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Mapping the global potential exposure of soaring birds to terrestrial wind energy expansion

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The wind energy sector is steadily growing, and the number of wind turbines is expected to expand across large areas of the globe in the near future. While the development of wind energy can contribute to mitigating climate change, it also poses challenges to wildlife, particularly birds, due to increased collision risk with wind turbines. Here we quantify and map potential conflicts between the potential for wind energy development and the distribution of terrestrial soaring birds. We explore the relationship between species traits (including body mass, migration ecology and extinction risk) and exposure to potential wind energy development, and identified areas of potential conflict between wind power production and soaring bird conservation. We considered the full range of each species, as well as separately analyzing the breeding, non-breeding and passage ranges for migratory species. We show that exposure to potential wind energy development is similar for soaring and non-soaring bird species. Within different parts of the range of soaring bird species, passage distributions have significantly higher potential for wind energy development than the full, breeding or non-breeding ranges. Moreover, exposure to potential wind energy development was higher within the ranges of heavier soaring bird species and those that are migratory. We show that areas of conflict between soaring bird conservation and potential wind energy development could be very large, particularly when the passage ranges of soaring bird species are considered. Such areas of potential conflict are largely unprotected. This highlights a risk for soaring birds from potential wind energy development wherever it is not carefully sited in order to minimise environmental impacts.

1. Introduction

Mitigating climate change and averting global biodiversity loss are the two main environmental challenges the modern world is facing (IPCC 2014, Secretariat of the Convention on Biological Diversity 2014). In the attempt to mitigate climate change, the global energy sector is undergoing a slow but progressive transition, shifting from fossil fuels to renewable energy sources (REN21 2014). Among these, wind energy generation is one of the fastest growing sources of renewable energy globally (AWEA 2014, REN21 2014, EWEA 2015). This trend is projected to continue in the coming decades because wind, as well as other renewable energy sources, can contribute to mitigating global climate change and help countries to achieve targets on greenhouse gas emissions (IPCC 2014).

Like most energy sources, wind energy expansion can result in some associated negative environmental impacts (Wang & Wang 2015), including negative impacts on wildlife (Northrup & Wittemyer 2013, Pearce-Higgins & Green 2014). Wind energy development can cause direct mortality of volant wildlife through collision with wind turbines, which may impact the persistence of populations (Northrup & Wittemyer 2013). It can also impact species by altering their behavior, displacing populations from an area and/or reducing fecundity and breeding success (Northrup & Wittemyer 2013, Sansom *et al. 2*016). Furthermore, in remote and less accessible areas, wind energy development may hasten the loss and fragmentation of previously continuous habitats through road network and electric grid development (Northrup & Wittemyer 2013). Although the extent of the impacts of wind energy development on wildlife varies between taxa and location, soaring birds (mostly raptors) are generally reported to be most affected (de Lucas *et al.* 2008, Korner-Nievergelt *et al.* 2013, Thaxter *et al.* 2017).

Large-bodied soaring birds typically have low flight maneuverability, which increases their risk of colliding with wind turbines (Noguera *et al.* 2010, Pearce-Higgins & Green 2014). Moreover, large raptors, such as vultures of the genus *Gyps*, typically fly with their head pointing downwards in order to scan the ground. This posture creates a blind field in the direction of travel that can further increase the risk of collision with wind turbines (Martin *et al.* 2012). The added mortality from collision with wind turbines may be particularly detrimental for species whose life history makes their populations highly sensitive to such losses. This is the case for most large birds of prey, such as eagles and vultures, which take several years to reach sexual maturity and have low reproductive rates, making them least able to compensate for the additional losses (Carrete *et al.* 2012, Dahl *et al.* 2012, Martinez-Abrain *et al.* 2012, Pearce-Higgins & Green 2014).

Many studies have been conducted on the impacts of wind energy development on wildlife, but most have been restricted to specific taxonomic groups or geographic areas (see some examples in Northrup & Wittemyer 2013). However, the imminent and growing conflict between potential wind energy development (hereafter, we use the term “potential wind energy development” to indicate current or future potential development of wind farms) and wildlife protection may require implementation of best management practices that cover large spatial scales and a wide range of species. For this to take place, there is a need to improve our understanding of how potential wind energy development may affect particular groups of species with specific life history traits and conservation status (González-Suárez *et al.* 2013). There is also a need to characterize and locate areas of conflict between potential wind energy development and bird populations across the entire distributions of migratory species, including their passage and non-breeding ranges. Such basic understanding is largely lacking, thereby hindering the development of broad management practices to minimize the rise of potential conflicts between potential wind energy development and birds.

Here we aim to quantify and map conflicts between potential wind energy development and terrestrial soaring birds. Specifically, we first compare the potential for wind power development within the distributions of all non-soaring bird species (excluding seabirds) with that within the ranges of soaring bird species. We then model the potential for wind power development within the ranges of soaring bird species in relation to a suite of species' life history traits (such as foraging strategy, body mass and migration ecology) and species extinction risk (using IUCN Red List categories, BirdLife International 2015).

This analysis aims at understanding the traits that best correlate with the exposure a species may face from potential wind energy development. For migratory bird species, we also assess in which parts of their ranges (breeding, non-breeding, or passage distributions) exposure is greatest. Finally, we identify areas across the globe where conflicts between potential wind energy development and soaring bird conservation are most likely to arise. The overall aim of this work is to provide information that would help targeting further in-depth studies and conservation efforts towards the regions of high conflict and the soaring bird species at highest exposure from potential wind energy development.

2. Material and methods

2.1. Study environment and study species

This study focuses on the terrestrial areas of the world, where data on potential for wind energy development are available (see below) and where the potential impacts of wind energy on birds are best known. Most of the evidence gathered so far suggests that some of the major impacts of wind farms on wildlife are through collision of, mainly, soaring birds with wind power turbines (Northrup & Wittemyer 2013, Thaxter *et al.* 2017). However, disturbance effects of wind farms on birds have also been reported (Drewitt & Langston 2006). We therefore analyze distributions of soaring bird species in relation to distribution of potential wind energy development across terrestrial areas. Here we considered all raptors (all species in the orders: Accipitriformes, Cathartiformes and Falconiformes), and also other taxa that regularly soar and have been recorded to collide with wind turbines as soaring bird species. These taxa are represented by selected species within the orders Ciconiiformes and Pelecaniformes, all species within the families Aramidae and Gruidae (order Gruiformes) and *Corvus* spp. and *Pyrrhocorax* spp. (family Corvidae). Overall, soaring birds as defined here amounted to 520 species. From these, we excluded from the analyses 15 soaring bird species because their distribution is restricted to small oceanic islands where no wind data were available or because their range is too small (i.e., < 150km^2) compared with the resolution of the wind data. The list of the 505 species used for analyses is provided in Supplementary Table S1.

We also analyzed the distributions of 9069 other bird species of the world (excluding seabirds) for comparison of the exposure from potential wind energy development between soaring and non-soaring bird species.

2.2. Species data

We used range maps of bird species (BirdLife International and NatureServe 2014), taking only the range polygons where the presence of the species was classified as extant or probably extant, and the origin was classified as native or reintroduced. For soaring birds only, in addition to the full range of each species, we also considered three different subdivisions of the range (see e.g., Somveille *et al.* 2013): the breeding range (i.e., the part of the overall range where the species is classified as being resident all year round or present during the breeding season only); the non-breeding range (i.e., where the species is resident or known to occur in the non-breeding season); and the passage range (i.e., the areas the species regularly passes through during migration, hence limited to migratory species only). The latter ranges were only available for a subset of migratory species (68 species out of 194 soaring bird species considered here). We hereafter refer to these four different range classes for soaring birds as: full range, breeding range, non-breeding range, and passage range. The rationale for using the three additional and more specific range class combinations is to gain better insight into parts of the species' ranges that are important for critical life stages (see e.g., Runge *et al.*, 2015).

We then compiled available information about the status and traits of all soaring bird species. IUCN Red List category of extinction risk was taken from BirdLife International 2015), and comprised Critically Endangered, Endangered, Vulnerable, Near Threatened, Least Concern, or Data Deficient. We extracted information about body mass and foraging strategy from a large, recently published and freely available database on Elton traits of the birds of the world (Wilman *et al.* 2014). The main rationale for considering body mass is because larger-bodied animals are more likely to collide with wind turbines than smaller ones (Pearce-Higgins & Green 2014) for pure probabilistic reasons and also because maneuverability of large birds is reduced, which may influence their ability to avoid wind turbines (Drewitt & Langston 2006). Moreover, larger-bodied species are typically K-selected, long-lived species, for which additional mortality from collision with wind turbines may have a much higher impacts on population persistence compared with small-bodied species (Katzner *et al.* 2016).

Foraging strategy represents the percentage of time the species is estimated to forage well above vegetation or human-made structures (Wilman *et al.* 2014). That is, if the species forages exclusively in the air above e.g., forest canopy it will have a foraging strategy value of 100, but if it exclusively forages close to the ground or e.g., below or just above the canopy then it will have a value of zero or close to zero. Considering the foraging strategy of species in relation to potential wind energy development is relevant because species that forage in the air, such as many large raptors, may be more exposed to wind energy infrastructures than species foraging in the lower canopy or close to the ground. We acknowledge that some behaviours, such as display, prey delivery and territorial defence, may take place at different flight heights than the preferred foraging height. However, as these behaviours are less frequent than foraging, we opted for foraging flight height as our explanatory variable. Finally, we calculated the centroid of the distribution range of each species of soaring birds using ArcGIS 10.1 (ESRI 2011).

2.3. Calculation of potential wind energy development within species' distributions

We used a global map of terrestrial unrestricted potential for wind energy production, in which power potential was calculated based on incident wind harnessed by a horizontal axis wind rotor, unrestricted by factors such as available land, cost and power distribution (see Pogson *et al.* 2013 for further details). At the country level, unrestricted potential for wind energy production significantly and positively correlates with the country's installed wind energy capacity (see Supplementary Fig. S1). This correlation, although weak, indicates that potential wind energy development, as used in this study, may represent a valid proxy for future wind energy infrastructure development at a broad spatial scale (i.e., more wind farms are predicted to be installed in areas of high wind energy potential).

We used the zonal statistics function in ArcGIS 10.1 to calculate the sum of wind energy potential within each bird species' range, the area of the species' full range (in km^2), and the area and fraction of the range with at least some wind energy potential (i.e., > 0). We then derived, for each species, a potential wind energy development measure (referred to in the text as "potential wind energy development" for clarity) calibrated according to the fraction of the species' range with wind potential. Firstly, potential wind energy development was calculated by dividing the summed wind energy potential from across the cells (10km × 10km in size) within the species range by the summed area of the cells within the range with some wind potential. We then multiplied this value by the fraction of the overall range with at least some wind potential.

The latter component of the multiplication was used in order to account for the extent of a species' range potentially affected by exposure to wind energy development. For example, a species may be exposed to a very high level of potential wind energy development but only in a small fraction of its range, which renders the overall exposure to potential wind energy development rather low for that species. Conversely, a species may be exposed to a very high level of potential wind energy development across most of its range, making that species at high overall exposure. For migratory soaring bird species, we also calculated potential wind energy development for each of the three additional range classes (i.e., breeding, non-breeding and passage ranges). The derived measure of potential wind energy development calibrated according to the fraction of a species' range with wind energy potential >0 was used as a response variable in the following analyses.

2.4. Statistical analyses

We used univariate analysis of variance to compare the mean values for potential wind energy development between the two main groups considered: non-soaring birds (excluding seabirds) and soaring birds. We then used the same approach to compare mean values for potential wind energy development within the four different ranges (i.e., full range, breeding, non-breeding and passage range) of soaring birds. We ran pair-wise group comparisons using *post-hoc* tests corrected with the Tukey method to adjust for multiple testing.

Next we built four separate general linear mixed models (GLMM) in which the response variable was in turn the potential wind energy development relative to the full range, and relative to the breeding, non-breeding and passage range of soaring bird species. The model assumed a normal distribution and identity link function.

The structure of each of the four GLMMs was the same, and included as predictors the IUCN Red List category of extinction risk for the species (as a categorical variable), body mass (log-transformed), foraging strategy (as continuous variable; see above). In addition, for three out of the four models for soaring bird species (i.e., the ones for full range, breeding range, and non-breeding range), an extra categorical variable denoting whether the species is migratory or not was also included.

Across all models, the response variable was log-transformed to fit a normal distribution, and the taxonomic order was included as a random factor to account for the phylogenetic relatedness of the species (see e.g., Sanderson *et al.* 2015). Where spatial autocorrelation was detected in the residuals of the final models, this was treated by creating and including spatial eigenvectors (using the "spdep" package in R; Bivand & Piras 2015, Bivand *et al.* 2013) in the models with the purpose of accounting for residual spatial autocorrelation (Dormann *et al.* 2007). One soaring bird species (*Erythrotriorchis buergersi*) had an IUCN Red List category of Data Deficient. We treated this species as Vulnerable (following Butchart & Bird 2010). For the model of potential wind energy development within the passage range of bird species, only one species (*Geronticus eremita*) was listed as Critically Endangered. We thus excluded this species from that model as we had a categorical variable depicting the IUCN Red List status of each species, and having only one observation in the category level of Critically Endangered would lead to problems in model convergence. The effective sample size thus consisted of 505 species for the full range, breeding range, and non-breeding range models, and 68 for the passage range model.

We applied model selection based on the Akaike's information criterion (AIC), followed, when necessary (e.g., if there was high model uncertainty), by multi-model inference and averaging (Burnham & Anderson 2002) using the MuMin package in R (Bartoń 2014). We first run all model combinations, starting from the full model and based on the predictors available in each set of models. We then compared all nested models in a set based on AIC. When performed, model averaging was based on the best ranked (i.e., with $\Delta AIC < 4$) models. For the significant categorical predictors (e.g., Red List category) we also ran *post-hoc* comparisons (with p-values adjusted according to the Tukey method) in order to identify which pair-wise comparison was significant.

2.5. Priority areas for soaring bird conservation in relation to potential wind energy development

We used the distributional data from 505 soaring bird species (see above and Supplementary Table S1) to rank the terrestrial areas of the world according to their priority for conservation in relation to addressing the risk of wind energy development to soaring birds, taking into account complementarity of species' occurrence between different areas. In doing so we used the spatial conservation prioritization tool Zonation v.4 (Moilanen *et al.* 2005, Moilanen *et al.* 2014). The tool

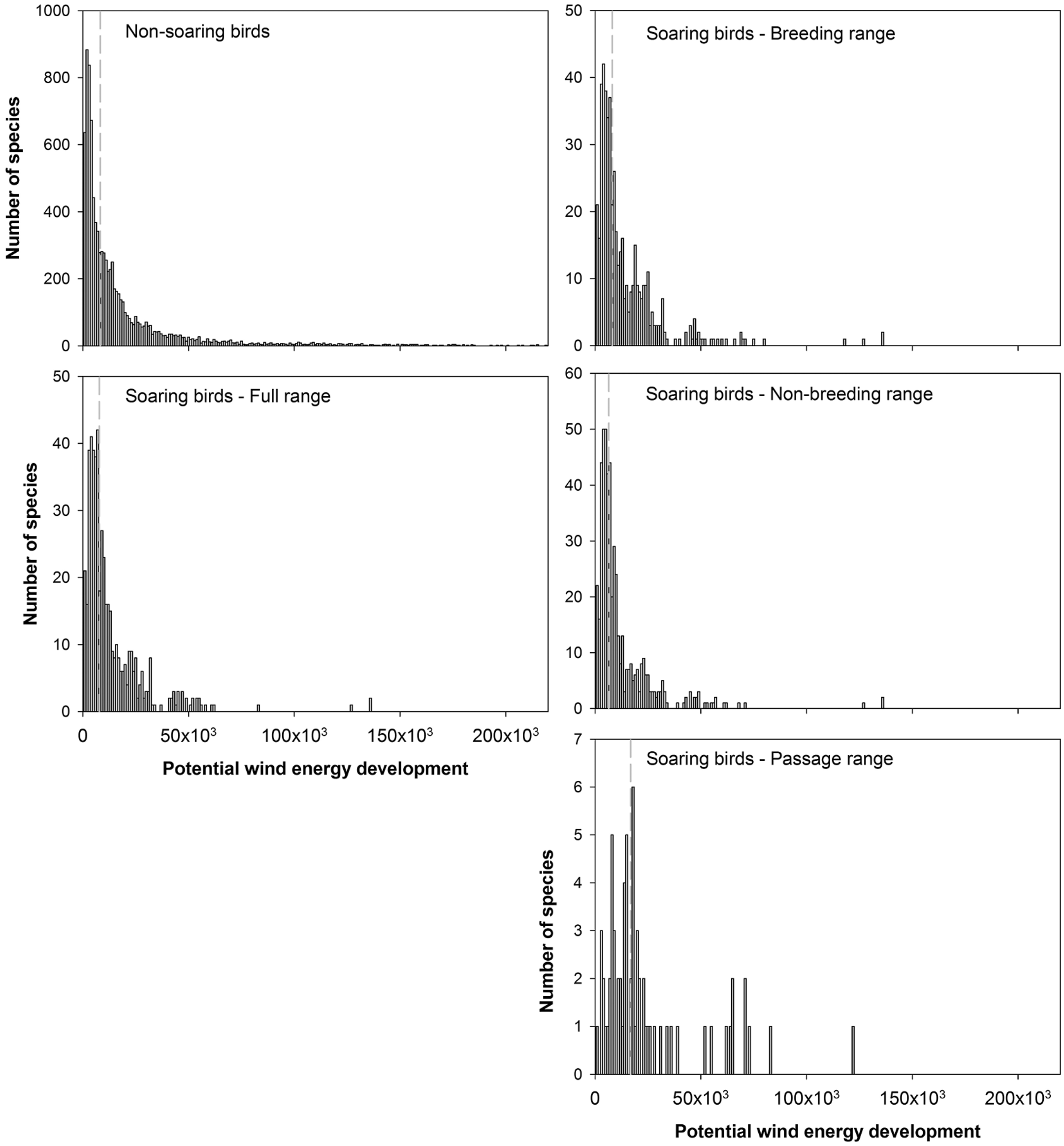

Fig. 1. Number of species in relation to potential wind energy development across the full range of non-soaring bird species (excluding seabirds) and soaring bird species (left panels), and across the breeding, non-breeding and passage ranges of soaring bird species (right panels). Vertical dashed lines indicate median values in each case. Note the different Y axis scales.

iteratively ranks all areas from lowest to highest priority for conservation, guided by principles such as balance between representation of all input features, minimization of aggregate extinction rates, and preference for spatial aggregation (Montesino Pouzols *et al.* 2014). The Zonation algorithm operates by successively removing those cells whose loss results in the smallest reduction in the value of a species in the landscape. The removal order of the cells depends on the cell removal rule (Moilanen *et al.* 2005). We used the additive benefit function removal rule, which favours the selection of areas with high species richness. Because our primary focus is in the identification of priority areas to aid conservation of soaring birds, we assigned a weight to each species ac-

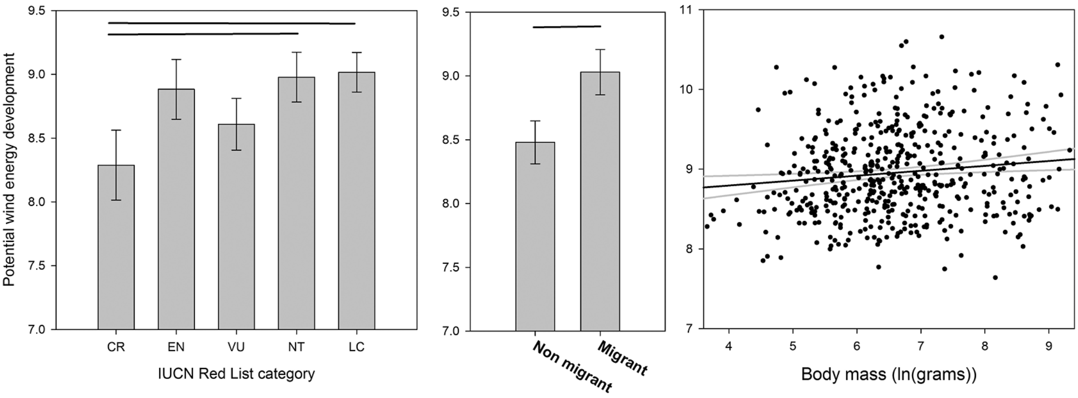

Fig. 2. Potential wind energy development (on log scale) within the full range of soaring bird species with different IUCN Red List categories (left panel; CR Critically Endangered, EN Endangered, VU Vulnerable, NT Near Threatened, LC Least Concern); potential wind energy development for migrant versus non migrant species (central panel), and in relation to body mass (right panel). In the left and central panels, values are least square means (±SE) derived from the best-ranked general linear mixed model (see text for further details on model structure and model selection). Horizontal lines above the bars indicate significantly different pairs of categories resulting from *post-hoc* testing adjusted with the Tukey correction method. The potential wind energy development and body mass values in the right panel are shown on a log scale.

cording to its IUCN Red List category (following Montesino Pouzols *et al.* 2014). That is, higher weights were assigned to the more threatened species (weight of 1 for Least Concern, 2 for Near Threatened, 4 for Vulnerable, 6 for Endangered, 8 for Critically Endangered). We ran four separate sets of analyses, using the full range of the species, the non-breeding, breeding (all based on 505 species' distributions), and the passage ranges (based on 68 species' distributions).

Next we extracted the top 30% ranked priority areas for soaring bird conservation (hereafter: top-ranking soaring bird areas) from the outputs based on the four types of distributions. The choice of using the 30% top priority areas for soaring bird species was made following Santangeli *et al.* (2016b). This choice is somewhat arbitrary, but nevertheless may represent a precautionary scenario for ensuring soaring bird conservation through sparing a large enough land for wide-ranging soaring bird species. This was a conservative threshold as compared with, e.g., Aichi Target 11 of the Strategic Plan on Biodiversity adopted through the Convention on Biological Diversity (CBD 2010, Montesino Pouzols *et al.* 2014).

We then also extracted the top 50% of areas of highest potential wind energy development (hereafter: top-ranked wind areas). Although arbitrary, the choice of using the top 50% areas for potential wind energy development was driven by a precautionary and conservative approach whereby large areas of relatively high potential for wind energy development are considered (we also present maps where a threshold of 30% is considered; see Supplementary Fig. S2). Finally, we calculated the proportion of top-ranking soaring bird areas overlapping the top-ranking wind areas, and how much of these areas falls within and outside of protected areas (using the protected area categories I to VI of IUCN, IUCN and UNEP-WCMC 2017, Montesino Pouzols *et al.* 2014) and Important Bird and Biodiversity Areas (IBAs, BirdLife International 2014).

3. Results

3.1. Potential wind energy development within bird species' ranges

Potential wind energy development within the full distributions of soaring bird species was similar to that within the full distributions of non-soaring species (mean = 8.95 ± 0.02 SE and 8.95 ± 0.06, respectively, $F = 0.00$, p = 0.97, DF = 1; see Fig. 1 left panels for the frequency distribution and median values of each of the two groups). However, the potential wind energy development within the different parts of the range of soaring bird species was significantly different (Anova test: $F = 11.41$, $p < 0.001$, DF = 3; Fig. 1 right-hand panels). Specifically, potential wind energy development was higher ($p < 0.001$ after *post-hoc* comparison) within the passage distributions of soaring bird species (mean ± SE = 9.66 ± 0.13) compared with potential wind energy development within the full range, breeding and non-breeding range (mean ± SE: 8.95 ± 0.05; 9.00 ± 0.05; 8.85 ± 0.05; respectively).

3.2. Correlates of potential wind energy development within the range of soaring bird species

3.2.1. Full range

Among alternative models (based on Red List category, body mass, foraging strategy and migration ecology) compared using AIC, two models appeared to be similarly supported (i.e., $\Delta AIC < 2$; see Supplementary Table S2). We thus proceeded with multi-model averaging, which revealed that three of the four variables had significant effects. Specifically, potential wind energy development differed within the ranges of species under different IUCN Red List categories ($F = 3.0$; $p = 0.019$; statistics derived from the best ranked model; Fig. 2 left panel). Critically Endangered species had significantly lower potential wind energy development within their ranges compared with Near Threatened and Least Concern species. Moreover, potential wind energy development was significantly higher within the range of migratory compared with resident species ($F = 65.8$; $p < 0.001$; Fig. 2 central panel), and was higher within the range of heavier soaring bird species ($F = 9.6$; $p = 0.002$; Fig. 2 right panel).

3.2.2. Breeding range

Analyses based on potential wind energy development within the breeding ranges of soaring bird species suggest some model uncertainty, with two models having similar support (i.e., $\Delta AIC < 2$; see Supplementary Table S3). Multi-model averaging performed on the best-supported models indicates that migration ecology was significant ($F = 74.1$; $p < 0.001$), with migrant species having higher potential wind energy development within their breeding ranges compared with resident species (least square means ± SE: 9.09 ± 0.16 and 8.49 ± 0.15, respectively). Potential wind energy development also increased with body mass ($F = 19.7$; $p < 0.001$), while foraging strategy remained non-significant ($p = 0.318$). Moreover, potential wind energy development again varied, albeit only marginally, according to the Red List category of the species ($F = 2.8$; $p = 0.024$), being marginally higher for Least Concern than for Vulnerable species (least square means ± SE: 9.06 ± 0.14 and 8.64 ± 0.19, respectively).

3.2.3. Non-breeding range

Again model uncertainty was apparent (see Supplementary Table S4) and we therefore proceeded with multi-model averaging. The results were consistent with those for the previous two models, with potential wind energy development within the non-breeding range being higher for migratory species and large-bodied species, and also in relation to species Red List category (migration ecology: $F = 16{,}5$; $p < 0{,}001$; body mass: $F = 21.6$; $p < 0.001$; Red List category: $F = 3.3$; $p = 0.010$). For Red List categories, the only significant result was the finding that Least Concern species had higher potential wind energy development within their non-breeding range compared with Critically Endangered species (least square means ± SE: 8.86 ± 0.14 and 8.15 ± 0.27, respectively).

3.2.4. Passage range

The models based on potential wind energy development for the passage ranges of soaring bird species indicated high model uncertainty (see Supplementary Table S5), thus multi-model averaging was applied. Averaging across the best-supported models suggested that potential wind energy development was similar across species irrespective of their Red List category, foraging strategy or body mass; $p = 0.12$, 0.98, and 0.12, respectively).

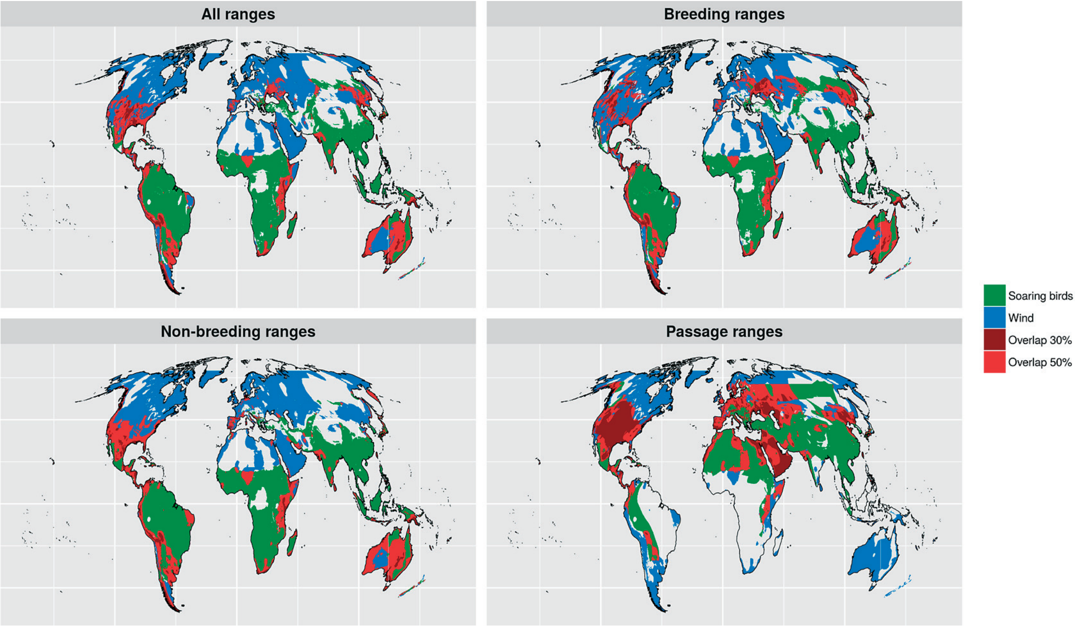

Fig. 3. The distribution of the top-ranked areas for potential wind energy development (top-ranked 50%; in blue), the top-ranked areas for soaring bird species conservation (top-ranked 30%; in green), and the areas where these above two overlap (in red) when the full, breeding, non-breeding and passage ranges of species are considered for deriving priorities for soaring bird conservation. Areas of overlap based on thresholds of 30% top-ranked areas for soaring bird species conservation and for potential wind energy development are highlighted in dark red. See also Supplementary Fig. S2 for the distribution of these latter areas using the 30% threshold separately for soaring birds, wind energy and their overlap.

3.3. Potential areas of conflict between potential wind energy development and soaring bird species

There were large areas of overlap between areas of high potential wind energy development and areas of importance for soaring bird conservation, spanning a wide range of latitudes and regions (Fig. 3). Areas of Central and Southern Eurasia and Southern North America, and large parts of Central and South America, Africa and Oceania appear to have high potential for conflict between potential wind energy development and soaring bird conservation.

This spatial pattern is broadly similar when considering the full range or the breeding range of soaring bird species (Fig. 3), largely because priority areas for these two are very similar (see also Supplementary Fig. S2 and S3). When conflict areas are identified using the non-breeding ranges of soaring bird species, potential conflict areas shift within Eurasia and redistribute towards lower latitudes (Fig. 3). Conversely, when the passage ranges of migratory species (N = 68) are considered, potential conflict areas occur across large parts of central Eurasia and North America, the Arabian peninsula and north and east Africa, including along flyways for soaring birds that migrate from Eurasia to Africa (Fig. 3).

The potential conflict areas identified (i.e., overlapping regions of top-ranked areas for soaring bird conservation and potential wind energy development; Fig. 3) are less likely to be protected and also more likely to contain independently identified important sites for bird conservation than the wider landscape. Only 8–10% of their area is covered by protected areas (compared with 14% of the global terrestrial area covered by protected areas, Fig. 4), while 12–14% of potential conflict areas fall within IBAs (compared with 7% of the global terrestrial area covered by IBAs, Fig. 4).

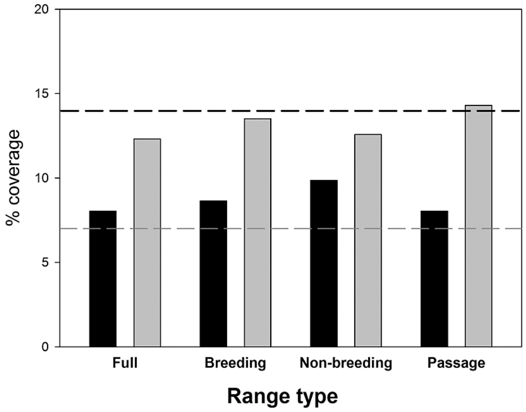

Fig. 4. The percentage coverage of high potential conflict areas (i.e., areas with high potential wind energy development and of high priority for soaring bird conservation; shown in Fig. 3) by terrestrial protected areas (black bars) and by Important Bird and Biodiversity Areas (IBAs; grey bars) separately for the full, breeding, non-breeding and passage ranges of soaring bird species. As a reference, the approximate coverage of terrestrial areas by protected areas (14%) and IBAs (7%) are also shown with horizontal dashed lines (black and grey for protected areas and IBAs, respectively).

4. Discussion

We quantified the relationship between species traits and exposure from potential wind energy development, and identified potential areas for conflict between potential wind energy development and soaring bird conservation globally. To our knowledge, no previous study on this topic has had such a wide scope. We show that exposure to potential wind energy development is similar for soaring and non-soaring bird species, but exposure is highest across the passage ranges of soaring bird species, and for heavier and migratory species. In addition, we identified areas where conflicts between soaring bird conservation and potential wind energy development are most likely to occur. The vast majority of these areas are currently unprotected, and have thus greater potential for wind power plant development.

Overall, the results of this study provide evidence across a broad taxonomic and spatial coverage that soaring birds may be at highest exposure to potential wind energy development within their passage ranges. This is of particular concern given that soaring birds often concentrate in large numbers along narrow flyways and at bottleneck sites on migration (Newton 2007). Developing wind farms within such sensitive areas may thus have severe impacts on the populations, with demographic consequences across the entire range of the species (Katzner *et al.* 2016).

Furthermore, across their full distribution range, including the breeding, non-breeding and passage ranges, migratory soaring bird species and heavier species may be highly exposed to potential wind energy development. Migratory soaring birds are already well known to be strongly impacted by potential wind energy development along their migration flyways (Drewitt & Langston 2006, Pearce-Higgins & Green 2014). The high potential wind energy development within their passage range underscores a potentially high exposure of migratory soaring birds to potential wind energy development. Our findings also suggest that exposure of soaring birds to potential wind energy development may be further exacerbated by the fact that larger-bodied species, which are typically (although not exclusively) more vulnerable to collision with wind turbines (Drewitt & Langston 2006), appear to have higher potential wind energy development on average within their ranges. The lack of a correlation between the foraging strategy of soaring birds and potential wind energy development within their range may be due to the coarse nature of the foraging strategy dataset relative to the diversity of flight styles and foraging behaviors.

The regions of overlap between the top-ranked areas for potential wind energy development and those for soaring bird conservation further underscore the importance of addressing potential impacts of potential wind energy development on soaring birds across their entire distribution. We show that conflicts between potential wind energy development and soaring bird conservation appear to be evenly distributed across latitudes when considering the full ranges of soaring bird species. However, when only the passage range is considered, conflict areas appear to be largely concentrated in low and mid-latitudes in the Northern hemisphere. These regions are predominantly represented by relatively wealthy countries, such as those of Europe, the Arabian Peninsula, and the US, with high technical and financial capacity to expand their national wind energy production (Santangeli *et al.* 2016a). Therefore, in these areas, potential wind energy development may have high negative impacts on soaring bird populations migrating between their breeding and non-breeding ranges if it is not sited and operated carefully at the local scale. This risk is further exacerbated by the finding that most (92%) of the highlighted conflict areas between potential wind energy development and soaring bird conservation across their passage range are currently unprotected. Worse, an above-average proportion of these potential conflict areas (14%) have already been identified as internationally significant for the bird populations they support, and qualify as Important Bird and Biodiversity Areas (BirdLife International 2014). Our results expand current knowledge on the exposure of soaring bird species to potential wind energy development, which has so far been largely studied at specific sensitive areas, such as migration bottlenecks, and for a restricted number of species (see e.g., Carrete *et al.* 2009, Smallwood *et al.* 2009, de Lucas *et al.* 2012, Martínez-Abraín *et al.* 2012).

Potential wind energy development is not yet considered a major threat to many bird species: of 10,060 bird species worldwide (excluding seabirds), only 35 species (of which 29 are raptors or owls) have wind energy development listed as a current or future threat by BirdLife International (2015). BirdLife documents threats based on published and unpublished information and expert opinion. In many parts of the world, such information is sparse for wind energy development, so it is entirely plausible that the number of species currently or potentially threatened by wind energy development is underestimated. Hence, it is important to identify emerging threats and to address them before is too late (Sutherland & Woodroof 2009). To this end, our finding that species in lower categories of extinction risk are associated with higher potential wind energy development suggests that there are opportunities for producing timely science and making evidence-based decisions about wind energy development before impacted species become highly threatened. Ultimately, development informed by robust scientific evidence would facilitate sustainable extraction of wind energy with limited impacts on wildlife. At the international scale, allocation of financial investments could be targeted towards regions where impacts on wildlife are predicted to be minimal, such as the areas highlighted (Fig. 3). At the national level, best management practices, in addition to careful siting of wind energy development, are essential (Northrup & Wittemyer 2013, Allison 2017).

Our study has some limitations that should be born in mind when interpreting the results. Both the potential wind energy development and species distribution maps are rather coarse, as is the scale of the analyses of this study. In addition we do not consider the temporal variation in potential wind energy development, so that correlation with migration times is not considered. Moreover, the species traits used here are limited in fully explaining species' vulnerability to potential wind energy development. For example, the foraging strategy used here may be more relevant in consideration to the breeding and wintering range than the passage range where the collision vulnerability of soaring birds may be better explained by e.g., local weather conditions (Vansteelant *et al.* 2016).

Moreover, some other species-specific behavioral traits not considered here, such as aerial courtship displays that some large raptors perform, e.g., Golden eagle *Aquila chrysaetos*, may also influence bird collision vulnerability on their breeding grounds (Pearce-Higgins & Green 2014). Thus, a wide range of other behavioral and morphological factors, for which no systematic data were available across most taxa, may also affect species' exposure to potential wind energy development. It is also important to note that the potential wind energy development used here is only a proxy for risk of current or future potential development of wind farms (but see Supplementary Fig. S1), a rapidly expanding industry worldwide (REN21 2014). Similarly, it should also be noted that it is the density of wind turbines, rather than the density of wind power, which increases collision risk. In this study we have only considered the impact of land based wind turbines and as migratory paths cross seas this study should be extended in future to potential offshore wind farm developments and also include seabirds.

Wind, as well as other renewable energy sources such as solar, will play a crucial role in contributing energy with low associated greenhouse gas emissions (IPCC 2011). It is, however, important that the development of these renewable energies does not come at the expense of wildlife such as soaring birds. To this end, our findings raise concerns, particularly for the fate of migratory soaring bird species which appear highly exposed to potential wind energy development and are inadequately covered by protected areas (Runge *et al.* 2015). Nevertheless, there is considerable scope for conserving biodiversity while expanding renewable energy development, including wind (Santangeli *et al.* 2016b). Ultimately, a cross-national and interdisciplinary collaboration between academics, conservationists, engineers, governments, corporates and civil society is needed in order to find joint solutions that allow efficient and sustainable energy production from wind while minimizing its associated impacts on wildlife (Kareiva & Marvier 2012, Santangeli & Katzner 2015).

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Tuulivoiman laajentamisen vaikutusten globaali riskikartoitus liiteleville linnuille

Tuulivoiman käyttö ympäri maailman on kasvussa ja tuuliturbiineja asennetaan lisää laajoille alueille. Tuulivoima on eduksi ilmastonmuutoksen torjunnassa, mutta siitä voi olla haittaa erityisesti linnuille, johtuen törmäysriskistä turbiinin roottoriin. Tässä työssä kartoitamme globaalisti alueita, joissa konfliktit tuulivoiman ja terrestristen liitelevien lintujen välillä ovat todennäköisiä. Tutkimme, onko lintulajin ominaisuuksien (ml. ruumiinpaino, migraatioekologia ja punaisen listan hävintäriski) ja sen esiintymisalueella olevan tuulivoiman kehityspotentiaalin välillä yhteyttä.

Tutkimme erikseen tuulivoimapotentiaalin päällekkäisyyttä lajien koko esiintymisalueiden, lisääntymisalueiden, muuttoreittien, ja levähdysalueiden kanssa. Analyysimme mukaan tuulivoima-altistus on keskimäärin samaa luokkaa liiteleville ja ei-liiteleville linnuille. Liitelevien lintujen muuttoreiteillä on kuitenkin merkittävästi korkeampi tuulivoimapotentiaali kuin niiden lisääntymisalueilla tai ei-liitelevillä linnuilla yleensä.

Lisäksi, tuulivoiman kehityspotentiaali on korkea erityisesti suurikokoisille ja muuttaville, liiteleville linnuille. Kun muuttoreitit huomioidaan, saattaa konflikteja tuulivoiman kehittämisen ja liitelevien lintujen välillä esiintyä hyvin laajoilla alueilla. Nämä alueet ovat valtaosin suojelemattomia, mistä seuraa riskejä liiteleville linnuille. Tuulivoiman lintujen kannalta kestävään rakentamiseen tulee siis kiinnittää huomiota.

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Online supplementary material

Additional supporting information may be found in the online version of this article:
Figure S1. Correlation between national wind energy potential and installed wind power capacity.
Figure S2. Areas of overlap between top-ranked areas for potential wind energy development and for soaring bird species conservation using a threshold of 30% to select top-ranked areas for both wind and soaring birds.
Figure S3. Ranked priority areas for soaring bird conservation across the global terrestrial realm.
Table S1. List of 505 soaring bird species used for the analyses.
Table S2–5. Ranking of the models used for multi-model averaging and inference investigating the link between predictors and potential wind energy development within the full range, the breeding, non-breeding and passage range of soaring birds.