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Reconciling endangered species conservation with wind farm development: Cinereous vultures (*Aegypius monachus*) in south-eastern Europe

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ABSTRACT

Harnessing wind energy is seen as an environmentally friendly strategy to combat climate change. However, adverse environmental impacts have come to light for species that are prone to collision with wind turbine blades, such as vultures, leading to a conflict between wind energy industry and conservation. Our study area epitomized such a conflict, containing the only population of cinereous vultures in south-eastern Europe while also being the location for substantial existing and planned wind farms. We used long-term remote telemetry data to produce a species-specific sensitivity map for guiding wind energy development and to estimate vulture collision mortality due to currently operating wind farms. Most operational wind farms were in the population core area and in the highest priority areas for vulture conservation. Collision mortality due to the thirteen operating wind farms was estimated by combining global position system (GPS) telemetry data on vulture space use with a collision risk model (CRM). Estimated mortality varied greatly according to the CRM's 'avoidance rate'. Under the most likely avoidance rates annual predicted collision mortality was 5–11% of the population, creating risk of population decline. Collision mortality was expected almost exclusively in the population core area, rendering further future development plans there severely problematic for vulture population persistence. Our sensitivity map, as a conservation prioritization system, offered a spatially explicit solution to the conflict between wind energy development and vulture conservation. Combining spatial use models derived from telemetry data with collision mortality models offers a novel conservation tool for evaluating large scale wind energy development proposals.

1. Introduction

Harnessing wind energy is a rapidly expanding sector of the renewable energy industry, which is considered to be technologically mature and financially profitable, while receiving increasing public and governmental support (Abbasi et al., 2014). Although harnessing wind energy is often recognized as an environmentally friendly strategy to combat climate change, it is not without adverse environmental impacts, in particular for bats and birds, which are prone to collision with wind turbine blades (Abbasi et al., 2014; Georgiakakis et al., 2012). Raptors and old world vultures are known to be especially vulnerable to collision due to their flight behaviour, to an extent where fatalities may be high and population persistence threatened (Carrete et al., 2012; de Lucas et al., 2012; Gove et al., 2013; Martínez-Abraín et al., 2012; Sanz-Aguilar et al., 2015). As pressure for new wind farm projects increases, a development versus conservation conflict can arise, which can be increasingly aggravated when the effects of development projects accumulate (Bastos et al., 2015).

To resolve such conflicts, a suite of legislative tools are available in the European Union (EU), which support the conservation of vulnerable bird species (EC, 2009), safeguard the sustainable spatial planning of development projects through a Strategic Environmental Assessment (SEA) process (EC, 2001), while improving the implementation of Environmental Impact Assessment (EIA) plans (EC, 2011). Despite the well-developed legislative framework for biodiversity conservation in the EU, EIA studies may be poorly implemented (Kati et al., 2015), while SEA processes have not been accomplished in several EU States when planning for wind power, aggravating the development-conservation conflict (Gove et al., 2013).

Wind farm spatial planning that avoids or minimizes adverse environmental effects requires replete data for several species' distributional patterns across a wide area to map 'sensitivity' (Bright et al., 2008; Dimalexis et al., 2010). Producing detailed species-specific sensitivity maps for raptors and vultures can be challenging because they may be at low density and/or range widely and so spatial modelling of their

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ranging behaviour can be a cost-effective tool at the scale required by SEAs (Madders and Whitfield, 2006; Obermeyer et al., 2011). So far, such models have mainly been built on empirical knowledge of ranging behaviours (Fielding et al., 2006; Tellería, 2009; Eichhorn et al., 2012; Tack and Fedy, 2015) and few studies have used remote telemetry, with its increasing utility through technological advances and its recognized capability to improve sensitivity mapping (Katzner et al., 2012; Reid et al., 2015). On their own, however, spatial models of ranging behaviour provide only a spatial measure of relative collision risk (Eichhorn et al., 2012).

A second approach employs collision risk models (CRMs) to predict collision mortality rates. CRMs combine three-dimensional records of bird flight activity in the vicinity of proposed turbines with the probability of collision for birds passing through the rotor swept volume, incorporating the physics of moving turbine blades with the size and flight speed of the target species (Band et al., 2007; Smales et al., 2013). An open-access and peer reviewed CRM is the “Band CRM” (Band et al., 2007; Chamberlain et al., 2006) which, as in all CRMs, has so far been restricted to specific wind farm projects during the EIA process (e.g. Chamberlain et al., 2006), and not to forecast collision mortality on a wider spatial scale.

Eichhorn et al. (2012) attempted for the first time to combine spatial models of bird flight activity with a CRM, but only simulated red kite *Milvus milvus* flight activity at a local scale. Here, we have advanced this approach, by combining spatial models of flight activity with a CRM over a larger scale (Schaub, 2012), so as to predict collision mortality at a level that can explore population consequences of strategic wind energy plans with greater rigour (Reid et al., 2015).

Our study area holds the sole Balkan breeding population of cinereous vulture (*Aegypius monachus*) and hosts several sites protected for bird interest (Dimalexis et al., 2010; Skartsi et al., 2008). Yet it is also identified as a top priority area for wind farm development by the Greek government, setting a target of establishing 960 MW in the near future (with operating wind farms of 253 MW, and 56 MW approved for construction), on the purported basis of a SEA (MEECC, 2007; RAE, 2015). As such, the area provides an acute example of the potential for conflict between plans for extensive wind farm development and the conservation of a threatened species that is vulnerable to such development.

Our overall objective was to use telemetry data from cinereous vultures to develop tools that can be applied to resolve this specific Balkan conflict, and thereby illustrate how our approach could be widely adopted for sustainable spatial planning of development projects in a suite of conflicts in other similar situations. Our particular aims were: (1) to produce a sensitivity map for the whole population, combining the concepts of core area and relative spatial use, as a broad spatial guide to conservation prioritization and wind farm planning; (2) to estimate collision mortality for currently operating wind farms by combining spatial models of vulture flight activity with a CRM, as a basis for future consideration of the potential impact of planned wind farms.

2. Materials and methods

2.1. Study area and species

The study area was located in the Eastern Rhodopes mountains in the Balkans (Fig. 1), covering parts of Greece and Bulgaria (15,000 km^2). The climate is Continental–Mediterranean and the area is characterized by gentle topography up to 1000 m (mean altitude: 171 ± 117 SD). It comprises hills covered by broad-leaved and pine woods, alternating with pastures and agricultural mosaics (Vasilakis et al., 2008). It is a thinly populated area, and includes five sites of the Natura 2000 network of protected areas and hosts 32 of the 38 European diurnal raptor species (Poirazidis et al., 2011). It supports a cinereous vulture breeding population of 24 breeding pairs on average (in Dadia–Lefkimi–Soufli National Park of Greece, hereafter DLS NP), having a relatively stable population with an average size of 103 individuals (period 2004–2012: comprising 12.7% fledglings, 11.6% juveniles, 20.3% immatures and 55.5% adults) (Skartsi et al., 2008; Skartsi Th., *pers. Comm.*). The cinereous vulture is a tree-nesting, non-territorial but wide-ranging semi-colonial species, behaving as a central-place forager when breeding (Carrete and Donazar, 2005) that is endangered in Greece and globally near-threatened with a decreasing population outside Europe (Legakis and Maragou, 2009; IUCN, 2014).

2.2. Data collection and treatment

We trapped vultures outside the breeding season (in September–January), using a walk-in cage with a sliding-door. Captured vultures were aged as fledglings (1st Calendar Year; CY), juveniles (2nd CY), immatures (3rd–4th CY) or adults (≥5th CY) (De La Puente et al., 2011) (see Appendix A). Transmitters were attached as backpacks (Vasilakis et al., 2008), and backpacks were removed as soon as tags stopped transmitting. Backpacks (transmitters plus harness) weighed less than 3% of each vulture's body mass (mean mass 7944 g, SD = 657, n = 19), as recommended by Kenward (2001) and no lesions or other physical problems were evident on birds whose tags were later removed due to non-transmission. We observed no behavioural, survival or reproductive consequences from tagging vultures. The tagging process was undertaken under specific permission from the Ministry of Environment Energy and Climate Change (Greece) and the Hellenic Ringing Centre.

Tagged vultures produced two datasets. The first dataset consisted of radio-tracking data, derived from twelve vultures tagged with very high frequency radio-transmitters weighing 75 g (Model-TW3, Biotrack-Ltd., Dorset, UK) between 2004 and 2007. Vulture locations were obtained from triangulations with an estimated mean linear location error of 1 km (Schindler et al., 2006), following a standard protocol (Vasilakis et al., 2008). Radio-tracking data involved records during 316 bird-months and were only applied to home range estimation underlying sensitivity mapping.

The second dataset consisted of records from seven birds tagged with battery-powered Global Position System (GPS) units during the years 2007–2008: three GPS-Plus weighing 155 g (Vectronic Aerospace GmbH, Berlin, Germany), and four Telus-Mini weighing 200 g (Televilt/TVP-Positioning, Lindesberg, Sweden). We programmed the GPS-Plus transmitters to record vultures' locations randomly three times per day during daytime, as well as every hour for two random days per month. We programmed the Telus-Mini transmitters to obtain locations every 45 min, during daytime. Only three-dimensional locations were included in the analysis with positional dilution of precision ≤10 (1.1% of locations removed), resulting in a mean linear location error ≤±9.1 m (SE = 0.15) (D'Eon and Delparte, 2005). GPS data came from 74 bird-months of transmissions and provided coordinates and flight height above sea level (a.s.l.). They were used for home range delineation to produce the sensitivity map, and collision mortality estimation.

2.3. Sensitivity map

We produced a sensitivity map for the cinereous vulture population in five steps. First, we estimated the home range for breeding season (courtship in February to fledging in August) and non-breeding season. We included in the analysis only individuals with more than 50 locations per season (Seaman and Powell, 1996). In order to avoid location aggregation around nesting sites for incubating individuals and the subsequent range underestimation, we randomly selected one location per tracking day from the set of locations inside a buffer around nests (Seaman and Powell, 1996), which was defined after the mean linear location error (as defined above for each dataset). We included all locations up to the home range stabilization per individual and season, determined by plotting home range size versus the number of locations

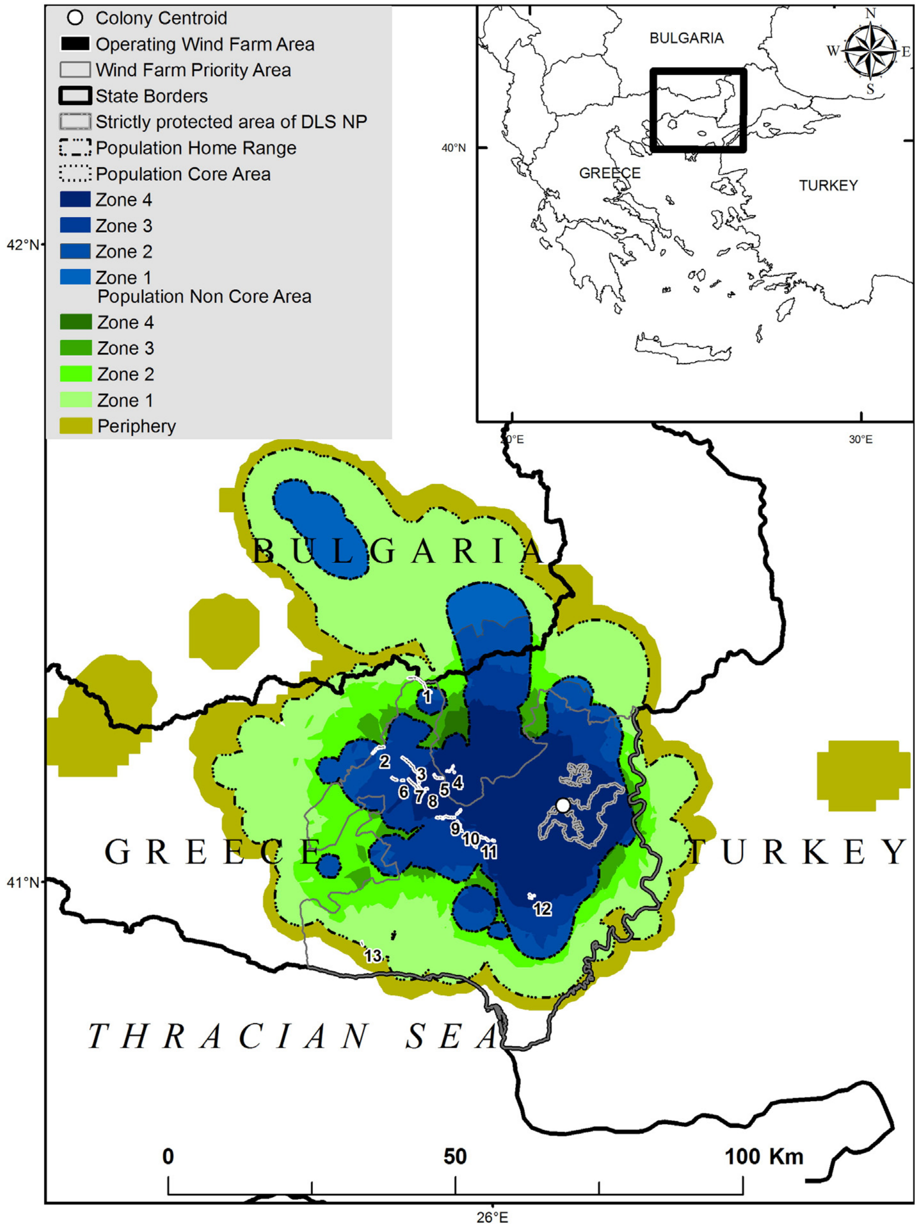

Fig. 1. Study site showing operating wind farm locations and cinereous vulture (*Aegypius monachus*) population sensitivity map. The map illustrates cinereous vulture 'population' range (95% Fixed Kernel), core area, and non-core area. The core and non-core areas are further divided in four conservation zones each in terms of the number of individuals that use each zone: 1: 1–4, 2: 5–9, 3: 10–14, 4: 15–19 individuals. Half of the Wind farm Priority Area (53%) suggested by a Strategic Environmental Assessment study falls within the core area of the cinereous vulture population and also envelopes the Strictly Protected Area of the Dadia Lefkimi Soufli National Park (DLS NP) that contains the vulture colony.

(Kenward, 2001). We employed Fixed Kernel (FK) home range analysis (Kie et al., 2010; Krüger et al., 2014) using a grid cell of 2 × 2 km and a smoothing factor defined by least squares cross validation, in order to determine home range as the 95% use-contour, with internal range configuration in 5% steps (Worton, 1989). The home range analysis was performed using ArcView (Version 3.2; ESRI Inc., 1994) with the extension "Animal Movement" (Alaska Science Center, Anchorage, USA).

Second, we estimated the core areas for each individual by season, by integrating the output of the FK analysis (internal configuration see above) into a core area definition algorithm, which fitted an exponential regression curve to our data (Vander Wal and Rodgers, 2012). The output was a contour value that defines the boundary of the core area, where the animal's time is maximized relative to the periphery. In a third step, for each individual we merged the seasonal home ranges and core areas across years, before merging all 19 individuals' home ranges (and core areas) to estimate the 'population' home range and core area (Appendix A).

Fourth, we used overlay analysis of all 19 home ranges, so as to identify how many individuals used the same sub-region (polygon) within the 'population' range, and assigned a value from one to four to each polygon, reflecting four conservation prioritization zones in terms of population quartiles, as follows: zone 1: 1–4 individuals, zone 2: 5–9, zone 3: 10–14, zone 4: 15–19.

Finally, we produced a sensitivity map following two criteria: (a) whether a specific area (polygon) fell within the population core area, the population non-core area, or outside the home range (outside the 95% contour; periphery), and (b) the quartile category each polygon fell. The final output mapped the population spatial use in terms of time (core, non-core, periphery), and the number of individuals using each polygon (four quartiles) within the core and non-core zones, to produce nine conservation prioritization zones sensitivity map.

To compare the population core area given by our preferred algorithm approach, we repeated the second step, using the fixed 50% contour value for individual's core area delineation, which previously has been commonly used (e.g. Krüger et al., 2014; Monsarrat et al., 2013). Overlay analysis was performed using ArcMap 9.3, while core area delineation with the algorithm approach used R software (R Development Core Team, 2010).

2.4. Wind farm originated mortality

To estimate potential collision mortality of cinereous vultures, we combined the FK method (population utilization distribution estimation) with 'Band CRM' (Band et al., 2007). Only data from the seven GPS-tagged birds were used (Appendix A), at a resolution of 200 m pixel and a buffer zone of 200 m around wind turbines. We extracted the annual mortality for operating wind farms, by summing seasonal mortalities, which were calculated as follows. First, we estimated the average individual utilization distribution per breeding or non-breeding season, by calculating the average percentage of time spent per season at each pixel. Second, we calculated the percentage of time spent by the population per km^2 for each pixel, per season (t_S): we multiplied the average value above with the population size (90 individuals) excluding fledglings due to their restricted mobility (Vasilakis et al., 2008; De La Puente et al., 2011), and we divided with the standard pixel area (0.04 km^2).

Third, we calculated the predicted seasonal mortality by inserting the following metrics in the CRM's parameters for each operating wind farm: (a) the percentage of time spent by the fraction of the population that used each wind farm area per season, calculated as the sum of the products of t_s with the exact area (km^2) of all pixels falling within wind farm area (Appendix B). (b) The total duration of vulture activity (daylight hours), during the breeding season (2850.6 h) and non-breeding-season (1601.4 h) (Time and Date, 2014). (c) The percentage of time flying at collision risk height, according to the rotor swept heights for each wind farm (Appendix B) and the frequency distribution of flight heights. The latter was calculated by subtracting the elevation a.s.l. (extracted from Digital Elevation Model, DEM with 30 m resolution using Spatial Analyst) from the flight height a.s.l. (provided by GPS) (METI and NASA, 2011). We considered all flight heights from the locations over ridges of the study area (ridges buffered with 200 m radius, 3126 GPS locations), identified with DEM and the Hydrology toolbox of ArcMap 9.3. The GPS locations used had a positional dilution of precision <2.8 m (SE = 0.02), indicating a maximum linear location error of ±7.3 m (SE = 0.13) (D'Eon and Delparte, 2005). The maximum flight height error is estimated to be 46 m (sum of maximum GPS location error, average DEM error, and interpolation error) (Katzner et al., 2012; METI and NASA, 2011). However, the usual flight height error in our study is expected to be small, at the level of the DEM error (8.68 m), due to the gentle topography of the study area and the unobstructed sky (D'Eon and Delparte, 2005; Katzner et al., 2012). (d) The cinereous vulture's length (1.11 m), wing span (2.75 m) (WAZA, 2014), and flying speed of 10 m/s for our non-migratory population (Gavashelishvili et al., 2012; Vasilakis et al., 2008). (e) The technical characteristics of the 13 operating wind parks. (f) Given that avoidance rate is the most influential component of the Band CRM's outputs (Chamberlain et al., 2006), we ran the analysis for four avoidance rates (95%, 98%, 99%, and 99.5%) as in other studies (Eichhorn et al., 2012). The range of these values span avoidance rates derived empirically for other raptorial 'soaring' species, such as the golden eagle *Aquila chrysaetos* (99%: Whitfield, 2009) and the white-tailed eagle *Haliaaetus albicilla* (95% to 99%: May et al., 2010, 2011), and also includes the default value of 98% that is suggested when avoidance rates under the Band CRM are unknown (SNH, 2010), as is the case for vultures. The final output was the estimated collision mortality per operating wind farm according to each avoidance rate.

To gain an insight into the likely avoidance rate we employed the results of daily searches for cinereous vulture carcasses (12 months; 2009–2010) in a 50 m buffer around 47% of the operating turbines (88 of the 185 turbines in our study) (Doutau et al., 2011). This survey estimated 0.018 cinereous vulture carcasses/turbine/year, and by simple extrapolation this gives 3.33 vulture deaths/year for all currently operating turbines.

3. Results

Our tracking datasets involved 19 cinereous vultures (18% of the population). It consisted of 367 bird-months, and comprised 21,599 locations. Adults were tracked for 49% of the monitoring time, immatures for 30%, juveniles for 19%, and fledglings for 2% (for details see Appendix A). Male: female ratio in our sample of tagged birds was 1:1.2, similar to the 1:1 ratio of our population (Poulakakis et al., 2008).

3.1. Sensitivity map

The average inter-annual individual home range was 1763 km^2 (SD = 839, n = 19) (Appendix A). Vulture home ranges (95% FK) clearly had areas of intense use, defined as core areas. The contour values describing individuals' core areas, according to the core area definition algorithm (slope equals to one), had a mean value of 70% (SD = 2.2, n = 19), indicating the percentage time spent in the core area. The mean individual core area (defined by algorithm) was estimated as 481 km^2 (SD = 259, n = 19) while as calculated by the 50% fixed contour value method it was 234 km^2 (SD = 120, n = 19; i.e. 51% smaller than the algorithm method). The population range was estimated to be 4970 km^2, of which 39% (1942 km^2) was the population core area and the remaining 3028 km^2 was the non-core area (Fig. 1). Unsurprisingly, therefore, the population core area as calculated by the 50% fixed contour value method (1175 km^2) was only 61% of the population core area as derived by the algorithm method, and only 24% of the population range.

The sensitivity map included nine conservation prioritization zones, ranging in size from 26 km^2 to 2234 km^2 (Fig. 1, Table 1). The large majority (84%) of the 185 operating turbines were within highest conservation prioritization zones of the sensitivity map (Fig. 1, Table 1).

3.2. Collision mortality

The 13 operating wind farms accounted for an overall nominal power output of 253.2 MW (Appendix B). Cinereous vultures spent on average 34.4% of their time at rotor risk heights when flying over ridges and 10.9% of overall flying time within the 200 m buffer zone around wind farms. We predicted overall annual collision mortality of 5.6 deaths, under 99% avoidance rate (Appendix B), while it varied from 2.8 up to 28.0 under 99.5% to 95% avoidance rates respectively (Fig. 2, Appendix C).

Table 1
Operating wind farms per conservation zone in the core area, non-core area and periphery, and their respective estimated impact on cinereous vulture population in terms of annual estimated number of collisions (CRMs with 99% avoidance rate).

	Zones		Wind farms		Mortality	
	Code	A (km^2)	Po (MW)	Tu	C	C (%)
Core area	1	255	–	–	–	–
	2	353	13	12	0.13	2.27
	3	540	72	57	1.62	28.89
	4	794	134	87	3.76	67.27
	Total	1942	219	156	5.50	98.42
Non-core area	1	2235	21	19	0.05	0.93
	2	593	13	10	0.04	0.65
	3	174	–	–	–	–
	4	26	–	–	–	–
	Total	3028	34	29	0.09	1.58
Periphery		1580	–	–	–	–
Total		6550	253	185	5.59	100

Zones: 1: 1–4, 2: 5–9, 3: 10–14, 4: 15–19 individuals, A: zone area, Po: Power, Tu: Number of turbines, C: Annual collisions in zone, C (%): Percentage of annual collisions in zone.

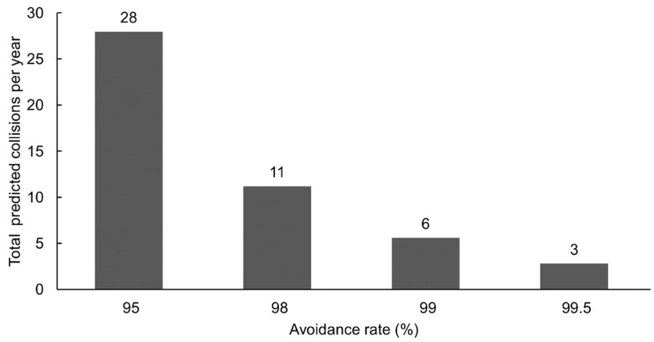

Fig. 2. Predicted annual collision mortalities summed for the 13 operating wind farms under different avoidance rates.

Taken at face value, the carcass survey results (3.33 deaths/year: Doutau et al., 2011) indicated an avoidance rate between 99% and 99.5% (Fig. 2, Appendix D). The collision mortality predicted in the population core area accounted for almost all collision mortality (98%), regardless of the avoidance rates considered (Fig. 1, Table 1, Appendix D).

4. Discussion

4.1. Spatial conservation prioritization

We found that cinereous vultures used a large foraging area far away from their breeding colony that is located within the DLS NP, with the population range including former nesting grounds in Bulgaria (Hristov et al., 2012; Skartsi et al., 2008).

Our results clearly showed that the population core area enveloped most operational wind turbines. The population core area was much larger than expected if a standard 50% use threshold was used, and accounted for a large part of the population range (39%). The core area is recognized as the most vital area for population survival (Vander Wal and Rodgers, 2012), and consequently its biologically meaningful delineation is of great importance for robust conservation decision-making and spatial planning. Our delineation method is most typically used in mammalian studies (Vander Wal and Rodgers, 2012) and we have shown that the standard avian choice of 50% contour (e.g. Krüger et al., 2014; Monsarrat et al., 2013) can lead to important size underestimations of both individual and population core areas. We suggest therefore that the more biologically meaningful algorithm approach should be used in future studies of wide-ranging birds (e.g. raptors), in order not to omit important priority areas, or reach erroneous inferences on species' conservation ecology.

4.2. Avoidance rate for cinereous vulture

Avoidance rate is a correction factor that incorporates several sources of uncertainty in biological variables associated with collision risk (Cook et al., 2014), and is heavily influential on CRM outputs (Chamberlain et al., 2006). As the avoidance rate for cinereous vulture was unknown, we cross-validated our predicted mortalities with those of a carcass survey (Doutau et al., 2011), which suggested an avoidance rate between 99% and 99.5%. However the pilot character of the carcass survey (partial data, the specific fraction of study area surveyed) in combination with the inherent underestimation errors of such surveys (Bernardino et al., 2014) could indicate an avoidance rate less than 99%. This is further supported given behavioural and morphological similarities of our species with white-tailed eagle, for which an avoidance rate of 98% has been estimated (May et al., 2011). We suggest 98% as an appropriate value to be used in future EIAs for cinereous vulture, therefore, in light of the precautionary principle.

4.3. Collision mortality effect on the population

Our study attempted for the first time to predict turbine collision mortality for a cinereous vulture population. Considering an optimistic scenario of 99% avoidance rate, our results estimated that currently operating turbines (253 MW) would cause an annual loss of 5.4% of the population (5.6 deaths per year), whereas a more precautionary avoidance rate of 98% would double the annual loss (10.8%). Such mortality is not inconsequential given the population's abundance, typical survival rates for such large birds and their sensitivity to small changes in mortality (Whitfield et al., 2004). Wind farm originated mortality, acting perhaps in synergy with other threat factors such as unintentional poisoning (Sanz-Aguilar et al., 2015; Skartsi et al., 2008), may be preventing a population increase, as the population has been stable since 2004. Furthermore, some very influential wind farms in vicinity with the colony were only recently established (Appendix B) and their negative impact on the population might be time lagged (Hunt, 1998). Finally, further wind farm construction might impede future expansion of the existing colony (Martínez et al., 2010). The future of the population is more certainly imperilled, however, should plans for four times the currently installed turbines (MEECC, 2007) take place without proper spatial planning for environmental impacts.

4.4. Win–win spatial planning and conservation

The persistence of the cinereous vulture population is fundamentally vulnerable to wind farm development, as it is the only breeding population in south-eastern Europe, it is geographically isolated (Vasilakis et al., 2008), and probably genetically distinctive from others (Poulakakis et al., 2008). Our study area is a conflict terrain between wind farm development and cinereous vulture conservation. On the one hand, the study area is of top priority for harnessing wind energy at a national scale, with a governmental target of establishing almost four times more wind power than currently (960 MW) (MEECC, 2007). On the other hand, the same area has been recommended as a wind farm exclusion zone, due to its well-documented ornithological value (Dimalexis et al., 2010); not least the several Natura 2000 sites designated for this purpose. Our sensitivity map provides a spatial guideline for evaluating operational wind farms and establishing future wind farms on the basis of cinereous vulture space use. Collision mortality estimation allows the impact of operating and future wind farms on the population to be evaluated more precisely.

Our findings pinpointed the inadequate site selection for operating wind farm planning consents, and evinced once more the poor control over EIA studies' quality (Kati et al., 2015), as several wind farms were located in the most vital area for cinereous vultures. Virtually all (98.6%) collisions of cinereous vultures from operating turbines are expected to occur there, regardless of the avoidance rate considered. We also provided strong evidence for the weaknesses of SEA to reach balanced decisions for wind farm site selection which appropriately incorporate the ecological-impact dimension at a national scale (Gove et al., 2013). Our study found that the greatest percentage (53%) of the wind farm priority area suggested by SEA for future wind farms falls within the core area of the cinereous vulture (MEECC, 2007). Our results emphasize that enacting such plans would probably have a severely detrimental effect on the chances of the cinereous vulture population's persistence.

We argue that the national target for renewable energy development in the region could still be readily met, as the areas for such development are considerable, provided the following conditions would be met: (a) exclusion of the population core area as ground for future wind farms, (b) spatial prioritization of future wind farms from the periphery to the outer component of the population non-core area (Fig. 1), (c) high-quality EIA studies that properly assess the collision mortality of the proposal at a pre-construction phase, on the basis of the current methodology, (d) adequate implementation of EIA studies, including a long-term systematic post-construction monitoring scheme, (e) adoption of a suite of mitigation measures to combat cinereous vulture collision mortality from the currently operating wind farms in the core area (e.g. night operation or translocation of turbines, selective shutting down programme, carcass removal from wind farms), (f) implementation of a suite of compensatory measures for cinereous vultures proportional to the collision mortality predicted for each wind farm (e.g. elimination of poisoning, power line insulation, vulture feeding enhancement, subsidizing extensive livestock grazing) (Skartsi et al., 2008).

The suggested win–win spatial planning seems to be beneficial for other species as well. The cinereous vulture population core area includes all the griffon vulture *Gyps fulvus* colonies of the study area, more than half of the remaining breeding pairs of the globally endangered Egyptian vulture *Neophron percnopterus* in Greece (WWF Greece, 2013), and most golden eagle nests (69% of the 23 nest sites in the study area; Sidiropoulos L. *pers. Comm.*). However, a multi-species approach is urgently needed, incorporating our methodology when applicable, so as to define a multi-species sensitivity map and to implement a suite of adequate conservation measures for other species prone to collision such as other birds of prey, migrants, and bats (Georgiakakis et al., 2012; WWF Greece, 2013).

4.5. Potential data limitations

We attempted to produce a sensitivity map for cinereous vulture, using a heterogeneous dataset of different sources (radio and GPS telemetry). The sex ratio of our sample was similar to the wider population (Poulakakis et al., 2008), and home range size is known not to be sex-dependent for this species (Carrete and Donazar, 2005). Our sample was reasonably representative of the population studied in terms of age structure, though age is known so far not to have a significant effect on home range size for cinereous vulture, with the exception of fledglings that are attached to the natal area (De La Puente et al., 2011; Vasilakis et al., 2008). Fledglings were therefore not included within collision mortality estimations and had only a minor contribution to sensitivity map delineation. Of our two datasets (VHF-radio and GPS), GPS data involved the fewest birds (seven), accounting for 7% of our cinereous vulture population, which has been considered as a representative sample for other vulture populations (Carrete and Donazar, 2005; Krüger et al., 2014; Monsarrat et al., 2013).

To overcome the different precision of the two datasets used in sensitivity mapping via home range estimation, we respected three conditions: sampled locations for home range estimation were standardized, the same pixel size was used when FK was applied (informed by the more imprecise radio telemetry data), and the smoothing parameter was estimated with the same technique (Pellerin et al., 2008). For this analysis, our radio-telemetry mean linear location error (1 km) is considered to be acceptable for vulture home range delineation (Carrete and Donazar, 2005; Vasilakis et al., 2008). On the other hand, for mortality estimation, only high-precision data on spatial use (GPS telemetry) populated the CRM. We suggest therefore that it is possible to combine low and high precision datasets stemming from different data collection methods for species sensitivity mapping, respecting a set of rules. Collision mortality estimation should however be fed only by high precision data.

4.6. Methodological applications

We introduced a refined approach for sensitivity mapping that led to a spatially explicit zoning system across a wide area for an entire population. We combined the notion of a population core area that indicates vital areas for a population's persistence (Vander Wal and Rodgers, 2012) with the internal spatial configuration of population range use, as bird activity might affect collision mortality at a landscape scale (Carrete et al., 2012). This methodological approach to sensitivity mapping could serve as a basis for spatial conservation prioritization for other species and for a wide range of development projects worldwide.

We attempted for the first time to predict collision mortality from wind farms at a broad scale, by marrying spatial modelling generated from telemetry data and a CRM. Many authors have recognized the value of such an integrated approach, since the effects that might arise when multiple projects are evaluated individually and over a restricted time period might be underestimated (Carrete et al., 2012; Ferrer et al., 2012; Garvin et al., 2011; Schaub, 2012). Our methodological approach confirms the advantage of applying telemetry data for wide-ranging species when site-specific observation data on flight time at collision risk heights are lacking. Such benefits potentially have extensive application for other studies elsewhere.

5. Conclusions

Predicted losses to the Balkan cinereous vulture population were sufficient to cause concern over wind farm impact. At only 24 breeding pairs and facing several other anthropogenic threats, the population is vulnerable without additional pressure through turbine collision mortality. Future wind energy development plans, if enacted without accounting for environmental impacts, would probably endanger the population's existence per se. Our study allows such impacts for cinereous vultures to be accounted for, and to produce a win–win scenario for wind energy development and vulture conservation. Furthermore, our novel approach, combining CRM with species space use at a broad scale and refining the core area delineation process, extended previous use of telemetry data to evaluate wind farm effects (Katzner et al., 2012; Reid et al., 2015). The approach is potentially a powerful and cost-effective tool in both SEAs and EIAs and allows assessment at a scale which is impractical and unlikely to be available for observational studies. An advancement of our methodology is urgently needed towards a more integrated multi-species approach, as it can provide win–win spatial planning solutions for large scale wind farm developments worldwide.

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