Barriers to movement: impacts of wind farms on migrating birds

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Masden, E. A., Haydon, D. T., Fox, A. D., Furness, R. W., Bullman, R., and Desholm, M. 2009. Barriers to movement: impacts of wind farms on migrating birds. – ICES Journal of Marine Science, 66: 746–753.

Advances in technology and engineering are enhancing the contribution that wind power makes to renewable energy generation. Wind farms, both operational and in planning, can be expected to impact negatively on wildlife populations, particularly birds. We propose a novel approach to assess the impacts through the energetic costs of avoidance behaviour for a long-distance, migratory seaduck. Flight trajectories were recorded using surveillance radar at a Danish offshore wind farm with emphasis placed on the 200 000+ migrating common eiders that pass through the area annually. Minimum distance to wind farm and curvature of trajectories were compared pre- and post-construction. Additional costs of the avoidance response were estimated using an avian energetic model. The curvature of eider trajectories was greatest post-construction and within 500 m of the wind farm, with a median curvature significantly greater than pre-construction, suggesting that the birds adjusted their flight paths in the presence of the wind farm. Additional distance travelled as a consequence of the wind farm's presence was ca. 500 m and trivial compared with the total costs of a migration episode of 1400 km. However, construction of further wind farms along the migration route could have cumulative effects on the population, especially when considered in combination with other human actions.

Keywords: avoidance behaviour, Baltic Sea, barrier effect, common eider, radar, wind farm.

Received 17 July 2008; accepted 13 January 2009; advance access publication 24 February 2009.

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Introduction

To curb climate change, governments are seeking to enhance the proportion of energy generated from renewable resources. Advances in technology and engineering realistically enable wind energy to form a significant proportion of this contribution (Larsson, 1994). More than 20 000 offshore wind turbines have been proposed for European waters, with the UK government recently announcing an expansion of their wind-energy programme and proposing that 7000 turbines be built off the UK coast by 2020. However, wind-farm developments are likely to impact negatively on the distribution and abundance of wildlife populations, particularly birds. Potential impacts of wind farms on bird populations can be categorized into three types: direct mortality of individuals as a result of collision with turbines and infrastructure; modification of the physical habitat as a consequence of the footprint of the turbines and associated structures; and avoidance responses of birds to turbines (Fielding *et al.*, 2006; Fox *et al.*, 2006). The latter includes displacement from habitat and extension of flights, where wind farms act as barriers to movement.

Studies to date have concentrated on collision mortality (Barrios and Rodriguez, 2004; Hötker *et al.*, 2006) and habitat loss, either direct (Fielding *et al.*, 2006; Bright *et al.*, 2008) or effective, through avoidance behaviour (Larsen and Guillemette, 2007). Although the problem has been identified, researchers have not yet evaluated wind farms as barriers to movement (Langston and Pullan, 2003; Fox *et al.*, 2006; Madders and Whitfield, 2006), and there is no standard methodology to tackle this issue. Animals often respond to spatial heterogeneity by altering their movement patterns (Frair *et al.*, 2005), particularly in relation to novel objects (Jander, 1975). Seaducks, particularly common eiders (hereafter eiders, *Somateria mollissima*), exhibit behavioural avoidance responses to wind farms (Desholm and Kahlert, 2005; Larsen and Guillemette, 2007). Consequently, the construction of wind farms along a flyway is likely to affect eider populations by increasing the distances travelled and the energy required to detour around these barriers. In many bird species, reproductive success is related to body condition at the time of breeding (Wendeln and Becker, 1999), and this is especially so among eiders because of the heavy investment of female body reserves during reproduction (Parker and Holm, 1990; Meijer and Drent, 1999). Any reduction in mass as a result of increased flight requirements could be detrimental and directly impact breeding output.

Eiders are abundant throughout the Baltic, although the population is adversely affected by human activities such as hunting and fishing, both bycatch in gillnets and through competition from the bivalve fishery, and potentially eutrophication (Rönkä *et al.*, 2005). The Baltic Sea population of eiders decreased by 30–40% between

1991 and 2000 (Desholm *et al.*, 2002) and the species has also been highlighted as one sensitive to climate change (Huntley *et al.*, 2007). The Birds Directive and other international agreements require States to maintain bird populations, which necessitates an understanding of the processes and pressures acting on a population. The cumulative impact of all pressures on a population may be negative, but the challenge is to understand the impact of each pressure in isolation.

This study develops an approach to evaluate barrier effects associated with wind farms and uses it to assess the impact of the Nysted wind farm on eiders. The following questions were addressed:

(i) do eiders avoid the Nysted wind farm and at what distance?

(ii) do eiders increase their migration distance in the presence of the wind farm?

(iii) what is the cost of additional flight in the context of eider seasonal migration and from the likely construction of many more marine wind farms?

Methods

Study site and species

The study area covered the Nysted offshore wind farm, in the western Baltic south of Denmark, comprising 72 turbines placed in eight north–south orientated rows, 850 m apart at 480 m intervals east–west, covering an area of ca. 60 km^2 (Figure 1). Flight trajectories of migrating waterbirds were collected between September 2000 and October 2005 using surveillance radar mounted on an observation tower located northeast of the wind farm (Desholm and Kahlert, 2005; Petersen *et al.*, 2006). Wind conditions during radar measurements ranged from 0 to 12 m s^{-1} with a mean of 5 m s^{-1}. At windspeeds of >10 m s^{-1}, there was some interference from sea clutter. Echoes from fixed targets were not displaced between the sweeps of the radar, so it was concluded that the spatial movements of birds had been monitored precisely without displacement. Each flock of birds entering the detection area created an echo on the radar display, and by monitoring the movement of echoes, the migration trajectory of any given flock could be followed. During daylight and out to a range of ca. 11 km (Desholm, 2003; Desholm and Kahlert, 2005), the birds were identified visually to species, but such identification was not possible at night. All species trajectories were recorded, but here we focus on eider and make comparisons with all other trajectories gathered for waterbirds collectively. We present only data from the autumn migration because these had greatest coverage of the approach sections of trajectories towards the wind farm owing to the location of the radar facility. However, we have no reason to believe that birds would respond differently in spring than in autumn when approaching the wind farm, so assume that the response and the associated energetic cost will be comparable during the spring migration. The Finnish eider population is likely to be affected by the Nysted wind farm because their migration route takes them from wintering areas in the Wadden Sea to breeding areas in the Finnish Baltic, via southern Denmark. Between 200 000 and 300 000 eiders pass the study site each spring and autumn (Alerstam *et al.*, 1974; Petersen *et al.*, 2006).

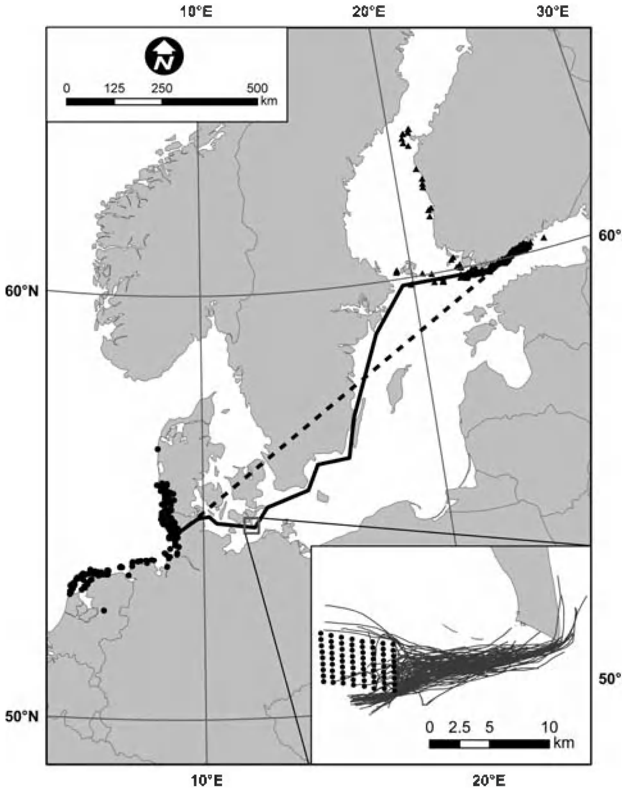

Figure 1. Estimated migration routes taken by eiders compared with the corresponding straight-line distance (dashed line). Triangles represent capture sites of breeding adult females in Finland, and circles the recovery sites of these Finnish-marked birds in winter in the Wadden Sea. The insert denotes the study site and an example of eider trajectories recorded near the wind farm post-construction.

Data analyses

Deviation from a straight-line trajectory, or curvature, was estimated to assess the additional distance travelled by individual birds in the presence of the wind farm. Curvature in this case is defined as the length of trajectory divided by the Euclidian distance from start to endpoint. This measure of curvature is similar to the modified index of straightness (Batschelet, 1981), and Desholm (2003) used such a method to assess how small changes in flight direction affected migration distance. For each trajectory, curvature was calculated from the beginning to the end. The minimum distance to the wind-farm area was also estimated for each trajectory, as a measure of the avoidance response.

Trajectories were categorized into those recorded pre- and post-construction, then further categorized as near or far from the wind farm; 500 m was considered an appropriate threshold to differentiate between near and far, because the distance between turbines in a row was $\sim$500 m. Larsen and Guillemette (2007) reported avoidance of eiders at 200 m, so it was reasonable to set our threshold greater than this distance. Visual examination of the data suggested that the curvature of trajectories did not vary greatly beyond 500 m from any single turbine (Figure 2).

Curvature data were not normally distributed, so non-parametric Kruskal–Wallis analysis was used to test for differences in the curvature of trajectories between different categories. We also used a multiple comparison test to identify the categories that were significantly different (Siegel and Castellan, 1988). Distributions of space use around the wind-farm area were produced using a quartic, kernel-density interpolation in the ArcGIS Spatial Analyst module. All data analyses were conducted

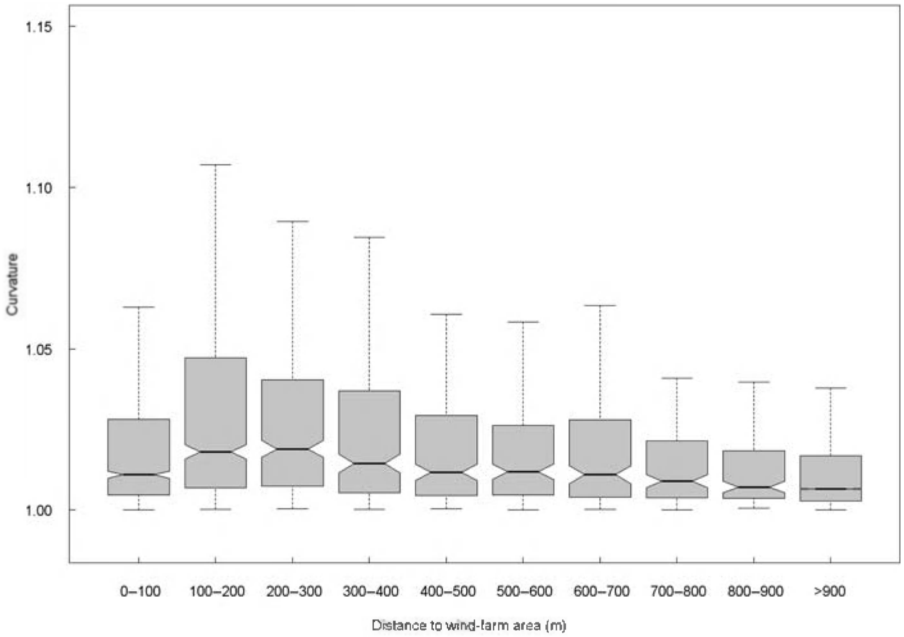

Figure 2. Curvature for all trajectories categorized by nearest distance to the wind-farm area. Kruskal–Wallis: $\chi^2 = 642.0$, d.f. = 9, $p < 0.05$. Boxes represent the lower quartile, median, and upper quartile values. Whiskers connect adjacent values within 1.5 times the interquartile range from the ends of the box.

using ArcGIS (version 9.2) with the additional package Hawth's Analysis Tools for ArcGIS (Beyer, 2004), and R (version 2.7.0).

Migration scenarios

To assess the additional cost associated with the presence of the Nysted wind farm, we first estimated the additional distance travelled by eiders post-construction within the study area:

$$\text{Distance} = (C_{\text{post}} - C_{\text{pre}}) \times \text{median trajectory length}. \tag{1}$$

C_{pre} and C_{post} are curvature pre- and post-construction, and trajectory length was measured in metres. Satellite-tracking data are not available for eider, so the precise migration distances remain unknown. Previous estimates (Alerstam, 2001) were used in combination with location data from ringing recoveries of breeding and wintering female eiders from the Finnish population (Figure 1).

The overall cost of migration and the additional costs incurred because of the wind farm were estimated using the modelling software Flight 1.18 (Pennycuick, 2007). The model was used to estimate the cost of flight using aerodynamic principles and hence to measure the cost of avoiding the Nysted wind farm. We investigated different scenarios associated with the construction of additional wind farms based on multiples of the response observed at Nysted. Also included was a comparison with the straight-line distance between breeding and wintering grounds, because eiders already extend their annual migratory distance travelled over that of the shortest distance by avoiding flying over land. Model input parameters are listed in Table 1. The wingspan and wing-area data were from adult, female eiders collected from Kalø Vig and Ebeltoft Vig, Denmark. The wing measurements were taken from 14 birds following Pennycuick (1989). Fat mass was estimated by comparing the empty mass (bird body mass, with nothing in its crop) with the mass of lean females immediately after breeding (Christensen, 2008).

Table 1. Input values to the migration modelling software Flight 1.18 (Pennycuick, 2007).

Variable	Value	Source reference
Empty mass	2500 g	H. Noer, DMU, pers. comm.
Wingspan	0.9045 m	See Methods
Wing area	0.1192 m^2	See Methods
Altitude	0 m above sea level (m.a.s.l.)	–
Fat mass	1 040 g	See Methods
Distance to destination	To be determined	–
Cruising altitude	10.9 m	Desholm (2003)

Results

The data comprised 13 323 trajectories, of which 2593 were recorded pre-construction and 10 730 post-construction of the wind farm. Of these, 806 trajectories were identified as eider, 245 pre-construction and 561 post-construction.

The median curvature for all trajectories was 1.0079 compared with 1.0174 for the records of eider. The trajectories recorded post-construction near the wind-farm area had greater curvature and variance than the other categories among all trajectory data (Figure 3). Kruskal–Wallis and multiple comparison tests suggested that all categories were significantly different (Kruskal–Wallis: $\chi^2 = 664.78$, d.f. = 3, $p < 0.05$), although comparisons including post-near had observed differences in the sum of the ranks an order of magnitude greater than for all other comparisons. A similar pattern was evident among the eider records (Figure 4). The median curvature of trajectories post-near was significantly greater than the curvature among the other categories (Kruskal–Wallis: $\chi^2 = 89.77$, d.f. = 3, $p < 0.05$), and the variation in curvature was greater for the post-near category.

Minimum distance to the nearest wind turbine varied with category and species. Pre-construction, the trajectories for both eider

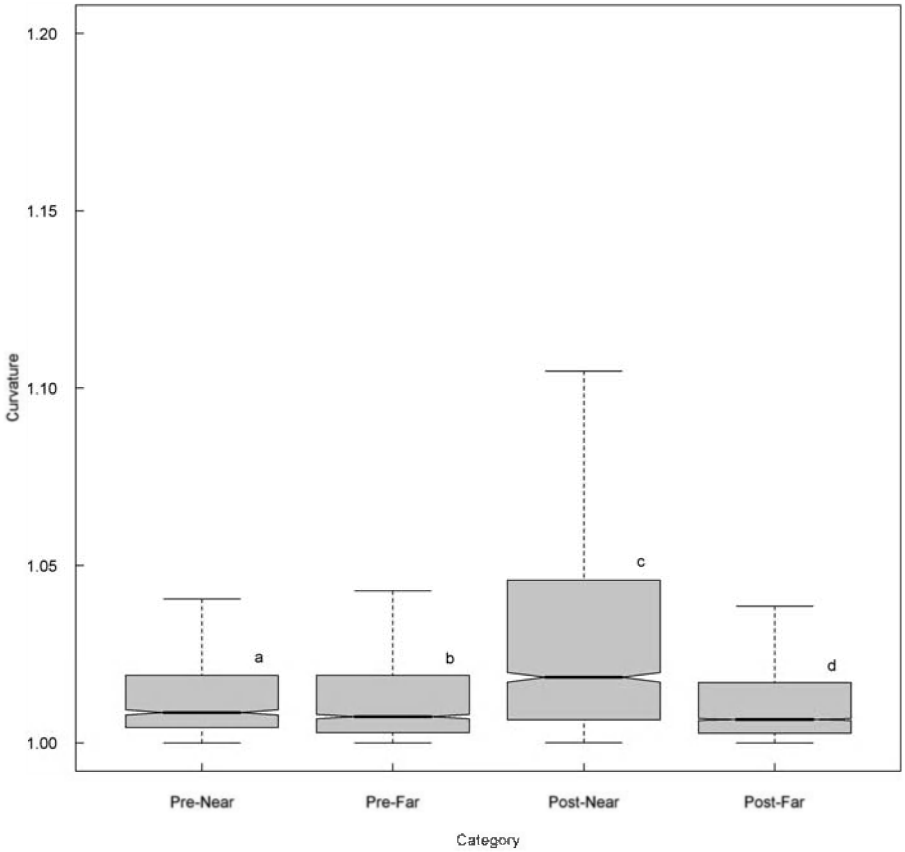

Figure 3. Curvature for all tracks both near (<500 m to turbines) and far (>500 m to turbines) pre- and post-construction of the Nysted wind farm. Kruskal–Wallis: $\chi^2 = 664.8$, d.f. $= 3$, $\alpha < 0.05$. Letters denote significant differences; multiple comparisons test, $\alpha = 0.05$.

and all data were not significantly different (Figure 5). Post-construction, the median minimum distance to the wind-farm area increased significantly by 104 m, from 56 to 160 m, for all trajectories. Eiders exhibited a greater response, the median minimum distance to the wind-farm area increasing from 50 to 224 m, a displacement of 174 m. The response of eiders to the wind farm and the differences in space use are illustrated in Figure 6. Post-construction, the space used by eiders was reduced in the area of the wind farm when compared with that pre-construction, and there was a corresponding increase in the use of surrounding areas, particularly to the south.

The additional distance incurred in the presence of the wind farm was ca. 500 m. The straight-line (great circle) distance between breeding and wintering grounds was ~1200 km, requiring an estimated energetic expenditure of 13 300 kJ for eiders to fly the distance. The estimated distance of the likely migration route taken by eiders was 1400 km, equating to flight costs of 15 200 kJ. This difference between the two routes equates to a reduction in eider body mass of 0.06 kg. Increasing the distance travelled by 1 km (equivalent to twice the distance associated with the Nysted wind farm) had no detectable energetic cost or extra loss of mass. Only when the distance was increased to 1450 km, i.e. equivalent to 100 Nysted wind farms, did the further reduction in mass of the bird exceed 1% (Table 2).

Discussion

Little is known of the effects of wind farms on bird populations because of a lack of pre- and post-construction comparative studies, and Stewart *et al.* (2007) highlighted the lack of rigorous analysis and the short duration of existing studies. Application of the BACI (before–after–control–impact) method is advocated as the gold standard for study design in the context of wind farms, but is rarely feasible with time or monetary constraints and a lack of legislative necessity. We present here an unusual dataset recording bird-movement data before and after the construction of an offshore wind farm, in an area of dense migratory movements. This has allowed us to answer questions not addressed previously.

Birds show avoidance responses to wind farms, but these vary within and between species (Hötker *et al.*, 2006). Comparison of the pre- and post-construction data from Nysted showed that birds adjusted their flight trajectories to avoid the wind-farm area post-construction. This was especially evident among eiders (Figure 6), which flew predominantly east to west pre-construction and northeast to southwest post-construction, generally avoiding the area within the wind farm. Few trajectories passed between the turbines and most birds flew to the south of the facility. The variation in trajectories recorded may be a result of differences in the distance at which birds show avoidance, some reacting to the wind farm at several kilometers and others at close range. The differences observed in the route taken around the wind farm might also be due to differences in the prevailing wind direction and a risk-aversion strategy to prevent being blown into the turbines. Only six trajectories navigated to the north, all during the prevailing southerly winds; because eiders generally avoid flying over land, an alternative explanation of the data may be that birds avoided travelling to the north to avoid proximity to land.

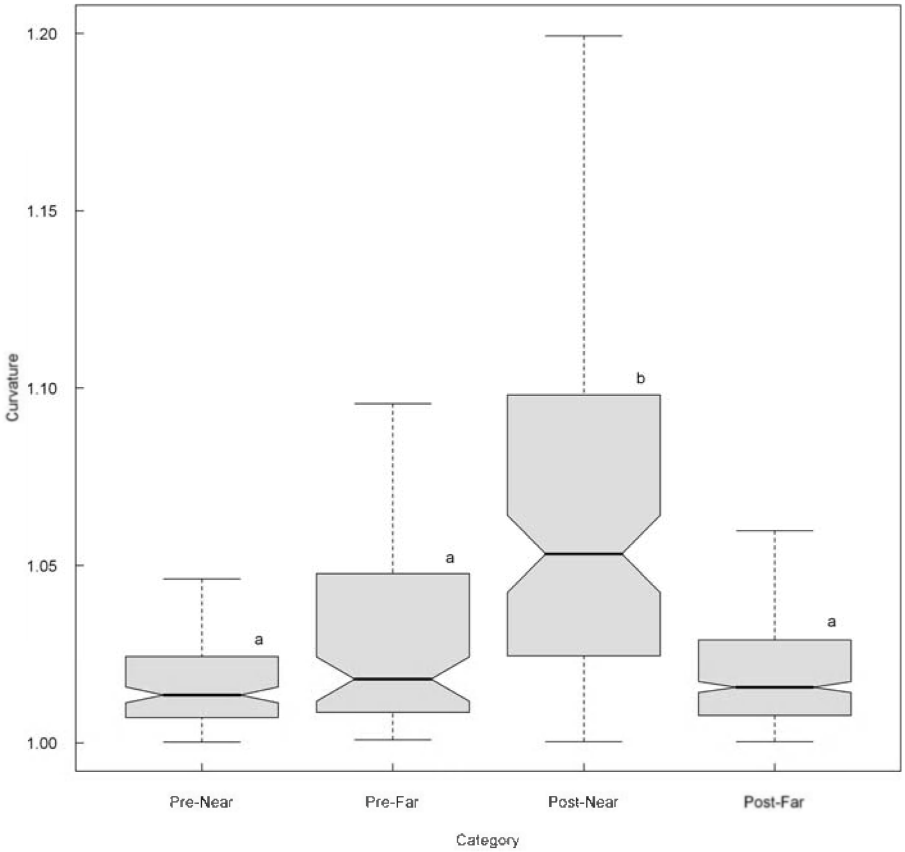

Figure 4. Curvature for eider tracks both near (<500 m to turbines) and far (>500 m to turbines) pre- and post-construction of the Nysted wind farm. Kruskal–Wallis: $\chi^2 = 89.8$, d.f. $= 3$, $\alpha < 0.05$. Letters denote significant differences; multiple comparisons test, $\alpha = 0.05$.

Several studies have suggested that birds avoid wind farms, but few have quantified avoidance rates or distances, and these measurements are vital to understanding bird–wind farm interactions. Pettersson (2005) reported that waterfowl rarely flew within 100 m of the wind turbines at Kalmar Sound, Sweden, and eiders at Tunø Knob, Denmark, showed avoidance at ca. 200 m from that wind farm (Larsen and Guillemette, 2007). These results are similar to the median minimum distance of 224 m observed among eider at Nysted post-construction, representing a displacement of 174 m from the pre-construction state. Other species flew closer to the wind farm, but post-construction data also showed significant displacement. Hence, all birds responded to the wind farm, but eiders showed a greater avoidance response. One explanation for this could be that eiders are more risk-averse when migrating than other species in the study.

Fox *et al.* (2006) highlighted barriers to movement as one of the effects of wind farms on bird populations. Our study showed that birds, eider in particular, avoided the Nysted wind farm and flew around it, rather than between the turbines. The extent to which avoidance is considered an impact depends on the species, the size of the wind farm, the spatial arrangement of the turbines, the type of movement, i.e. local movements between feeding, nesting, and roosting areas, or annual migrations, and the incurred energetic cost (Fox *et al.*, 2006). The Nysted wind farm has 72 turbines occupying an area of ~60 km^2, so the extra distance required to fly around the farm is almost certainly trivial for eiders migrating 1400 km or more. Trivial or not, the expectation was that curvature would differ significantly between trajectories recorded pre- and post-construction because of an avoidance response. However, we predicted there to be no difference in curvature between trajectories far from the wind-farm area pre- and post-construction, because the birds were travelling at distances far enough from the area to require no change in flight path. Figures 3 and 4 illustrate the differences in curvature pre- and post-construction for all bird species as well as for eiders. The results for both analyses indicated that birds near the wind-farm area flew farther post-construction. Among eiders, the curvature was significantly greater for trajectories recorded near and post-construction, equating to an additional 500 m travelled while traversing the study area. When all trajectories were analysed, all categories were significantly different. This result probably stems from the high statistical power emanating from the analysis of >13 000 trajectories. The result is therefore statistically significant, but may not be biologically significant or relevant, and graphically (Figure 3) it would seem that there was little difference between the categories pre-near, pre-far, and post-far.

General migration routes are known for many species, but knowledge of the fine-scale movements of birds on migration is limited. The Baltic/Wadden Sea population of eiders mainly winters in the western Baltic and Wadden Sea and makes the journey back to the Baltic Sea to breed. Individuals from this population therefore pass through the area of the Nysted wind farm and are potentially impacted by it. In the extreme, the energetic costs of avoidance behaviour and increased distance travelled would reduce the mass and condition of an individual to the point of adversely affecting breeding success. The marginal increase in

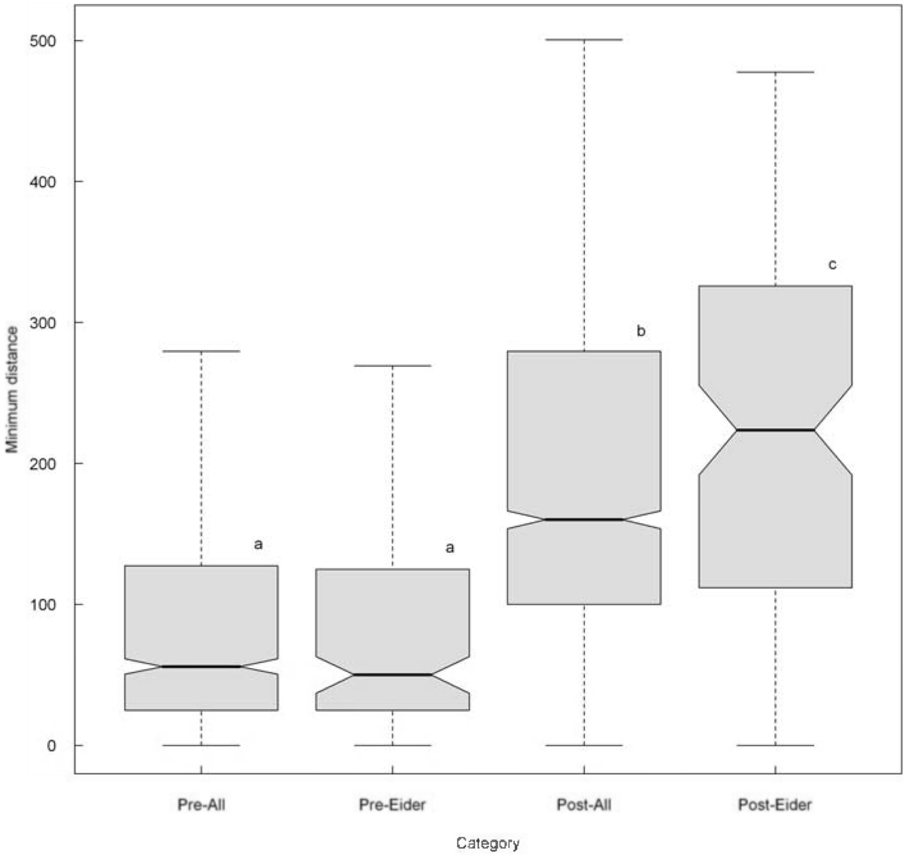

Figure 5. Minimum distance to wind turbines for all tracks and only eiders that were <500 m from the turbines, pre- and post-construction. Letters denote significant differences; multiple comparisons test, $\alpha = 0.05$.

distance travelled by eiders in the presence of the Nysted wind farm was ca. 500 m, 0.04% of the estimated distance travelled between wintering and breeding grounds. The cost of the additional distance travelled to avoid the wind farm was undetectable, and a response similar to that of passing 100 similar wind farms was required to achieve a loss in body mass in excess of 1% (Table 2). The energetic cost for a single journey avoiding one wind farm is therefore insignificant compared with factors such as strong or unfavourable wind conditions (Pennycuick, 1978; Hedenström and Alerstam, 1995). Although birds can choose favourable wind conditions to begin migration, it is clear that wind is undoubtedly a more important factor in relation to the energetic cost of migration than circumventing a wind farm. This cost will differ annually dependent on wind conditions: headwind or tailwind and wind drift in relation to wind direction (Alerstam and Hedenström, 1998). However, not only wind but also other weather factors may affect the energetic cost of migration. For example, seaducks prefer to fly in sight of the coast, so visibility will also dictate the length of the migration route.

The Nysted wind farm may have limited impact on the eider population, but two larger offshore wind farms are planned in the western Baltic: 200 turbines at Kriegers Flak and 200 turbines south of Öland and in Kalmarsund. If these and others are constructed along the eider migration route the impact on the population may increase. Eiders avoid flying over land and navigate around southern Sweden, as shown in Figure 1 (Alerstam, 2001), yet these same birds fly over mainland Denmark to reach the Wadden Sea. The associated energetic cost of this behaviour to avoid land is also greater than that of navigating around the Nysted wind farm (Table 2). Similarly, the migration route of eiders has probably changed continuously over the past 10 000 years, so eiders are well adapted to more or less constant changes in their migration route. In the greater context, the effect of Nysted is just one of many ways in which human activities impact on bird populations, others being collisions with buildings, predation by domestic animals, climate change, and hunting (Woods *et al.*, 2003; Erickson *et al.*, 2005; Veltri and Klem, 2005; Huntley *et al.*, 2007; Kurle *et al.*, 2008). For example, the annual Danish hunting "bag" for eiders is 30 000–70 000 birds (Christensen, 2008).

This study is based on several assumptions that should be tested. It was assumed that each journey was an independent event and that individual birds could compensate for the extra energetic costs by increased feeding rates between events. If this is not the case, then the impacts may be cumulative over time (Kalmbach *et al.*, 2004). We considered a population undertaking long-distance annual migration, and in this situation the cost of avoidance was trivial. However, if the population were commuting daily, the cumulative energetic costs of frequently avoiding a wind farm would be greater (Fox *et al.*, 2006). Examples of such behaviour are common scoter (*Melanitta nigra*) and long-tailed ducks (*Clangula hyemalis*) moving between marine feeding and roosting areas daily during winter, or breeding terns moving frequently between marine foraging grounds and terrestrial nest sites. Moreover, we only considered the displacement of individuals in latitude and longitude, but not altitude. Desholm and

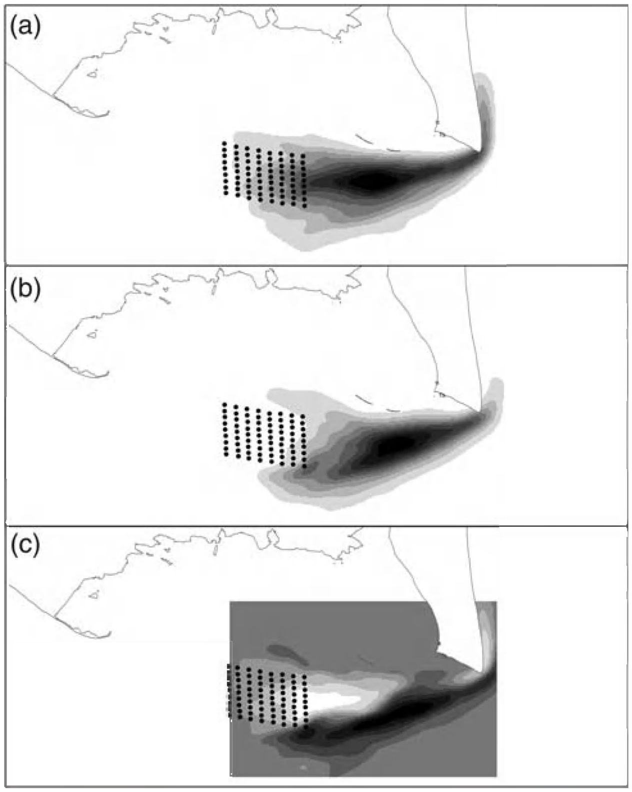

Figure 6. Kernels of space use by eider across the study area (a) pre-construction, (b) post-construction, and (c) the difference in space use between (a) and (b). Darker colour represents greater use. Dots denote the wind turbines.

Table 2. Estimated cost of flight associated with increasing distance travelled as a consequence of the avoidance response of eiders to wind farms (Pennycuick, 1989).

Nysted wind-farm factor	Distance travelled (km)	Cost (kJ)	Fat burnt (kJ)	Mass (kg)
0	1 200	13 300	12 700	2.06
0	1 400	15 200	14 400	2.00
2	1 401	15 200	14 400	2.00
4	1 402	15 200	14 400	2.00
10	1 405	15 200	14 400	2.00
100	1 450	15 600	14 800	1.98
1 000	1 900	19 500	18 500	1.85
3 000	2 900	26 900	25 600	1.61
4 000	3 400	30 200	28 700	1.50

Kahlert (2005) reported that the altitude at which birds fly increased at night, but that the trajectories could only be identified to species level during daylight. Here, therefore, altitudinal displacement was not considered, but it may add to the impact in other scenarios. However, it is also possible that with increasing altitudinal displacement, latitudinal/longitudinal displacement may be reduced with individuals flying above rotor height.

Conclusions

The additional distance travelled by eiders attributable to the Nysted wind farm is unlikely to impact the population because the increased distance and associated energetic costs appear to be trivial. This conclusion agrees with that of Pettersson (2005), who investigated the impact on eiders of two offshore wind farms in the Kalmar Sound, Sweden. However, the cumulative effects of many similar wind farms built along a migration route could impact a population. Also, if other actions, such as habitat degradation, were to be at work at the same time, then the relatively small effects of the wind farm *per se* may become important. Finally, we have considered a migratory scenario only: perhaps some species interact with wind farms daily and the effects may be greatly increased for such individuals.

Acknowledgements

We thank the Finnish Ringing Centre for providing information on the locations of breeding and wintering eiders, and Thomas Kjær Christensen and Henning Noer for advice on eider breeding biology. Hawthorne Beyer and Ib Krag Petersen gave advice on spatial analysis, and Jan Kube made helpful comments on the manuscript. Data were collected as part of the Danish Demonstration Project running at the Nysted offshore wind farm, and it was funded by the Danish Public Service Obligation funds (PSO funds), which are financed by the small fraction of each consumer's electricity bill that is earmarked for research and development projects. ADF and MD were also supported by a grant from the Danish Strategic Research Council.

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doi:10.1093/icesjms/fsp031