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Reduced breeding success in white-tailed eagles at Smøla windfarm, western Norway, is caused by mortality and displacement

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ABSTRACT

Climate change scenarios and efforts to reduce CO_2 emissions have increased the focus on wind power and other renewable energy sources. Despite producing "clean" electricity, windfarms do have impacts on the environment. We studied the impact from a coastal windfarm on the breeding success of white-tailed eagles (*Haliaeetus albicilla*) at Smøla, western Norway by means of a BACI (before–after–control–impact) approach. The objective was to compare pre- and post-construction breeding success. A 10 year dataset from 47 eagle territories were analyzed using a generalized linear mixed model. Successful breeding was used as a response variable, while distance to turbines, distance to roads and before/after turbine construction were used as predictors. There was a significant effect of the interaction between time period and distance to turbines, showing that territories within 500 m from the turbines in the post-construction period experienced significantly lower breeding success than the same territories before construction. We found that this effect was most likely due to territories being vacated. The results emphasize the importance of using a BACI approach when assessing possible effects from wind-power production on breeding birds, especially for species breeding at low densities. It also emphasizes the importance of conducting thorough pre-construction studies on vulnerable bird species.

1. Introduction

Climate change and global warming scenarios (e.g. IPCC, 2007) together with increased energy demands (IEA, 2009) have made renewable energy production a key issue worldwide to reach the international targets on reducing CO_2 emissions. The potential for wind power as a source for electricity is substantial in most countries (Hoogwijk et al., 2004; IEA, 2009; Lu et al., 2009) including Norway (NVE, 2009).

Like all energy generation, wind-power plants may have adverse environmental effects on wildlife. A particular concern is the potential effects on birds (Drewitt and Langston, 2006, 2008), especially on large birds of prey (Carrete et al., 2009). Research on impacts of windfarms on wildlife has so far mainly focused on mortality from bird collisions with turbines and with collision risk assessment, as this is thought to be the most severe problem from wind power generation (Hunt, 2000; Kingsley and Whittam, 2005; Smallwood and Thelander, 2008). Large soaring birds such as raptors are particularly vulnerable to collisions (Barrios and Rodriguez, 2004; Bevanger et al., 2009; Hunt, 2002). However, so far results are inconsistent and the numbers of casualties recorded differ widely between wind-power plants and species (Kuvlesky et al., 2007). Considering the high number of turbines in some power plants, even low mortality rates per turbine could have severe population impacts for some bird species, especially those with low reproductive rates (Orloff, 1992; Percival, 2003; Thelander and Rugge, 2000). Other possible negative impacts are loss of, or reduced, habitat quality and disturbance leading to displacement. Pearce-Higgins et al. (2009) found that seven out of 12 bird species occurred at lower densities close to wind turbines compared to more distant areas. Although these effects have received less attention, they could potentially be of equal importance to collision mortality (Kingsley and Whittam, 2005; Langston and Pullan, 2003). Increased human activity can influence the use of nest sites, foraging sites and flight paths in birds (Drewitt and Langston, 2008) as well as displace birds into suboptimal habitats reducing their chances of survival and reproduction (Drewitt and Langston, 2006; Frid and Dill, 2002). Unfortunately, few conclusive studies have been carried out on the relevance of such factors, which is mostly due to lack of BACI (before–after–control–impact, (Krebs, 1999) assessments (Drewitt and Langston, 2006). The fact that raptors in general occur at low breeding densities (Newton, 1979),

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together with a lack of studies with a BACI-approach, has led to very few displacement studies of breeding raptors (Madders and Whitfield, 2006).

From October 2005 to December 2009, 28 dead white-tailed eagles (*Haliaeetus albicilla*) were recorded as collision victims within Norway's first large-scale windfarm on Smøla island, Central Norway (Bevanger et al., 2009). In 2010, 11 additional eagles were found killed by turbines (own unpubl. data). Smøla holds a large and dense breeding population of white-tailed eagles, estimated at more than 50 breeding pairs (Bevanger et al., 2009). Follestad et al. (2007) investigated the spatial distribution of eagle territories on Smøla using Kernel densities (Worton, 1989), showing that the pre-construction breeding density was highest within the windfarm area. Several of the former territories within the windfarm area are now vacant, and the "high-density" area of occupied territories has shifted to an area west of the windfarm (Bevanger et al., 2009). Bird species that mature late, lay few eggs and have a long life span, have demographic characteristics making their population growth rate especially sensitive to changes in adult mortality (Sæther and Bakke, 2000). Eagles fall into this category, and are therefore vulnerable to increased adult mortality caused by windfarms.

In this study we focus on possible impacts of the wind power plant on the breeding success of white-tailed eagles on Smøla. The objective was to test if the proportion of successful breeding events changed over time by comparing the breeding success before and after windfarm construction, controlling for the distance to the wind turbines.

2. Methods

2.1. Study species

The white-tailed eagle is a monotypic species currently distributed throughout northern and central Eurasia, west Iceland and southwest Greenland (del Hoyo and Elliott, 1994). The European population is estimated at 5000–6600 pairs and comprises more than 50% of the global population. As a result of a population increase the species has been downlisted to "Least Concern" on the IUCN Red List (IUCN, 2009). Norway is a stronghold of the white-tailed eagle and has ca. 40% of the European population (BirdLife International, 2002). In 2000 the Norwegian population was estimated at approximately 2200 territorial pairs (Folkestad, 2003), and has probably increased since.

The white-tailed eagle is territorial, monogamous and pairs up to establish territories at an age of about 5 years. Adult pairs are sedentary throughout the year, holding onto specific territories for their lifetime (Cramp, 1980; Fischer, 1982).

2.2. Study area

Data were collected in the Smøla archipelago on the outermost coast of Møre & Romsdal county, Norway (63°24′N, 8°00′E) (Fig. 1). The archipelago consists of a large main island surrounded by more than 5500 smaller islands, islets and skerries. The total land area is 274 km^2, and the coastline length of the archipelago is 1913 km. The landscape on the main island is characterized by heather moors with some extensive blanket bogs and a few rocky outcrops. The main island is flat, the highest peak being 64 m, and there are only small patches of trees, mainly introduced Sitka spruce (*Picea sitchens*). Most white-tailed eagle nests in the archipelago are placed on flat ground or small outcrops, a few in trees. The human population of the island is about 2000, and most of the inhabited areas are close to the sea.

The archipelago supports a white-tailed eagle population breeding at a very high density (Follestad et al., 1999), an important reason for the island's status as an Important Bird Area, IBA (Heath and Evans, 2000). In 2002, the largest Norwegian energy company (Statkraft) began construction of a large-scale wind power plant on Smøla. The power plant consists of 68 turbines covering a formerly undisturbed area of 18.1 km^2, and was constructed in two stages. The first stage had 20 turbines, with an installed capacity of 40 MW, and was operating from September 2002. The second stage, an additional 48 turbines with an installed capacity of 110 MW, was in operation from August 2005, making the total installed capacity 150 MW. The power plant has a yearly average power production of 450 GWh. In addition to the turbines themselves, the power plant holds an extensive infrastructure with a power station, 14.7 km of power lines and 28 km of roads connecting the turbines (Statkraft, 2008).

2.3. Data collection

During 1997–2009 all known white-tailed eagle territories in the Smøla archipelago were monitored. A nesting territory was defined as an area that contained one or more nests within the home range of a pair of mated birds (Steenhof and Newton, 2007). An occupied territory was defined based on observations such as the presence of adult pairs and nests in use or newly fledged chicks (Oehme, 2003). There was considerable variation in the number of nest sites used within the territories of eagle pairs during the study period. Some pairs used only one single nest while other pairs used up to five different nest sites during the 13-year period. A nest was defined as used when it contained fresh twigs, fresh grass, eggshells, eggs or ultimately chicks. Breeding was categorized as either successful or unsuccessful. A successful breeding was recorded when one or more large nestlings were observed at the nest.

Each territory and every nest site were visited at least once a year between hatching and fledging, and all territories were checked late in the breeding season to determine breeding outcome. In addition, new territories and nest sites were actively searched for. Activity in the territories, ranging from no activity to young in the nest, was recorded. The distances from all nest sites to the nearest wind turbine, as well as to the nearest road, were determined using the function Near in ArcGIS- ArcInfo (version 9.3, ESRI, USA). The distance to roads was used as an indicator of human disturbance in addition to the wind turbines (Martinez-Abrain et al., 2010).

The spatial distribution of eagle territories on Smøla is complex, and a number of pairs breed in the archipelago surrounding the main island. These pairs are likely to be more influenced by other factors, such as other human traffic (boats), and less from distance from the wind turbines and the distance to roads. They are therefore excluded from the analyses to minimize effects of environmental variables not related to the main objectives of the study. Thus, only pairs breeding on the main island were included in the analyses (Fig. 1).

2.4. Statistical analyses

Two separate datasets were analyzed; one including territories from the year they were confirmed established until they were confirmed deserted (i.e. only occupied territories). In the second dataset, territories were included from the year they were established and onwards throughout the study period, regardless of whether or when they later were deserted or not. This separation was done to investigate if any possible effect was due to a change in breeding success among occupied territories or due to territories being vacated.

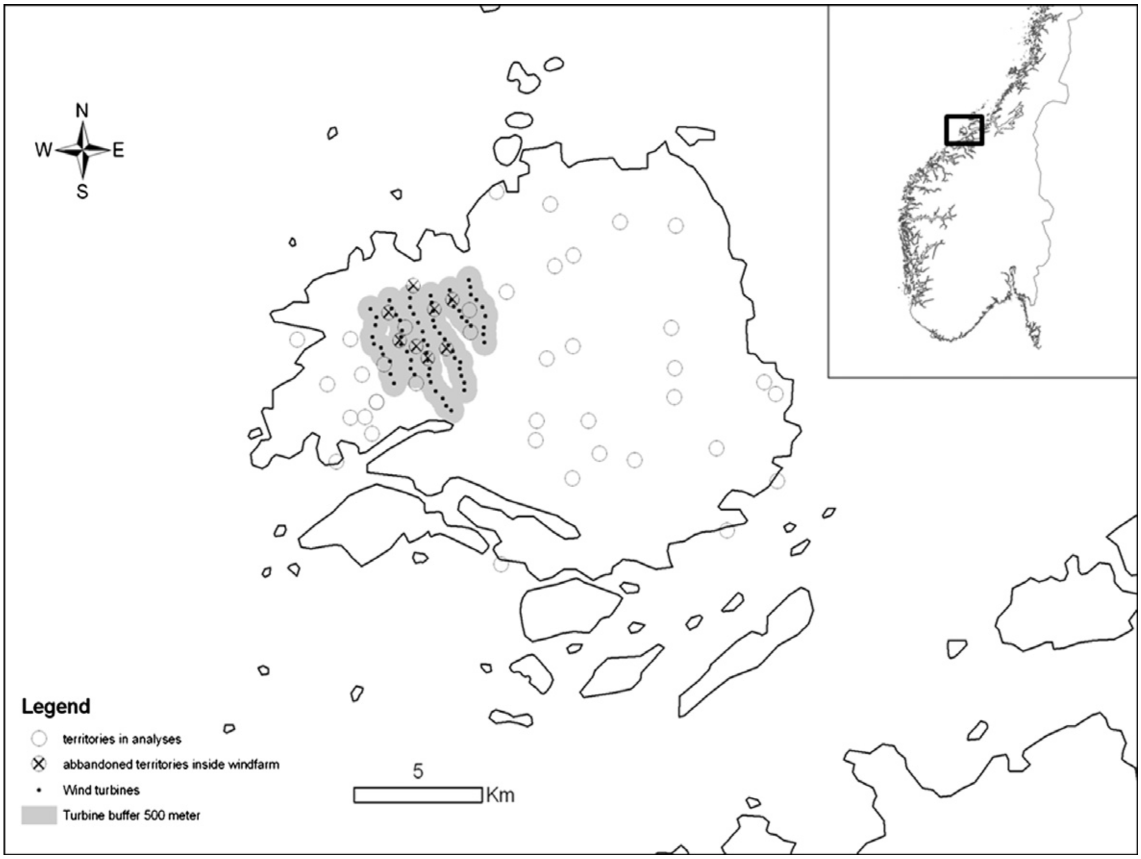

Fig. 1. Map of study area showing the windfarm with the turbines and the eagle territories.

Ten years of data (1997–2001, before construction of the windfarm, and 2005–2009, after construction) from 47 white-tailed eagle territories were analyzed using a generalized linear mixed model. *Timeperiod* (before/after construction), *turbinedistance* (inside/outside 500 m from the turbines) and *distance to roads* (other than the roads in the power plant) were the variables used in our analyses. The impact site, i.e. the wind-power plant, was defined as an area encompassing the wind turbines plus an extension of 500 m beyond outer turbines (Fig. 1) as the turbines are placed in strings up to ca. 800 m apart, giving a maximum distance of ca. 400 m from turbines for pairs breeding within the power plant area. This area inside 500 m from turbines will hereafter be called the windfarm, ('impact/treatment area'). The rest of mainland Smøla (outside 500 m from turbines) was defined as the 'control area'. Distance to road (excluding the roads within the powerplant) was used to control for other human activity than the wind power plant.

In order to obtain a binomial data distribution of the data and assure the same number of breeding seasons both before and after construction we omitted the years 2002–2004, with only 20 turbines (stage I) operating, from the analyses. Adding these intervening years to the analyses could have created noise as this was a temporary situation with considerable construction work towards stage II combined with stage I already operating.

The influence of the independent variables on the breeding success (number of chicks fledged/chicks produced) was tested using a binomial generalized linear mixed model (GLMM; family = binomial; link = logit), in which *timeperiod*, *turbinedistance* and *distance to roads* were included as fixed factors, while "territory" was included as a random factor. Akaike's Information Criterion value (AIC), corrected for small sample size (AIC_c), was calculated for the GLMM (Burnham and Anderson, 2002). Models were ranked in relation to each other using ΔAIC_c values ($\Delta_i = AIC_{c(i)} - AIC_{c(min)}$). Akaike weights were calculated (ω_i) to assess the likelihood of the model relative to the other models considered. From the models where $\Delta AIC_c < 2$, the principle of parsimony was used to find the model that best explained the variation in the data with the lowest number of explanatory parameters (K) included (Burnham and Anderson, 2002). Parameter estimates were calculated for the most

Table 1
Results from the GLMM analysis (data both from territories with confirmed activity and with no activity) showing variation in breeding success in white-tailed eagles on Smøla ($n = 332$ observations from 10 years in 47 territories). The table shows variables included in the models, and the influence from each model. Model selection is based on AIC_c. Timeperiod = period before and after disturbance; Turbinedist 500 m = inside or outside 500 m from turbines; Roads = inside or outside 500 m from roads, and *timeperiod:tunrbinedist* 500 m = interaction between the predictors time period and distance to turbines. K = number of estimable parameters in the models; $\Delta_i = AIC_{c(i)} - AIC_{c(min)}$; ω_i = Akaike weights explaining total variance. The most parsimonious model is highlighted in bold (see Methods for detailed description of procedure).

Models	K	AIC_c	Δ_i	ω_i
Timeperiod + turbinedist 500 m + *timeperiod:turbinedist* 500 m	**6**	**343.96**	**0.00**	**0.629**
Timeperiod + turbinedist 500 m + roads + *timeperiod:turbinedist* 500 m	7	345.90	1.94	0.238
Timeperiod	3	349.14	5.19	0.047
Intercept	2	350.67	6.71	0.022
Timeperiod + roads	5	351.01	7.05	0.018
Timeperiod + turbinedist 500 m	5	351.15	7.19	0.017
roads	3	352.37	8.42	0.009
Turbinedist 500 m	3	352.52	8.56	0.009
Timeperiod + turbinedist 500 m + roads	6	353.01	9.06	0.007
Turbinedist 500 m + roads	5	354.22	10.26	0.004

Table 2
Parameter estimates (β) from the most parsimonious model in Table 1 (highlighted in bold) explaining variation in breeding success in white-tailed eagles on Smøla. Model selection is based on AIC_c values. See methods for detailed description of procedure.

Parameter	β	SE	z-value	$Pr(\beta > \|z\|)$
(Intercept)	−0.159	0.467	−0.341	0.733
Timeperiod	−2.152	0.625	−3.444	<0.001
Turbinedistance	−1.132	0.533	−2.124	0.033
Timeperiod:*turbinedistance*	2.084	0.700	2.978	0.003

parsimonious models explaining most of the data variance, providing estimates of the relative influence from the different variables in the models selected. The GLMM analyses where carried out in R2.6.1, while SPSS 17.0 was used to graphically illustrate the results from the GLMM analyses.

3. Results

During 1997–2009, occupancy was recorded in 47 white-tailed eagle territories in our impact and control area altogether, with 73 successful breeding records (during the 10 seasons used in the analyses), out of 332 territory checks.

3.1. Generalized linear mixed model analyses of breeding success

The GLMM analyses of data from only those years were the territories were occupied included four top candidate models with ΔAIC_c values <2, all with medium to low ω_i values. The best model (lowest AIC_c value) included *distance to roads* only. From the parameter estimates of the four top candidate models none of the variables in these models influenced the breeding success. Models including *turbinedistance* and the interaction *timeperiod:turbinedistance*, were all low on the model ranking (low score both on ΔAIC_c values and ω_i values).

When the GLMM analyses were run with the data from the year the territories were established and onwards throughout the study period, regardless of whether they later were deserted or not, i.e. all territories, the results were different. Two models were top candidates with ΔAIC_c values <2 (Table 1), and the most parsimonious model included the variables *timeperiod*, *turbinedistance* and the interaction variable *timeperiod*:*turbinedistance*. This model had a high ω_i value (0.629), i.e. explaining a large proportion of the variance in the dataset. When analyzing the influence from the different variables in this model we found that *timeperiod*, *turbinedistance* and the interaction *timeperiod*:*turbinedistance* were predictors of breeding success in this dataset, with territories outside 500 m from turbines having more successful breeding attempts than inside 500 m. Likewise, territories before construction had more successful breeding attempts than after, and territories within 500 m in the period before construction had more successful breeding attempts than the same territories after (Table 2, Fig. 2).

We calculated the parameter estimate for the interaction between *timeperiod* and *turbinedistance* for the model (containing the variables *timeperiod*, *turbinedistance* and *timeperiod*:*turbinedistance*) with increasing distance from turbines for every 500 m up to 4 km to turbines (Fig. 3). The parameter estimate was high using distance 500 m to turbines (β = 2.084), relative to other distances, and the strength of the parameter dropped considerably already by 1 km (β = 1.098).

4. Discussion

The results from the present study, as one of very few assessing impacts from wind-power plants on the breeding success of birds, show that there was a negative effect of the wind-power plant on the proportion of successful breeding attempts of white-tailed eagles in territories close to and within the windfarm. The fact that this effect of the windfarm on breeding success was statistically significant only when territories that get vacated are included in the analyses, and no statistically significant effect was found when they were excluded, strongly indicates that the negative effect on breeding success within the windfarm was due to birds deserting their territories, rather than that birds still occupying territories performed differently than they did before the windfarm was built. Another factor could be that breeding birds killed by turbines were not replaced by immigrants.

Birds deserting territories could be a result of two different processes. Firstly, mortality from collision with turbines among birds holding territories within the windfarm could lead to territories being vacated. Secondly, birds could be displaced from their original territory as a response to windfarm construction. This displacement could occur through disturbance or through direct loss of habitat due to the power-plant's infrastructure. Although there is probably a mix of these effects, we were not able to quantify the contribution from each of them. Bevanger et al. (2009) found that areas with a high density of occupied white-tailed eagle territories changed from within the center of the windfarm towards the outskirts and outside of the windfarm after construction. This suggests that at least some of the effect is due to displacement.

Of the 28 white-tailed eagle casualties recorded within the windfarm in the period 2005–2009, 16 were adult birds and potentially holding a territory (Bevanger et al., 2009). Mortality among birds holding territories could lead to territory desertion by a surviving mate. We do not know the origin of each killed adult, but DNA-analyses of the victims shows that at least some of the adult white-tailed eagles were holding a territory inside or close to the windfarm (own data, unpublished). A majority of collision mortalities were recorded in March–May, so that the effect of the windfarm on the eagles is to a large extent season-specific (Bevanger et al., 2009). This period coincides with the early part of the breeding season, and several of the dead adult birds had a brood patch on their abdomen (Follestad et al., 2007), indicating that they either had eggs or chicks in their nests. The killing of an adult bird from a breeding pair will most likely lead to breeding failure. We observed that the strength of the interaction parameter *timeperiod*:*turbinedistance* was high at 500 m but dropped considerably by 1 km. This indicates that the effect could be local, and so most serious for territories close to the turbines; and then gradually diminishing with increasing distance from the turbines. This strongly suggests that avoiding central breeding areas for species such as the white-tailed eagle is crucial when constructing windfarms, our results also suggest that even an "avoidance" of 1 km will reduce the conflict.

Prior to construction the windfarm area was relatively undisturbed by human activities. White-tailed eagles are very sensitivity to disturbance in the breeding season, and this was probably the most important reason for the historically dense eagle breeding population. The area was also, pre-construction, recorded as having a higher proportion of successful breeding attempts than the control area (Fig. 2). After construction, the windfarm became an area with low breeding success. The power-plant construction was the start of a marked increase in human activities in the area, not only during the building period, but also thereafter. The windfarm area has become more available to people (e.g. for hiking, bicycling, skiing,) as a consequence of the internal road system, and dogs are often walked, not always on a leash. There are strong indications that the sum of disturbances from operational work and leisure activities has led to reduced habitat quality for the eagles holding territories in the area. These effects, together with mortality from collisions, are likely the main negative impacts from the wind power development on the species.

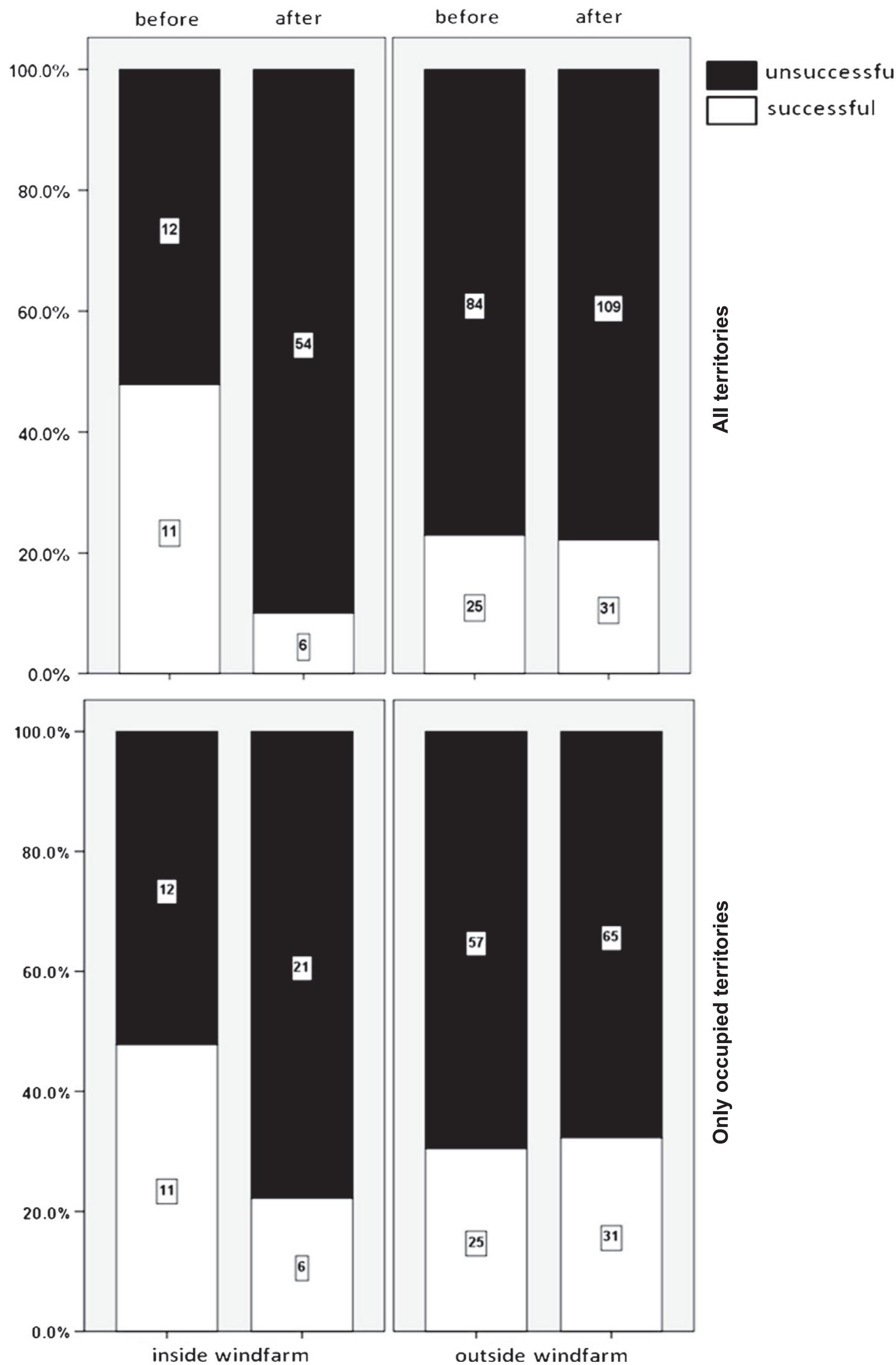

Fig. 2. Numbers and proportions of successful (white) and unsuccessful (black) breeding attempts for analyses with all territories (upper) and with only occupied territories (lower), inside and outside 500 m from the turbines within the Smøla windfarm. The two left columns represent the area inside 500 m from the turbines, the two right columns represent the area outside 500 m from the turbines. Number of cases in each category are given inside the columns.

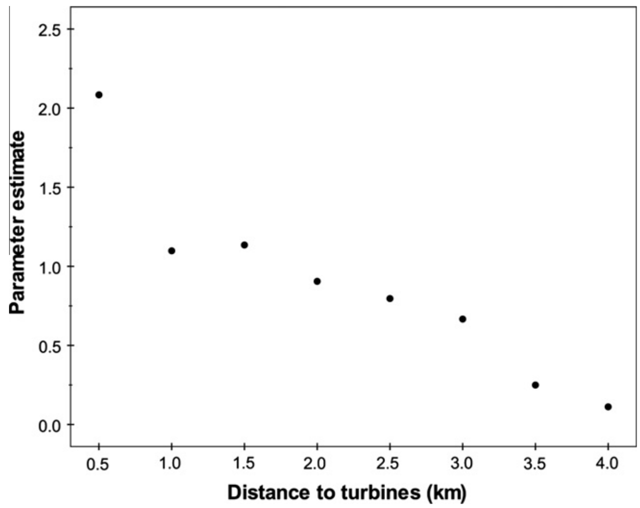

Fig. 3. Parameter estimate (β) of the interaction parameter *timeperiod:turbinesdist* from the most parsimonious model in Table 1, estimated at increasing distances to turbines. See Methods for detailed description of procedure.

Although the number of occupied territories in the windfarm area has decreased (Bevanger et al., 2009), there are still a few pairs holding onto their territories. This is likely to be a result of the pronounced territoriality of the species. Although this case is unusual in its potential for direct influence by being situated in a dense breeding area of a vulnerable large raptor species, there are further plans for windfarm development in areas of high breeding densities of white-tailed eagle and other large scavenger raptor species, both along the Norwegian coast and elsewhere in Europe. Results from our study underline the importance of careful siting of planned windfarms, to avoid important breeding areas for vulnerable raptors such as the white-tailed eagle. Other studies have either not been able to find any effects from wind-power development on breeding performance, or they have suggested low disturbance distances for breeding birds (Drewitt and Langston, 2006; Winkelman, 1992). Because of low sample sizes and low breeding densities, raptors are among the most difficult groups of birds for which to demonstrate such effects. Drewitt and Langston (2006) consider that this is often due to lack of BACI (before–after–control–impact) assessments. They also suggest that it could be an effect of the high site fidelity and long life-spans characteristic of the species studied, and that long-term effect on breeding birds will become evident only when new recruits are needed to replace lost breeding birds. The present situation in the Smøla windfarm area is that neither new recruits nor floaters seem to fill up deserted territories. Still the number of birds killed in collisions with turbines each year is not decreasing (Bevanger et al., 2011), indicating that eagles will continue to collide even if all territories are deserted. However, only by continued monitoring we will be able to disclose the long term effects of the windfarm on reproductive output and number of casualties.

Because we were able to employ a BACI approach in an area of high breeding density of white-tailed eagles, this study was able to demonstrate a relevant negative impact on the proportion of successful breeding attempts from the area of the wind-power plant. The fact that this effect was statistically significant only when vacated territories were included, suggest that the effect is mainly caused by high mortality and/or displacement among territorial birds in the power plant area. If other individuals do not replace the eagles still occupying territories in the windfarm, the long-term effect on breeding success will be even more significant. If the area still is attractive to prospecting birds, then these will face a higher mortality risk than other birds because of the collision risk, and the area will change its status from ‘‘source’’ to ‘‘sink’’.

5. Conclusion

The results emphasize the importance of thorough pre-construction studies identifying important breeding areas for sensitive species. The cumulative impacts from several wind-power plants along the Norwegian coast and elsewhere could potentially have a substantial negative effect on the white-tailed eagle breeding population if they are located in important breeding areas, turning them from sources to sinks. Moreover, the results underline the need for more BACI studies to properly assess the impact of wind-power plants on bird populations. Increased knowledge and understanding of the impacts of wind-farms on birds and other wildlife is essential for sustainable future wind-energy development in Norway and elsewhere.

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