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Proximity to wind-power plants reduces the breeding success of the white-tailed eagle

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Abstract

As a clean and renewable energy source, wind power is expected to play a major role in climate change mitigation. Despite its benefits, the construction of large-scale wind farms in many parts of the world is a cause of concern for wildlife, including the often vulnerable raptor populations. Here, we examined the influence of distance to wind-power plants on the white-tailed eagle *Haliaeetus albicilla* in terms of (1) breeding success; (2) post-fledging survival; and (3) territory occupancy and turbine avoidance (via nest site changes). Our results show that the probability of a pair breeding successfully is lower when the territory is located closer to turbines, potentially because of collision mortality (to which adults are particularly vulnerable). A capture-mark-recapture analysis showed no evidence for the effect of distance on post-fledging survival, suggesting that collision risk may not have been greater for juveniles that fledged closer to a power plant. The levels of disturbance experienced by birds in the study areas were not great enough to prevent breeding at closer distances to the turbines. Our findings on breeding success underline the importance of building appropriately sited wind farms as a way to reduce or avoid undesirable effects on avian populations.

Introduction

In the face of global warming scenarios and an ever-increasing demand for energy services (IPCC, 2011), the use of wind power is being increasingly promoted worldwide (Wiser *et al*., 2011). It has been estimated that around 8% of global electricity will be generated by wind turbines by 2020 (World Wind Energy Association, 2014).

Despite its benefits, the rapid development of large-scale wind farms raises concerns for wildlife (Drewitt & Langston, 2006). Turbines are placed where wind conditions are suitable for electricity generation (EEA, 2009). Unfortunately, the areas selected for this purpose may also be preferred by birds, a scenario that may lead to a conservation conflict. Recently, a number of avian interactions with turbines and associated infrastructure (e.g. collision mortality and displacement) have been identified in various places (Johnson *et al*., 2002; Krijgsveld *et al*., 2009; Masden *et al*., 2009; Pearce-Higgins *et al*., 2009; Stevens *et al*., 2013). In some cases, significant negative impacts, caused largely by collision mortality, have been demonstrated at the local population level (Barrios & Rodríguez, 2004; Everaert & Stienen, 2007; Smallwood & Thelander, 2008; Dahl *et al*., 2012).

Large, soaring raptors appear to be among the most vulnerable bird groups to collision (Gove *et al*., 2013). Because these species have long generation times and low annual reproductive output (Newton, 1998), turbine-related incidents may bring mortality to levels of concern. Notable examples include the golden eagle *Aquila chrysaetos* in the Altamont Pass Wind Resource Area in the USA (Hunt, 2002; Smallwood, Rugge & Morrison, 2009) and the griffon vulture *Gyps fulvus* in southern Spain (Barrios & Rodríguez, 2004; de Lucas *et al*., 2012).

In this paper, we examine how wind-power plants may impact the breeding of the white-tailed eagle *Haliaeetus albicilla* in Finland. This species, as part of a larger group of diurnal raptors which have been affected in Europe (Pearce-Higgins *et al*., 2009; Martínez-Abraín *et al*., 2012; Bellebaum *et al*., 2013) and the USA (Erickson *et al*., 2001), is vulnerable to wind-power generation. This is illustrated by the well-documented case of the white-tailed eagles on the island of Smøla in Norway (Bevanger *et al*., 2010). Dahl *et al*. (2012) showed that breeding success on the island was reduced after the construction of a wind farm because of collision mortality and displacement. Collisions have also been reported in Germany (Krone & Scharnweber, 2003), where this type of incident is a major threat to a local population (Krüger, Grünkorn & Struwe-Juhl, 2010), and in Poland (Zieliński, Bela & Marchlewski, 2011).

Research on the white-tailed eagle has tended to focus on small areas containing a relatively high number of turbines.

Moreover, the case of Smøla (however significant) represents an atypical scenario, because it involves an exceptionally high number of individuals (including *c.* 45 breeding pairs) and turbines that were installed where bird density was highest (Follestad *et al.*, 2007). It may therefore be that the degree of impact documented for Smøla is a spatially restricted phenomenon, with the response at a larger scale being less pronounced than in this high-density population. Here, we intentionally focus on multiple power plants in Finland, which also contain a lower number of breeding pairs in their surroundings.

The white-tailed eagle is listed as vulnerable in the *Red List of Finnish Species* (Mikkola-Roos *et al.*, 2010). The expected pace of wind-energy deployment in the country, with over 270 projects (with 1–127 turbines) proposed for 2015–2018 (Finnish Wind Association, 2014), raises important questions for its future conservation. About 1000 turbines (possibly more, as *c.* 4000 are planned) will operate by 2020, mostly on the coast (Finnish Wind Association, 2014). Around 80–90% of the Finnish breeding population of white-tailed eagles are found precisely on coastal areas (Herrmann *et al.*, 2009). For this reason, research, coupled with proactive management, is urgently needed to minimize the growing conflicts for avian conservation.

Here, we examine whether the distance to wind-power plants affects the white-tailed eagle in terms of (1) breeding success; (2) post-fledging survival; and (3) territory occupancy and turbine avoidance (via changes in nest site). Given the potential threats posed by these man-made structures, including collision mortality (to adults and juveniles) and displacement, we hypothesize that close distances impact negatively on the above-mentioned points.

Materials and methods

The white-tailed eagle

The white-tailed eagle is a diurnal, long-lived raptor whose population growth is highly elastic to changes in survival (Krüger *et al.*, 2010). The species appears to be vulnerable to wind-power generation, particularly to collision mortality during the breeding season (Bevanger *et al.*, 2010).

After severe declines in the 1960s and 1970s (mainly caused by environmental pollution; Stjernberg *et al.*, 2005), the Finnish breeding population has successfully recovered. Nowadays, it includes *c.* 450 known pairs (WWF Finland, 2014). Evaluated as least concerned on a global scale (BirdLife International, 2013), the white-tailed eagle is still vulnerable in Finland (Mikkola-Roos *et al.*, 2010) and enjoys protection in the European Union (Directive 2009/147/EC).

The study areas

The study areas consisted of wind-power plants that contained at least one white-tailed eagle nest in their vicinity. This vicinity was defined as an area of a 9-km radius from the turbine (where sites had only one turbine) or a position that corresponded to the average of the coordinates of each turbine (where there were multiple turbines). The 9-km radius was assumed to be large enough to contain a normal home range of a breeding pair, up to the point where it is unlikely that pairs holding a territory further away become affected by a power plant.

A total of 27 installations (distributed over an area *c.* 600 km north-south and *c.* 300 km east-west) were included in the study (Fig. 1). They had one ($n = 12$), two ($n = 6$), three ($n = 3$), four ($n = 2$), five ($n = 1$) or six turbines ($n = 3$). Eighteen power plants were built on islands, notably in the archipelago of Åland ($n = 10$). At all sites, topography is either low or flat, with turbines at points no higher than 61 m above sea level. In some places, they were arranged in a linear string on land or atop breakwaters for maritime activity, and their specifications varied among sites: 28–118 m in rotor diameter, 45–184 m in total height (hub height plus rotor radius), and 200–3600 kilowatts (kW) in generator nominal capacity (Finnish Wind Association, 2014; Wind Power, 2014).

Data collection and selection

Data on our study species have been collected by the WWF White-tailed Eagle Working Group since 1973. But here, we specifically used observations from 1992–2013 because it was only in 1992 that the first turbine was installed within 9 km from a nest.

Observations were recorded at two levels: nest and territory. Here, territory was defined as the area of a mated pair that encompasses all nests used for breeding over the years. Accordingly, the number of nests in a territory depended on whether a pair attempted to breed in alternative sites. In most cases, territory boundaries could be easily determined as the alternative nests were located on a contiguous piece of land. Sometimes, however, they were built on different islands. In this case, the distance between them, their occupancy history and observations of territorial birds were used by experienced fieldworkers to determine their territory. Because pair bonds of this long-lived species are monogamous, a territory was assumed to be have been used repeatedly by the same pair (Cramp *et al.*, 1980).

Only occupied territories (i.e. where breeding attempt occurred at least once) were considered ($n = 104$). Within a territory, a breeding attempt was considered to occur only if at least one nest was decorated, nearly built or ready for egg laying. An attempt resulting in live nestlings was recorded as successful (even without evidence of fledging); attempts with a different outcome were recorded as unsuccessful.

Nestlings were ringed by licensed volunteers, and post-fledging records were collected by resighting the coded rings. These records were mostly obtained by the use of photo cameras and spotting telescopes at winter feeding stations, primarily established to feed white-tailed eagles (Saurola, Valkama & Velmala, 2013).

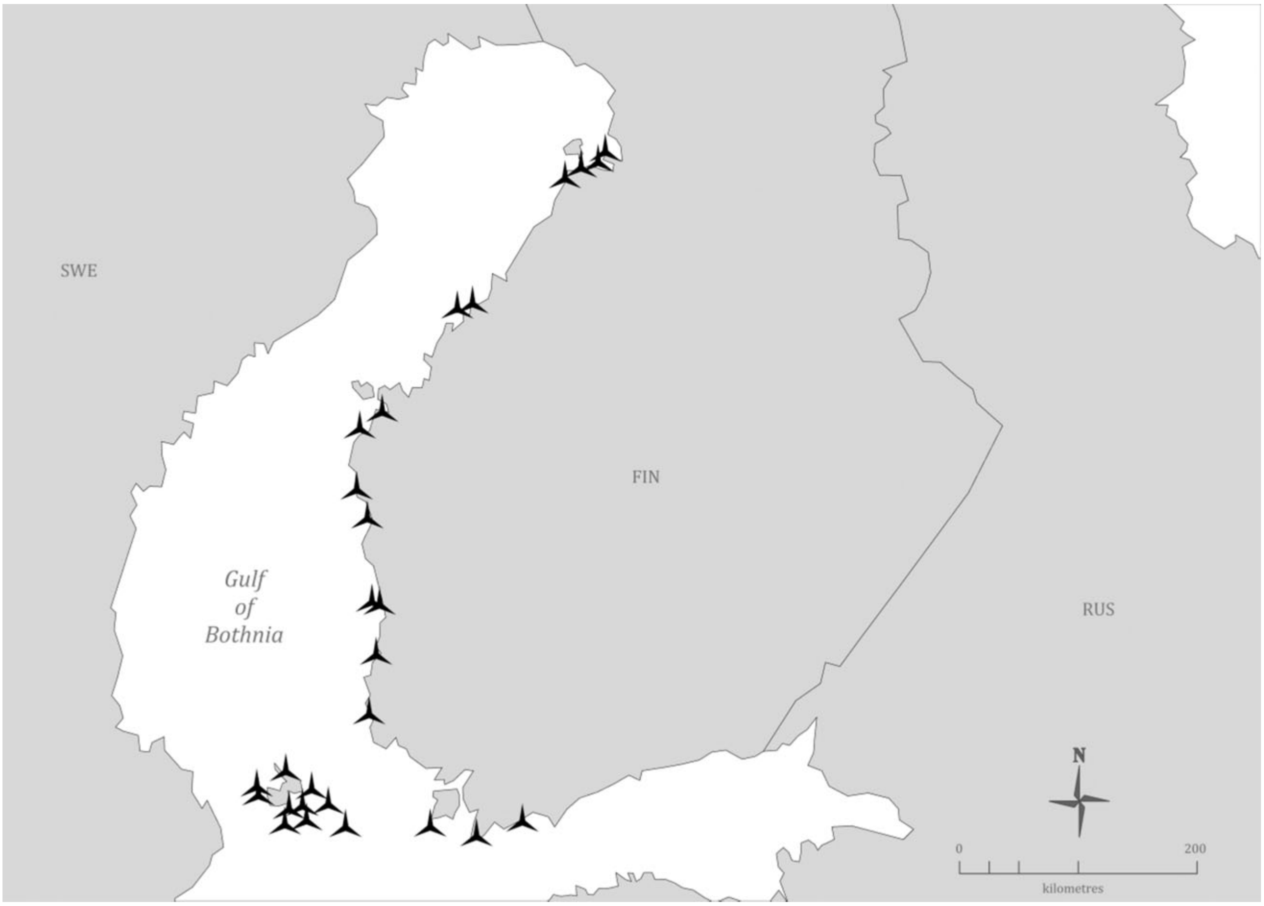

Figure 1 The symbols indicate the locations of all wind-power plants included in the study (n = 27). Most of them (n = 26) were located very close (< 2.5 km) to the sea.

Estimation of breeding success

We used a generalized additive mixed model (GAMM) to model the effect of distance to power plants on the breeding success of the white-tailed eagle. The distance we used referred to the territory, and was calculated as the average of the distances of all its nests in relation to the nearest installation (hereafter territory distance). This approach allowed us to obtain a representative value for the space used for breeding over the years.

For this analysis, only occupied nests (i.e. at least decorated) were considered. Breeding success was coded as 1 (successful) or 0 (unsuccessful), and the effect of territory distance (fitted as a smooth term in the model) was analysed with a logistic regression (logit link). Territories and years were included as random effects to allow for correlation between observations from the same territory and the same year, respectively. Turbine numbers per installation were excluded from the model because of a highly skewed distribution, given that most sites had one or two turbines. Road effects and distance to buildings (potential explanatory variables) were not considered as their disturbance to the white-tailed eagle was shown to be negligible in a major breeding area in Finland (Santangeli, Högmander & Laaksonen, 2013).

Nest distance effect

We modelled post-fledging survival with capture-mark-recapture (CMR), assuming the Cormack-Jolly-Seber model. Briefly, a CMR analysis uses individual encounter histories to separate the biological process (i.e. apparent survival) from the detection process (i.e. resighting/recapture). For our birds, the ringing represented the 'release' occasion and encounter histories were built using September (of a given year) to August (of the following year) as a reference. This period was chosen because its beginning coincides with a bird's independence after fledging. For example, a bird ringed in June 2000 was considered 'released' in the period 1 September 1999 to 31 August 2000. If seen in October 2000, its resighting would be recorded for 1 September 2000 to 31 August 2001. Because of insufficient data for the first 6 years, the analysis was restricted to 1998–2013 (with 5529 observations from 590 individuals).

Our general model was an age-structured model built from the biological knowledge of the species and the study design. Five developmental stages can be identified for the white-tailed eagle: one for juveniles, three for sub-adults and one for adults (Forsman, 1999). Survival rates increase until birds reach the breeding age (Evans *et al.*, 2009), hence the survival component of the model consisted of five age classes. Recapture probability was assumed to differ only for two age classes – juveniles and older birds – because the former are expected to be less resighted than the latter at the feeding stations because of their winter migration (Saurola *et al.*, 2013). Furthermore, we were interested in the effect of nest distance to a power plant (hereafter nest distance) on survival and resighting rates. The effect was tested on resightings, too, because the spatial configuration where the white-tailed eagles are resighted (i.e. along the coast) can potentially affect the probability of resighting an individual originating from a territory close to a power plant (primarily built along the coast). Thus, our general model can be expressed as $\{(\varphi a_5{*}t + d)\ (pa_2{*}t + d)\}$, where φ is the survival rate, p the resighting probability, a_5 the five age classes, a_2 the two age classes, and d the nest distance; $*t$ indicates time dependence with interaction between age classes.

The analysis was implemented in Program MARK (White & Burnham, 1999). We used Bootstrap GOF to evaluate the goodness-of-fit of the general model by calculating the variance inflation factor ($\hat{c}$), which was then applied to correct for overdispersion. Model selection proceeded with quasi-Akaike's information criterion (QAIC), with lower values indicating more parsimonious models (Burnham & Anderson, 2002). We tested the statistical effect of nest distance on post-fledging (first-year) survival by adding this covariate to the parameters of the candidate models. The covariate was added to the survival of the first-age class only because these individuals (juveniles) do not stay in the natal territory after obtaining their independence. Note further that we do not know the identity of breeding adults, and hence cannot test the nest distance effect on adult survival. The effect of the covariate was then interpreted on the basis of QAIC values. An analysis of deviance (ANODEV) was used to further test the significance of the covariate, and its results are solely presented as Supporting Information.

Territory occupancy and turbine avoidance

We used a GLMM to test whether territories closer to a power plant are more likely to have all nests unoccupied, thus resulting in no breeding attempt within the territory in a given year. To this end, nests were coded as 1 (occupied) or 0 (unoccupied), and the correlation with territory distance was analysed with a logistic regression (logit link). Territories and years were included in the model as random effects. In addition, we tested whether the distance between occupied nests and an installation increased over the years. This was done with a linear mixed effects (LME) model with territories included as random effects.

All analyses (except for the CMR) were performed in R 3.0.3 (R Core Team, 2014) with the packages lme4 (Bates *et al.*, 2014) and nlme (Pinheiro *et al.*, 2013).

Results

Territory occupancy

We found no evidence that the distance to a wind-power plant affected territory occupancy (GLMM, $Z = 0.094$, $P = 0.925$). Similarly, the presence of turbines did not lead to birds using nests located at ever-greater distances over time (LME, $t = -0.006$, $P = 0.995$). We therefore conclude that white-tailed eagles do not avoid breeding in the vicinity of power plants in Finland.

Breeding success

The territories considered here (with observations from 1992 to 2013) had an average of 7.44 (± 4.42 SD) breeding attempts. In nearly half of them (45%), attempts occurred in only one nest, while in the others mostly one or two alternative nests were used. Breeding was successful in most cases (63%). Only five territories (5%), mostly with one or two attempts, were never successful.

The distance at which a white-tailed eagle territory is located in relation to a wind-power plant was found to have an influence on the success of breeding attempts (GAMM; intercept: estimate = 0.573, SE = 0.099, t-value = 5.749; approximate significance of the smooth term: edf = 1, $F = 6.458$, $P = 0.011$). The closer the distance, the lower is the probability of a territory having a successful breeding outcome (Fig. 2).

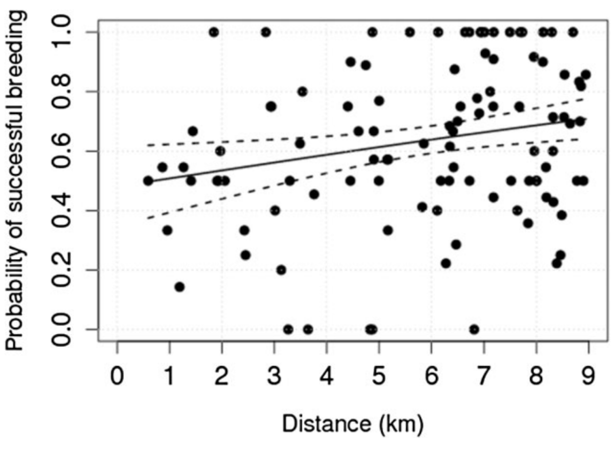

Figure 2 Scatterplot showing the probability of the white-tailed eagle (*Haliaeetus albicilla*) breeding successfully in relation to territory distance (km). Each data point represents a territory with either a single breeding attempt or multiple breeding attempts made over the years. Note that the breeding success analysis is based on annual breeding success, but that the data are here grouped on the level of the territory for ease of visual interpretation. The line was drawn on the basis of the fixed-effect estimates from the GAMM.

Table 1 Details of candidate models ranked in ascending order of their QAICc values

Model	QAICc	Delta QAICc	QAICc weight	Model likelihood	Parameters	Q deviance
{Phi(a_5 ./././././.) p(.)}	3173.689	0.00	0.30124	1.0000	6	3161.625
{Phi(a_5 ./././././.) p(a_2 t/t)}	3174.795	1.11	0.17330	0.5753	33	3107.035
Phi(a_5 d/././././.) p(.)}	3175.510	1.82	0.12122	0.4024	7	3161.424
{Phi(a_5 ./././././.) p(a_2 ./.)}	3175.707	2.02	0.10983	0.3646	7	3161.621
{Phi(.) p(a_2 t/t)}	3181.434	7.74	0.00627	0.0208	29	3122.074
{Phi(.) p(.)}	3184.214	10.52	0.00156	0.0052	2	3180.205
{Phi(a_5 * $t + d$) p(.)}	3194.789	21.10	0.00001	0.0000	51	3181.227
{Phi(a_5 * $t + d$) p(a_2 * $t + d$)}	3213.223	39.53	0.00000	0.0000	78	3047.204

The most parsimonious model (based on a $\hat{c} = 1.03$) appears in the top row; the general model is shown in bold. All combinations with the following structures were considered to test the covariate of interest: Phi(a_5 t/t/t/t/t), Phi(a_5 ./././././.), Phi(.), p(a_2 t/t), p(a_2 ./.), and p(.). Here, we only present a reduced set where models that represent an extended version of a simpler, nested model are omitted when their QAICc is higher than that of the simpler, nested model (Arnold, 2010).Notation characters are as follows: Phi, survival rate; p, resighting probability; t, time dependence; d, nest distance; *, interaction; + , additive effect; / separates different age classes; dots indicate constancy over time.

Nest distance effect on post-fledging survival

Our general CMR model showed an adequate fit to the data (Bootstrap GOF, $P = 0.35$) and exhibited slight overdispersion (Bootstrap, $\hat{c} = 1.03$). The most parsimonious model included constant survival for the five age classes considered as well as constant resighting (without an age structure) over time (Table 1; Supporting Information Table S1). Nest distance had no significant effect on the survival rates of juveniles that fledged within areas containing wind-power plants (Table 1; Supporting Information Table S2).

Discussion

Our results show that proximity to wind-power plants affected negatively the breeding success of the white-tailed eagle in Finland, but had no apparent effect on post-fledging survival, territory occupancy or nest site selection.

We found that pairs holding a territory closer to an installation had a lower probability of breeding successfully when compared with those in territories lying farther away. Dahl *et al.* (2012) showed similar results for Smøla, where breeding success in the vicinity of turbines declined dramatically. In our case, territories within 4 km had breeding success probabilities (< 60%) that fall below the recommended threshold of 60% success for breeding attempts on the Baltic Sea coast (where most of our territories were located; Helander, Herrmann & Stjernberg, 2013). Additionally, the up-to-4-km probabilities were lower than the breeding success rates of 60–80% observed in recovered populations (Probst & Gaborik, 2011).

Given the vulnerability of the species to wind-power generation, particularly to collision with turbines, we suggest that collision mortality played a role in our scenario. Adults have been suggested to be at the greatest risk, especially during spring because of their increased flight activity and territorial fights (Bevanger *et al.*, 2010). It is therefore possible that the lower breeding success associated with territories closer to turbines was driven by the death of adults during the breeding season. Although plausible, we are unable to confirm this suggestion because no carcass searches were conducted for this study. However, it is worth mentioning that at least six collision fatalities have recently occurred in Finland (WWF White-tailed Eagle Working Group, pers. comm.).

According to our results on territory occupancy and turbine avoidance through nest site changes, it seems that the disturbances associated with wind-power plants were not great enough to prevent breeding attempts at closer distances (at territory and nest levels, respectively). This contrasts with the major role of disturbance in the displacement of breeding white-tailed eagles on Smøla (Dahl *et al.*, 2012). This difference in results probably reflects a difference in the spatial distribution of the territories around the turbines. Our study areas had only a few territories within close distances. For example, no territories were found within 500 m and only 3% were within 1 km from the nearest power plant. On Smøla, on the other hand, there were 13 territories (later reduced to 4) within 500 m from the turbines (Bevanger *et al.*, 2010). While our scenario (which lacks displacement effects) enhances the importance of collision mortality, it does not completely exclude the potential influence of disturbance on the pairs that stayed and attempted to breed in the study areas. Disturbance (e.g. from turbine maintenance, increased access to the area through road construction and recreational activities) can affect the body condition of breeding birds (Gove *et al.*, 2013), and may well have contributed to breeding failure in territories closer to turbines. In the near future, disturbance will likely increase the risk of displacement in Finland.

We found no evidence of a nest distance effect on post-fledging survival. This suggests that juveniles that fledged closer to turbines faced no greater collision risk than those that fledged farther from turbines. This result is in agreement with the finding that juveniles are less vulnerable to collision than adults and sub-adults (Bevanger *et al.*, 2010). Nevertheless, juvenile fatalities have occurred elsewhere (e.g. on Smøla), probably because of their poor flight manoeuvrability (Bevanger *et al*., 2010) and weak response to displacement (May *et al*., 2013).

Recently, the WWF White-tailed Eagle Working Group has recommended a 2-km buffer zone for turbine deployment around white-tailed eagle nests in Finland (WWF Finland, 2011). Our findings on breeding success (based on eagle territories) suggest that perhaps an even more conservative approach would be justified. Naturally, the potential impacts resulting from turbine installation are dependent on a range of factors (not only on the distance to breeding sites), and should therefore be considered on a case by case basis through proper strategic planning (European Commission, 2011). As stressed in recent studies, the choice of location is among the most critical steps when planning the construction of wind farms (Stewart, Pullin & Coles, 2005; Drewitt & Langston, 2008). With the ambitious plans for wind-energy development in Finland, concerns have been raised as to whether poorly sited wind farms may impact the white-tailed eagle at the population level. These are well-justified concerns because cumulative effects from such installations may cause changes in adult survival (e.g. collision mortality) and breeding success (e.g. displacement caused by disturbance), resulting in population impacts (Powlesland, 2009; Krüger *et al*., 2010). Avoiding priority habitats and the geographical range of sensitive species (e.g. by building in already urbanized areas) seems to be paramount to prevent major impacts on avian populations (Gove *et al*., 2013).

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Supporting information

Additional Supporting Information may be found in the online version of this article at the publisher's web-site:

Table S1. Parameter estimates of the top CMR model.
Table S2. Results of the ANODEV.