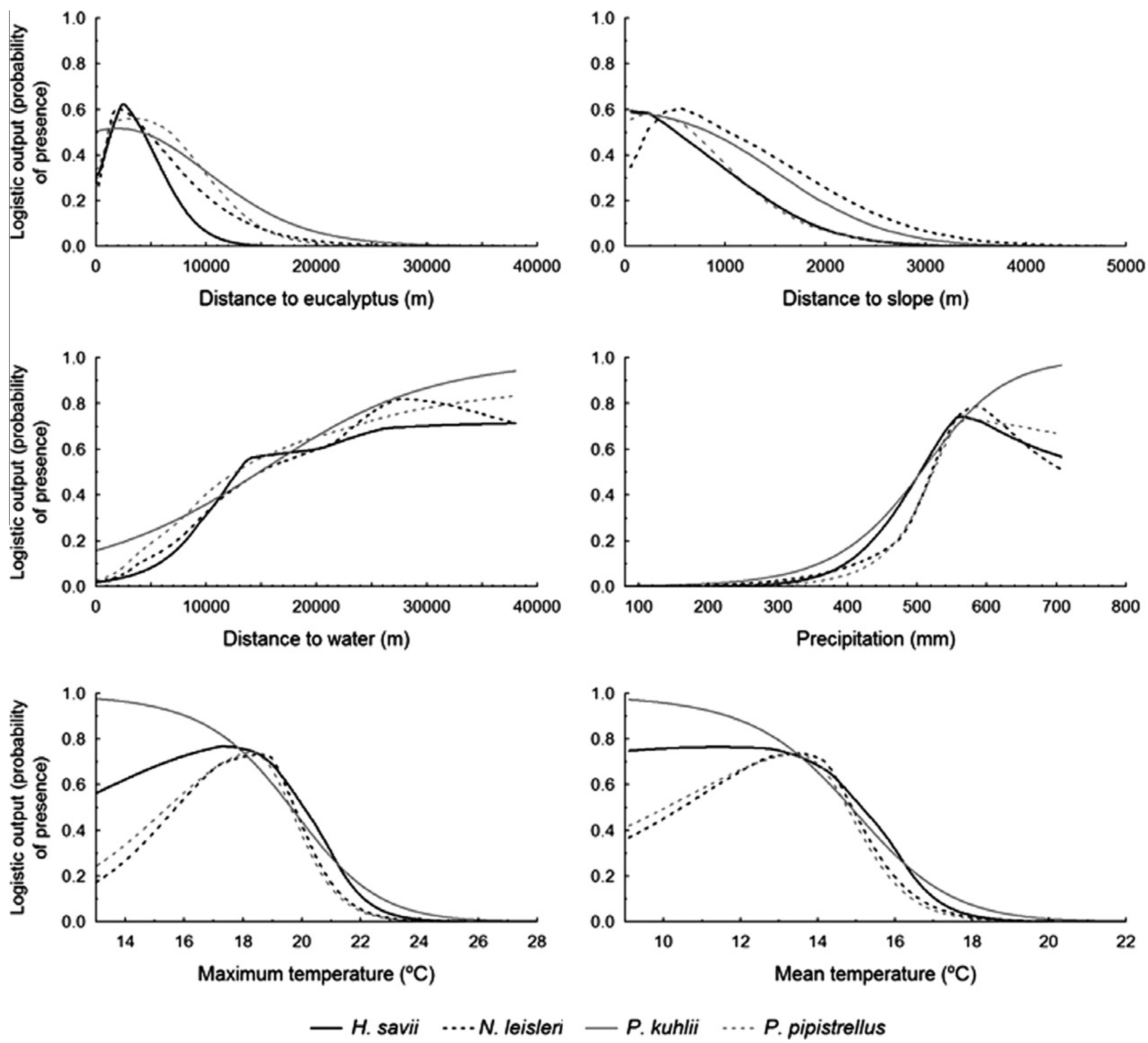

Fig. 5. Response curves of the environmental variables most related to the mortality of *H. savii*, *N. leisleri*, *P. kuhlii* and *P. pipistrellus* at wind farms.

effort for fatality searches differs in most mortality reports and when the time between search intervals is longer, actual fatalities are usually underestimated (Arnett et al., 2008; Jones et al., 2009).

A possible limitation of our approach to calculate mortality risk models arises when the full range of conditions that could promote bat mortality are not incorporated, thus producing conservative models that may fail to predict all potential areas where mortality occurs. That said, there seems to exist (at least in this study area) a narrow set of conditions that seem to promote mortality for all studied species. Consequently, only a small number of records could be sufficient to cover most of the conditions that promote this mortality. By similar reasoning, the modelling of the distributions of specialist species with a narrow niche breadth requires fewer presence data to cover their entire ecological niche (Rebelo and Jones, 2010).

In order to overcome most caveats and to actually estimate if models showed accurate predictions, it will be necessary to undergo model evaluation through ground-truthing. Fatality data published after model calculation can be used to give a preliminary indication of model performance. All new reports received after model calculations seem to corroborate model's predictions for the studied species (Supplementary Material C), although no data for *H. savii* and very few data for *P. pipistrellus* were available. These reports do not constitute a thorough ground-truthing of the models, particularly when considering the unreliability of absence data. Nevertheless, their results give an indication that models have high potential for generating accurate predictions, both in areas within and outside the geographical range of the training dataset, i.e., mortality risk models seem to have good potential for transferability. The fact that the *N. leisleri* mortality risk model had high sensitivity implies that our models are predicting mortality where it actually occurs, although showing low predictive capacity in the areas where mortality does not occur, i.e. low specificity (Supplementary Material C, Table C.1).

4.2. Mortality in the context of species distributions and wind farm construction areas

The distributions of all four bat species overlapped to some extent with predicted mortality risk areas. Most notably, the distributions of *N. leisleri* and *P. pipistrellus* showed high overlap with areas of high mortality risk (16.5% and 18.8% respectively). This is probably because *P. pipistrellus* is a resident species (Hutterer et al., 2005) and is abundant, widespread and a habitat generalist (Russo and Jones, 2003). Also, it is possible that *N. leisleri*, being a migratory species (Hutterer et al., 2005), may migrate through wind

Table 1
Species distribution area and mortality prevalence in respective distribution.

Species	Total distribution area (km^2)	Prevalence in study area (%)	Prevalence in mortality (%)
H. savii	8765.1	10.80	5.44
N. leisleri	30781.7	37.94	16.45
P. kuhlii	26862.2	33.11	1.80
P. pipistrellus	9981.7	12.30	18.78

Table 2
Proportion of overlap between mortality risk areas for 0 species, 1–2 species and 3–4 species and areas with low or high potential for wind farm construction.

		Wind farm potential	
		Low	High
Proportion of overlap (%)	0 species	73.9	26.1
	1–2 species	45.1	54.9
	3–4 species	28.6	71.4
No. of turbines		715	1937

farm sites, especially during August to October, when most mortality occurs (Amorim, 2009; ICNB, 2010; Rydell et al., 2010).

According to the UK's population estimates and the potential for fatalities at wind farms, *N. leisleri* populations are considered to be at high risk of threat there (Jones et al., 2009).

There is a large overlap between the location of the areas with high wind potential (and hence likely sites for wind farms in the future) and areas with high mortality risks for several species. Consequently, the further development of efficient mitigation and compensatory measures are of paramount importance.

5. Conclusions

Considering how little is known about the impact of wind farms on bat populations, the identification of the areas where bat mortality at wind farms is likely a pre-emptive measure of utmost importance for conservation. By identifying potential high-risk sites prior to wind farm construction and by determining which variables promote mortality and their range of values, this study will assist with environmental impact assessment studies at potential wind farm sites, and enables the creation of reference values for ecological conditions and local features that could promote mortality at planned wind farm locations.

Therefore, mitigation and monitoring efforts could focus in these problematic areas, and help in lowering mortality rates considerably.

With this study, we present a novel approach that can be potentially applied to a wider range of taxa and countries, thus enabling the determination of mortality risk areas for fauna in relation to wind farm siting.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biocon.2012.06.017.

References

Adams, R.A., Hayes, M.A., 2008. Water availability and successful lactation by bats as related to climate change in arid regions of western North America. J. Animal Ecol. 77, 1115–1121.
Ahlén, I., Baagøe, H.J., 1999. Use of ultrasound detectors for bat studies in Europe: experiences from field identification, surveys and monitoring. Acta Chiropterol. 1, 137–150.
Anderson, R.P., Lew, D., Peterson, A.T., 2003. Evaluating predictive models of species' distributions: criteria for selecting optimal models. Ecol. Modell. 162, 211–232.
Amorim, F., 2009. Morcegos e Parques Eólicos – Relação entre o uso do espaço e a mortalidade, avaliação de metodologias, e influência de factores ambientais e ecológicos sobre a mortalidade. MSc Thesis, Universidade de Évora.
Arnett, E.B., Brown, W.K., Erickson, W.P., Fiedler, J.K., Hamilton, B.L., Henry, T.H., Jain, A., Johnson, G.D., Kerns, J., Koford, R.R., Nicholson, C.P., O'Connell, T.J., Piorkowski, M.D., Tankersley Jr., R.D., 2008. Patterns of bat fatalities at wind energy facilities in North America. J. Wildlife Manage. 72 (1), 61–78.
Arnett, E.B., Huso, M.M.P., Schirmacher, M.R., Hayes, J.P., 2011. Altering turbine speed reduces bat mortality at wind-energy facilities. Front. Ecol. Environ. 9, 209–214.
Baerwald, E.F., Barclay, R.M.R., 2009. Geographic variation in activity and fatality of migratory bats at wind energy facilities. J. Mammal. 90, 1341–1349.
Baerwald, E.F., Edworthy, J., Holder, M., Barclay, R.M.R., 2009. A large-scale mitigation experiment to reduce bat fatalities at wind energy facilities. J. Wildlife Manage. 73, 1077–1081.
Brito, J.C., Acosta, A.L., Álvares, F., Cuzin, F., 2009. Biogeography and conservation of taxa from remote regions: an application of ecological-niche based models and GIS to North-African canids. Biol. Conserv. 142, 3020–3029.
BWEC, 2008. Bats and wind energy cooperative: 2008 workshop proceedings. Austin, Texas. Report prepared by Energetics, Incorporated, 8–10 January. <http://www.batsandwind.org/index.php?option=com_content&view=article&id=55&Itemid=18%E2%80%9D>.
Cabral, M.J. (coord.), Almeida, J., Almeida, P.R., Dellinger, T., Ferrand de Almeida, N., Oliveira, M.E., Palmeirim, J.M., Queiroz, A.I., Rogado, L., Santos-Reis, M. (Eds.), 2006. Livro Vermelho dos Vertebrados de Portugal. 2ª ed. Instituto da Conservação da Natureza, Assírio & Alvim, Lisboa.
Costa, P., 2004. Atlas do Potencial Eólico para Portugal Continental. MSc Thesis, Universidade de Lisboa.
Elith, J., Ferrier, S., Guisan, A., Graham, C.H., Anderson, R.P., Dudík, M., Hijmans, R.J., Huettmann, F., Leathwick, J.R., Lehmann, A., Li, J., Lohmann, L.G., Loiselle, B.A., Manion, G., Moritz, C., Nakamura, M., Nakazawa, Y., McC Overton, J., Peterson, A.T., Phillips, S.J., Richardson, K., Scachetti-Pereira, R., Schapire, R.E., Soberón, J., Williams, S., Wisz, M.S., Zimmermann, N.E., 2006. Novel methods improve prediction of species' distributions from occurrence data. Ecography 29, 129–151.
Elith, J., Phillips, S.J., Hastie, T., Dudík, M., Chee, Y.E., Yates, C.J., 2010. A statistical explanation of MaxEnt for ecologists. Divers. Distribut. 17, 43–57.
Fielding, A.H., Bell, J.F., 1997. A review of methods for the assessment of prediction errors in conservation presence/absence models. Environ. Conserv. 24, 38–49.
ESRI, 2006. ArcGis 9.2. Environmental Systems Research Institute, Inc., CA, USA.
EUROBATS, 2011. Report of the IWG on wind turbines and bat populations: 16th Meeting of the Advisory Committee, Tbilisi, Georgia.
Guisan, A., Zimmermann, N.E., 2000. Predictive habitat distribution models in ecology. Ecol. Modell. 135, 147–186.
Hernandez, P.A., Graham, C.H., Master, L.L., Albert, D.L., 2006. The effect of sample size and species characteristics on performance of different species distribution modeling methods. Ecography 5, 773–785.
Hutterer, R., Ivanova, T., Meyer-Cords, C., Rodrigues, L., 2005. Bat Migration in Europe – A Review of Banding Data and Literature. Federal Agency for Nature Conservation, Bonn, Germany.
ICNB, 2010. Avaliação do efeito dos parques eólicos sobre os morcegos em Portugal continental (análise dos dados disponíveis em Outubro de 2009). Instituto da Conservação da Natureza e da Biodiversidade, Unpublished report.
Jones, G., Cooper-Bohannon, R., Barlow, K., Parsons, K., 2009. Determining the potential ecological impact of wind turbines on bat populations in Britain: scoping and method development report. Report on Defra constract WC0742. <http://randd.defra.gov.uk/Document.aspx?Document=WC0742_8026_FRP.pdf>.
Kerns, J., Kerlinger, P., 2004. A study of bird and bat collision fatalities at the mountaineer wind energy center, Tucker County, West Virginia. Annual Report for 2003, Curry and Kerlinger, LLC, McLean, Virgina, USA.
Kunz, T.H., Lumsden, L.F., 2003. Ecology of cavity and foliage roosting bats. In: Kunz, T.H., Fenton, M.B. (Eds.), Bat Ecology. University of Chicago Press, Chicago, USA, pp. 3–89.
McLeish, T., 2002. Wind power. Nat. New Engl. 11, 60–65.
MEDIAS-FRANCE, 2006. Postel Global Land Cover 2006. <http://postel.mediasfrance.org> (accessed in 30.08.11).

Pasqualetti, M., Richter, R., Gipe, P., 2004. History of wind energy. In: Cleveland, C.J. (Ed.), Encyclopedia of Energy, vol. 6. Academic Press, San Diego, USA, pp. 419–433.

Pearson, R.G., Raxworthy, C.J., Nakamura, M., Peterson, A.T., 2007. Predicting species distributions from small numbers of occurrence records: a test case using cryptic geckos in Madagascar. J. Biogeogr. 34, 102–117.

Phillips, S.J., Anderson, R.P., Schapire, R., 2006. Maximum entropy modeling of species geographic distributions. Ecol. Modell. 190, 231–259.

Racey, P.A., Speakman, J.R., Swift, S.M., 1987. Reproductive adaptations of heterothermic bats at the northern borders of their distribution. South African J. Sci. 83, 635–638.

Rainho, A., Palmeirim, J.M., 2011. The importance of distance to resources in the spatial modelling of bat foraging habitat. PLoS ONE 6, e19227.

Rangel, T.F., Diniz-filho, J.A., Bini, L.M., 2010. SAM: a comprehensive application for spatial analysis in macroecology. Ecography 33, 46–50.

Rebelo, H., Jones, G., 2010. Ground validation of presence-only modelling with rare species: a case study on barbastelles *Barbastella barbastellus* (Chiroptera: Vespertilionidae). J. Appl. Ecol. 47, 410–420.

Rodrigues, L., Bach, L., Dubourg-Savage, M.J., Goodwin, J., Harbusch, C., 2008. Guidelines for consideration of bats in wind farm projects. EUROBATS Publication Series No. 3 (English version), UNEP/EUROBATS Secretariat, Bonn, Germany.

Russo, D., Jones, G., 2003. Use of foraging habitats by bats in a Mediterranean area determined by acoustic surveys: conservation implications. Ecography 26, 197–209.

Rydell, J., Bach, L., Dubourg-Savage, M.J., Green, M., Rodrigues, L., Hedenström, A., 2010. Bat mortality at wind turbines in northwestern Europe. Acta Chiropterol. 12, 261–274.

Szewczak, J.M., Arnett, E.B., 2008. Field test results of a potential acoustic deterrent to reduce bat mortality from wind turbines. Report for Bats and Wind Energy Cooperative. <http://www.batsandwind.org/index.php?option=com_content&view=article&id=55&Itemid=18>.

Webb, P.I., Speakman, J.R., Racey, P.A., 1995. Evaporative water loss in two sympatric species of vespertilionid bat, *Plecotus auritus* and *Myotis daubentoni*: relation to foraging mode and implications for roost site selection. J. Zool. 235, 269–278.

Wisz, M.S., Hijmans, R.J., Li, J., Peterson, A.T., Graham, C.H., Guisan, A., 2008. The NCEAS predicting species distributions working group. Effects of sample size on the performance of species distribution models. Divers. Distribut. 14, 763–773.