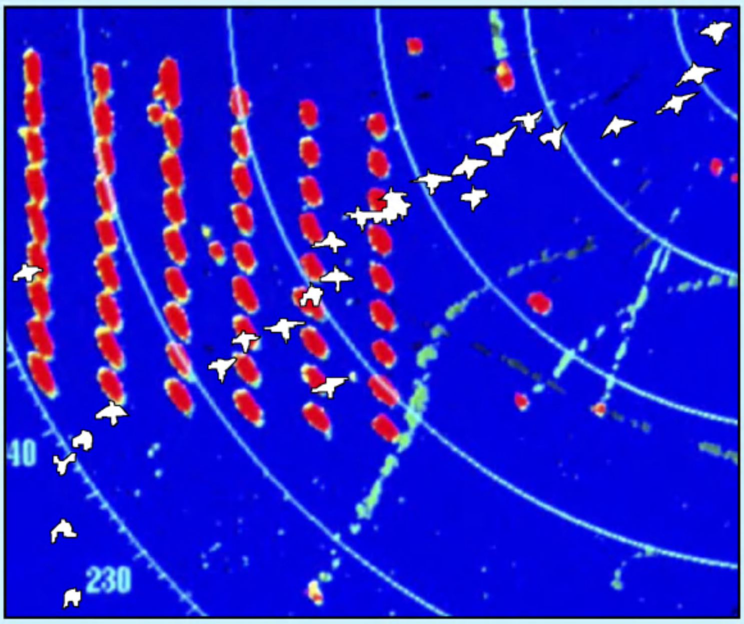
National Environmental Research Institute
Ministry of the Environment · Denmark

Wind farm related mortality among avian migrants

– a remote sensing study and model analysis

PhD thesis

Mark Desholm



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August 2006

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To you and our moon for lighting up my migration path

Data sheet

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Abstract: This thesis is the result of a PhD study on bird-wind farm collisions and consists of a synopsis, five published papers, one submitted manuscript and another ready for submission. The papers describe the findings from pre- and post-construction visual, radar and thermal imaging studies (1999-2006) of migrating birds at the Nysted offshore wind farm in the Baltic Sea, Denmark. This thesis poses and answers the following questions: a) what hazard factors do offshore wind farming pose to wild birds, b) how should one choose the key focal species to study, c) how can remote sensing techniques be applied to the study of bird wind farm interactions, and d) specifically, how do waterbirds react when approaching an offshore wind farm? The main aim of the study was the development of a predictive bird-wind farm collision model that incorporates the avoidance rate of birds at multiple scales. Out of 235,136 migrating sea ducks only 47 individuals were predicted to collide with the wind turbine rotor-blades, equivalent to an overall mean collision risk of c. 0.02%. This thesis shows the added value of modelling in supplementing sound empirical studies in accessing the effects of major human development pressures on migratory bird populations.

Keywords: collisions, birds, wind farms, radar ornithology, TADS, thermal imaging, avian migration, Nysted offshore wind farm, mortality, Denmark.

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Front page picture: Collage of a screen shot of the radar monitor showing six rows of wind turbines and four flocks of migrating waterbirds (red dots and green tails) and a thermal image recorded by the TADS showing 26 migrating Common Eiders (white silhouettes) flying towards the top of the picture. Mark Desholm.

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Preface

This thesis is the result of a 2½ year PhD study on bird-wind farm collisions and was carried out at the Department of Wildlife Ecology and Biodiversity, National Environmental Research Institute, Kalø and at the Institute of Biology, University of Copenhagen.

My thesis consists of a synopsis, five published papers, one submitted manuscript and one manuscript nearly ready for submission. The papers describe the findings from the visual, radar and thermal imaging studies (1999-2006) of migrating birds at the Nysted offshore wind farm in the Baltic Sea, Denmark. In addition to the strictly scientific output from the study, the project involved a strong developmental component which necessitated innovative approaches towards the choice of equipment, study design and framework for the analyses. The offshore marine location of the studied wind farm prohibited the use of standard carcass collection procedures normally associated with the study of wind farm-related mortality in birds on land and forced me to apply a modelling orientated approach.

Data were collected from visual observations, short-range surveillance radar and thermal imaging equipment and was analysed using GIS and standard statistics. The main aim of the study was the development of a bird-wind farm collision prediction model that incorporates the avoidance rate of birds at multiple scales. This thesis shows the added value of the modelling approach by not only providing an estimate for collision rate but also by helping the ecologist to understand the factors and processes governing the severity of wind farm related mortality.

Acknowledgements

First, and foremost, I want to express deep gratitude to all my colleagues at NERI-Kalø and at the University of Copenhagen for providing an always friendly and stimulating environment for our exciting research. I am particularly obliged to my two supervisors Tony Fox and Carsten Rahbek for generously sharing their scientific insights and friendship with me throughout my work – it is always serious and great fun to interact with the two of you – thanks. Carsten has always shared his office with me during my stays at the University of Copenhagen and his enthusiasm and ambitions (also on my behalf) were always a source of inspiration to good work. Tony kicked off my PhD study by stating "I will back you up to the hilt" – and even though I thought he said "hill" I felt very secure – and I was.

Thanks to Johnny Kahlert for fruitful co-authorship and for being my unofficial mentor during my first seven years at Kalø, to Henning Noer for connecting me with the wind farm PhD, to Preben Clausen for believing in me during my Master study, and to Ib Krag Petersen, Thomas Kjær Christensen, Ib Clausager and Karsten Laursen for wind farm discussions at Kalø.

I have also had the privilege to discuss my research and get inspired outside Kalø and little Denmark, so thanks to Morten Frederiksen, Kasper Thorup, Ommo Hüppop, Sjoerd Dirksen, Felix Liechti, Rowena Langston, Jan Kube and Sidney Gauthreaux for offering your time to me. Thanks to Sid and Carroll for looking after me during my visit at Clemson Universtity and for sharing your expertise on radar ornithology with me, I am looking forward to our future collaboration – in fact I can hardly wait. During my one month stay at the Department of Zoology, Norwegian University of Science and Technology in Trondheim, Bernt-Erik Sæther offered his time on my topics of interest – thanks for sharing your insight and views with me and for welcoming me into your group. I wish to express my gratitude to all my co-authors and referees of my manuscripts – without your input this thesis would not have been the same.

The many hundred of hours in the radar tower have been good fun, not least because of the good company of Søren O. Haugaard, Johnny Kahlert, Henning Kjørup and Ole Therkildsen. These studies could never had been performed without the practical help from the staff from ENERGI E2 A/S, Ebbe Bøgebjerg, Jens Peder Housisen, Henrik Quist, Martin Donnovan, Per from E2, Thøger Pauli, Hans Erik Dylmer and Charlotte Boesen – thanks for your help and good company. Thanks Ole for being my office room-mate for the majority of my PhD-period – what a lot of important talking we have done – I look forward to our Avian Flu-future.

Thanks to Thomas Damm Als for being my close friend also during the difficult times, for sharing your knowledge and excitement for research, and for all our discussions on how to write a good paper, design a good poster and especially on how to write a Nature-paper – I tried without success – you already did it – who knows, maybe we will do it in the future together? At least we know how to drink Islay whisky! Thanks to Jørgen Ravn for being my brother and friend, and for the lovely trip to Italy – a lovely break from the PhD with fly fishing in the rivers of the Alps and lots and lots of tasty coffee – it was here that I left the Kalø-coffee behind for good! Thanks to Søren O. Haugaard for all our deep and warm sun-set talks in the radar tower at Rødsand – I miss it. Thanks to Jan Riis, my only friend that is also a pilot, for our discussions on avian aerodynamics – a research field that is waiting for me in the near future – so Jan you will for sure receive many more stupid flight-questions from me.

Without exception, those with whom I worked gave me an abundance of wise and friendly assistance and encouragement, and I wish that there were space here to mention each by name – they, along with those unnamed, have my highest regard and my heartfelt thanks.

The PhD project was funded by my Institute. Thanks for investing in me.

Thanks to those scientists whose shoulders I am standing on – this is the true beauty of research – now I can just hope that my shoulders can be used by others in the future.

My always supportive parents, Birgit and Henning, that show up whenever we need somebody to take care of the girls when Daddy is sitting in his radar tower at sea or giving talks at conferences out there in the big world – thanks for all your love and support.

Finally, on the home front my little family is reminding me on a daily basis that life is not just about migrating birds, radars, infrared cameras and wind farms – so Lærke, Maj, Maggie and the new-coming little baby – you are the true meaning of my life.

1 Synopsis

1.1 Introduction

Europe rushes to exploit the wind energy potential of her seas, where at least 13,000 planned offshore wind turbines will contribute to achieving national Kyoto targets for sustainable development, safe from potential "Not In My Back Yard" protests on land.

In April 1996, the Danish government published a strategy for sustainable energy development, *Energy 21*, increasing the renewable share of domestic energy generation to c. 50% by 2030 (Paper I). Attaining this long-term aim necessitated a rapid expansion in capacity, hence five large offshore demonstration wind farms were proposed in 1999, two of which now contribute to the Danish grid. Their purpose was specifically to assess the engineering challenges, economic feasibilities and environmental impacts associated with such large offshore constructions, to guide future energy policy development.

The National Environmental Research Institute (NERI) undertook Environmental Impact Assessments (EIA) on bird populations for the proposed offshore Danish demonstration wind farms (commissioned by the power companies) involving an initial risk assessment to identify the critical avian species involved, their abundance, distribution, conservation status, vulnerability, seasonality and habitat use (Kahlert et al. 2000). Following the EIAs, the rationale has been to develop a programme of avian investigations during the pre-construction (c. 3 years), construction (c. ½ year) and post-construction phase (2-3 years) to detect changes in feeding distributions, migration trajectories, flight heights and relative volume of key species in time and space, taking into account annual variation in wind direction and strength, visibility, disturbance (construction, operation and maintenance) and time of the day (Desholm et al. 2003, Kahlert et al. 2002, Kahlert et al. 2004, Kahlert et al. 2005, Petersen et al. In press). Modelling of these parameters provides more refined predictions about the likely collision rates of particular species. Surveillance systems (such as remote-sensing infra-red video) have been developed to measure real time collision frequencies post-construction and are essential to provide modelling input data and to verify predictions from modelled impact rates (Desholm 2003, Verhoef et al. 2004, Desholm 2005a, Desholm 2005b, Paper II). The present thesis is based on the first post-construction study of avian collision risk at an large offshore wind farm (Petersen et al. In press). These results have been awaited nationally and internationally with some excitement, not the least because the effects of the construction of many large wind farms, in combination with other large-scale marine constructions, along the migratory corridors of bird populations are currently unknown.

1.1.1 Hazard factors presented to birds by wind farms

Several authors have summarized the different hazard factors presented to birds by the construction of wind farms (Langston & Pullan 2003, Hötker et al. 2004) but here I will use the theoretical framework developed in Paper I for offshore wind farms. Three broad classes of hazard factors can be identified (Fig. 1). These comprise:

1) a behavioural element, caused by birds avoiding the vicinity of the turbines as a behavioural response to a visual stimulus and/or sound stimulus;

2) a physical habitat element, where birds respond to destruction, modification or creation of habitat associated with turbine infrastructure construction; and

3) a direct demographic element, resulting from mortality arising from physical collisions with the superstructures.

Our Danish approach has been to attempt to quantify the physical effects of each of the three hazard factors on bird behaviour, abundance or distribution (Fig. 1). This helps to identify measurable parameters that can contribute to the measurement of local effects and feed directly into the local EIA process. Given the physical effects that arise from each of the hazard factors, the rationale has then been to determine the ecological effects on the birds, and in some cases translate these effects directly into additional energetic costs incurred as a result of the constructed wind farm. In some circumstances, changes in these energetic costs can be incorporated in individual behaviour-based models to determine the potential fitness consequences at the individual level, which can then provide a basis for assessments of the impacts at the population level (West & Caldow 2006). Hence, the ultimate impact or common currency for all three hazard factors will be the changes in overall population size. This necessitates the application of complex matrix population models in to which the wind farm related fitness consequences should be incorporated.

In the following I will focus on the collision mortality only at the Nysted offshore wind farm. This prioritisation should not be seen as a devaluation of the other hazard factors or of the collision issue at land-based wind farms, but it would be beyond the scope of this thesis to deal with all the potential hazard factors posed on birds by wind farms.

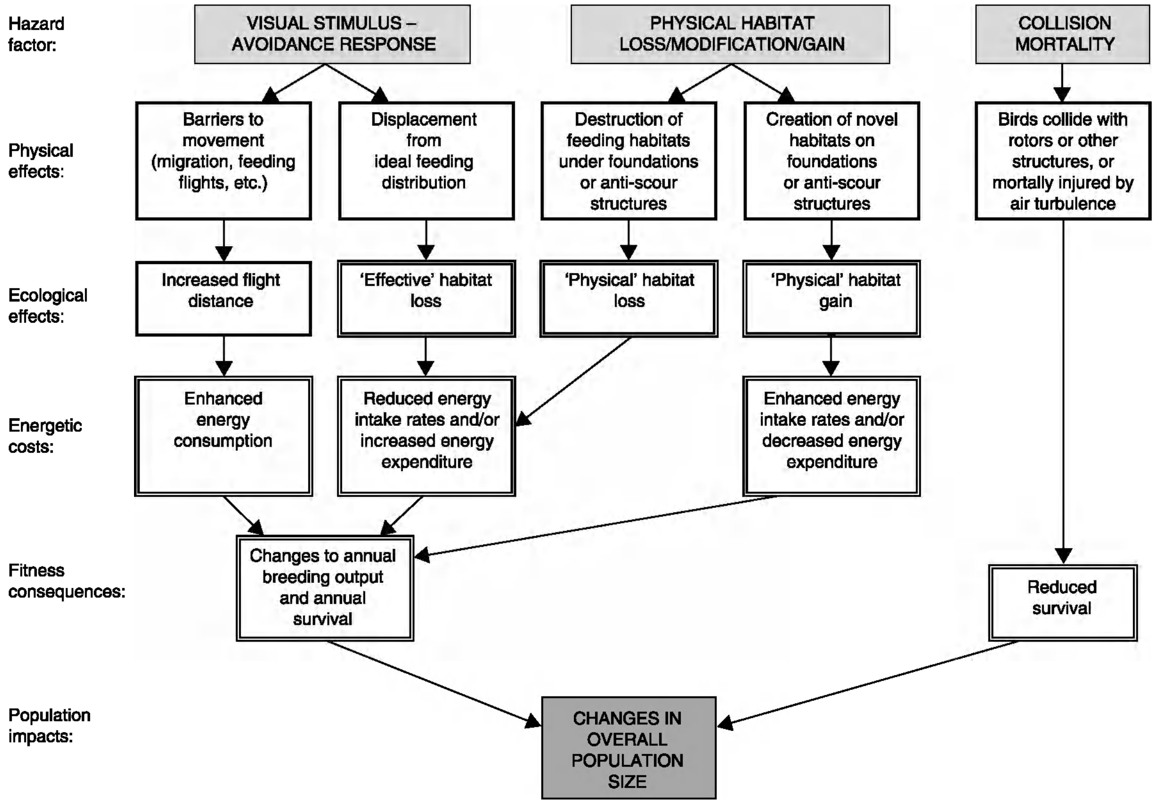

Figure 1. Flow chart describing the three major hazard factors presented to birds by the construction of offshore wind farms, showing their physical and ecological effects on birds, the energetic costs and fitness consequences of these effects and their ultimate impacts on the population level. The boxes with a heavy solid frame indicate potentially measurable effects, the double framed boxes indicate processes that need to be modelled and the dark box represent the common currency by which all adverse effects can be compared (adopted from Paper I).

1.2 Collision risk for avian migrants

Wherever a wind turbine is erected, birds will collide with it, and thus, the interesting question is not whether collisions will occur or not, but more "what is the magnitude of these wind farm related casualties?". Birds can either collide directly with the static (i.e. tower, foundation) or moving parts (i.e. nacelle, rotor-blades) of the super structure of the turbine or get hit by the wake (i.e. turbulence) behind the sweeping rotor-blades. The only study I am aware of that have been dealing with the wake-collision issue is the famous study by Winkelman (1992), who estimated that about 20% (n=16) of the casualties were due to turbulence.

However, the mortality rate will be far from uniform at a given spatial and temporal scale. First of all, the number of collisions will be directly proportional to the migration volume which shows high variability between sites, seasons, individual turbines and weather conditions. Some sites are situated at migration bottlenecks (e.g. peninsulas or straits) and therefore stand out as migration "hot spots" compared to more topographically uniform areas where "broad-front" migration is more evenly distributed (Alerstam 1990, Kjellén 1997). The strong seasonality of avian migration patterns naturally influences the migration volume throughout the year (Alerstam 1990), and hence, the collision rate of migrating birds will be highest during the spring and autumn migration periods. Even at the scale of a wind farm huge differences in migration density can exist between individual turbines also at sea (Petersen et al. In press). As with aircraft, the flight performance of avian migrants is highly influenced by weather conditions, where especially wind and precipitation play important roles in the decision-making process of birds, whether to migrate or stay grounded (Erni et al. 2002). In general, head wind and heavy precipitation are known to reduce migration volume (Alerstam 1990, Åkesson & Hedenström 2000, Liechti 2006). Furthermore, sudden changes in weather conditions, e.g. from good to adverse migration weather, will force migrants aloft to descent to lower altitudes (see the example from the Öresund bridge in Nilsson & Green 2002) and so enhance the collision risk with wind turbines. Among scientists there exist a general consensus that collision risk between birds and wind turbines will be highest during periods of poor visibility (Paper II and references herein). The simple explanation for this hypothesis is that birds that can not see the turbines can not avoid them. As we will learn during the course of my thesis this simple hypothesis may not account for reality amongst all bird species.

Figure 2. Photograph showing the study area with the Gedser Odde peninsular in the upper left corner pointing towards the south. The sandy island of Rødsand can be seen together with the radar tower in the centre of the picture. Photo: Jonas Teilmann/NERI.

1.2.1 Methods

Study area and the birds

All data presented in this thesis originate from the environmental study conducted by the Danish National Environmental Research Institute at the Nysted offshore wind farm in the Baltic Sea, Denmark (Petersen et al. In press and references herein). The study area is well known for its high concentrations of autumn migrating waterbirds and landbirds around the Gedser Odde peninsular (Fig. 2 and Fig. 3) and is situated in the southern part of Denmark (Fig. 3).

Landbirds (a minimum of 200,000 passerines and 15,000 raptors) depart from Gedser Odde mainly towards to south-south-west and c. 240,000 Common Eiders mostly follow the east-coast of the peninsular before making a westward 90-degrees turn when reaching the southern tip of land (heading directly towards the wind farm area; Fig. 3; Paper IV; Kahlert et al. 2000, 2002). Hence, from both a land- and waterbird point of view, the southern tip of Gedser Odde can be characterized as an autumn migration "hot spot".

From the outset of the study we realized the need to focus our attention and direct the (always) limited resources towards the most vulnerable species in the area. However, I recognized the need for a quantitative tool for assessing vulnerability, and hence, I developed a general framework for setting management priorities by categorizing species according to their relative vulnerability to wind farm related mortality (Paper III). The presented Environmental Vulnerability Index (EVI) was composed of an abundance indicator and a demographic indicator, two indicators believed to characterize the vulnerability of each species. In general, the waterbirds and raptors dominated the upper ranks of both indicators, and thus, since the raptors mainly head south-west from Gedser Odde (Fig. 3), waterbirds were chosen as the focal group of species with emphasis upon the decreasing population of Common Eider (Desholm et al. 2002) as the overall critical species. For this reason, my thesis will focus on autumn migrating Common Eiders at the study area at the Nysted offshore wind farm.

The tools

Wind turbines and even relatively large wind farms are nothing new in Denmark and in developed countries world-wide, but to date, wind power development has been an almost exclusively land-based phenomenon. Hence, many studies have been performed on the interactions between wind turbines and birds on land where the collision issue can be studied by search

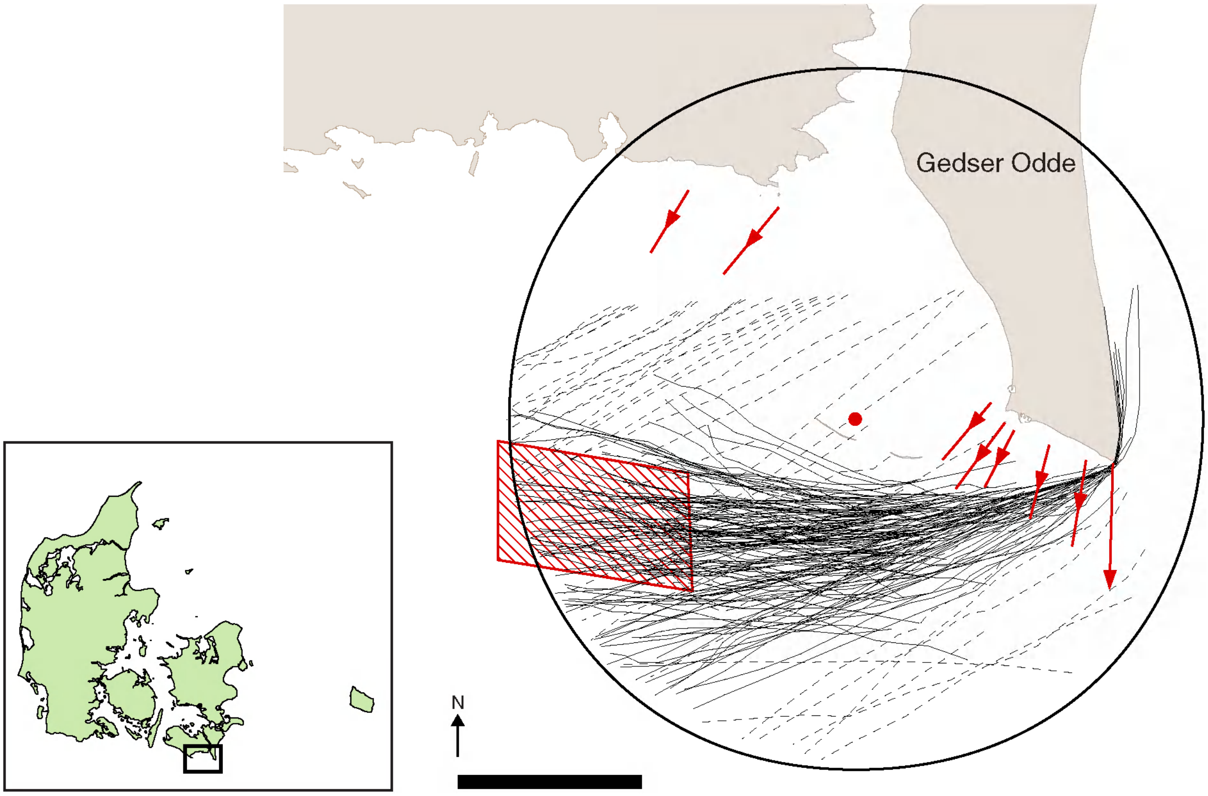

Figure 3. Map showing the area around Gedser Odde peninsula, Denmark and a presentation of autumn pre-construction migration pattern of geese (black broken lines) and Common Eiders (black lines) as recorded by radar and a theoretic presentation of the landbird migration pattern (red arrows). The Nysted offshore wind farm area is depicted as the red striped area, the radar tower as the red dot and the radar range as an open black circle. Scale bar, 5000 m (Redrawn from Paper III, IV, and VII).

protocols for collision casualties (Pedersen & Poulsen 1991, Langston & Pullan 2003 and reference herein, Barrios & Rodriguez 2004). Even though the ecologist has to consider the corpses removed by scavengers, this approach offers a straightforward method of measuring collision rates at a given spatial and temporal scale. However, we were faced with the challenge of dealing with the collision issue in the rather harsh environment of the Baltic Sea where the site for the Nysted offshore wind farm was proposed (Fig. 4) and where avian casualties most likely would either sink or drift away with the very unpredictable sea currents. Consequently, after long and extensive deliberations we decided to use radar and thermal imaging as our remote sensing techniques. Paper II gives an extensive review of the different remote techniques for counting and estimating the collision rate and was presented at the BOU Conference "Wind, Fire and Water" in 2005 (which can be accessed free online in the proceedings volume of Ibis at http://www.blackwell-synergy.com/toc/ibi/148/s1). We collected behavioural data on the migrants both pre-construction, during construction and post-construction. These behavioural data, especially on avoidance reactions, could then feed into our collision prediction model that would provide us with an estimate on the collision rate at our study site. Finally, it was our intention to use the thermal imaging equipment to also measure directly the actual collision rate, by automated monitoring, for use in the process of validating the modelled estimates.

Figure 4. Photo showing the Nysted offshore wind farm from the radar tower. Photo: Mark Desholm/NERI.

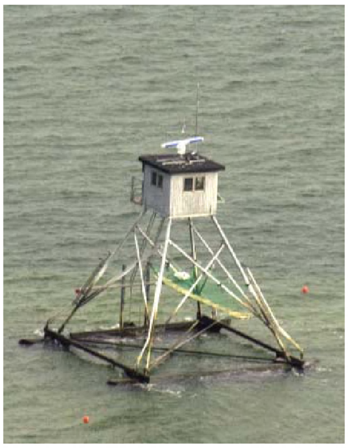

Figure 5. Aerial photo of the radar tower used during the environmental studies at the Nysted offshore wind farm. Photo: Jonas Teilmann/ NERI.

Figure 6. Installation of our marine surveillance radar at the Horns Rev offshore wind farm, Denmark. Photo: Thomas Kjær Christensen/NERI.

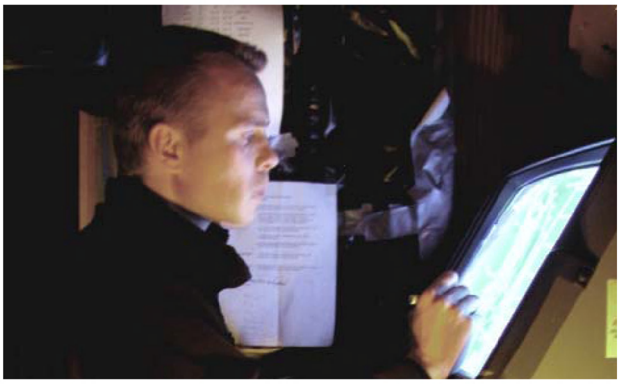

Figure 7. A radar ornithologist at work during the darkness of the night. Ole is taking his turn whilst I am trying to get some sleep in the radar tower. Photo: Mark Desholm/NERI.

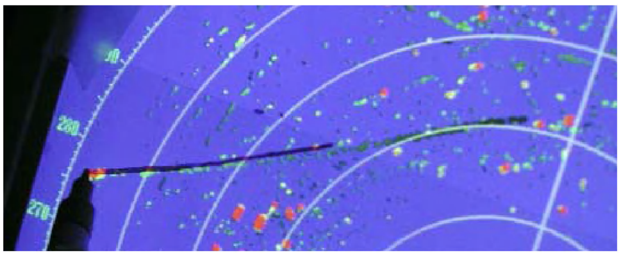

Figure 8. The migration trajectory of a flock of migrating waterbirds is mapped on to a transparency directly from the radar monitor. Photo: Mark Desholm/NERI.

The first challenge was how we should get out there at sea. We needed some kind of platform from which to operate our radar and from where visual observations could be performed. Employing a ship or fishing vessel as a radar platform is significantly constrained by the instability due to waves that results in heavy sea clutter on the radar monitor which makes data collection very difficult (Paper II, Blew et al. 2006). It was decided to re-use the tower (Fig. 5) designed by Ebbe Bøgebjerg that was used in former years for the bird studies at the Tunø Knob wind farm. The water tanks of the tower was emptied and it was sailed to the study area, where it was placed on the sandy sea bottom north of the island of Rødsand approximately 5 kilometres from the proposed wind farm area (Fig. 2 and 3).

The 8 ft t-bar radar antenna was mounted on the roof of the tower (Fig. 6) and the monitor of our X-band 25kw surveillance radar was installed inside the little cabin on top of the tower (Fig. 7). The radar was operated in horizontal mode which provided information on the spatial distributions of migrating flocks of birds but no data on the vertical distribution.

Using a surveillance radar in the vertical mode (like the rotor-blades of the wind turbine) would provide altitude data on the migrants but is again heavily constrained by sea clutter that mask the lower 0-100m altitude level to an unknown degree (Blew et al. 2006). Other types of radars (e.g. tracking radar or long-range Doppler radar, Paper II) can also provide vertical distributions but for various reasons the use of these radars were not feasible in the present study (Paper II). The flight trajectories of migrating waterbirds were traced onto a transparency (see the front page photograph and Fig. 8) and later digitized and transposed onto a GIS for spatial analyses (for further details see Paper V and VII).

The idea of using the thermal imaging technique for studying the behaviour and collision rates of avian migrants came from the Dutch study done by Winkelman (1992). These sensors are sensitive to heat radiation and can therefore produce visible pictures and video sequences of animals (Fig. 9) even during total darkness and during situations with poor visibility due to fog and precipitation (Desholm 2003, Paper II).

However, we had to develop a special application of a thermal video camera which: 1) could be mounted on the outside of an offshore wind turbine (Fig. 10), 2) should be controllable remotely via the optic fibre cables from the wind farm to land and then via the Internet, and 3) should be automated in a way that ensured that only video sequences of birds either passing or colliding the wind turbine would be stored on the computer hard-disk inside the turbine tower (Fig. 11). The system we developed during the first years of the study was named Thermal Animal Detection System and is now known under the acronym TADS (Desholm 2003, Langston & Pullan 2003, Drewitt & Langston 2006, Paper I, II, VI, VII).

Figure 9. Thermal images of living animals. Upper left: a flock of Pintails *Anas acuta* at a distance of c. 70 meters; upper right: a flock of Common Eiders migrating at a distance of c. 120 meters; lower left: a bat showing its characteristic sharp turn (image showing a whole array of frames grabbed by a video peak store at Clemson University, Radar Ornithology Lab); lower right: the happy author with his beloved hot (56.3°C) cup of coffee.

Figure 10. The TADS mounted on one of the turbines at the Nysted offshore wind farm. The pan and tilt head is set for vertical collision monitoring. Photo: Mark Desholm/NERI (adopted from Paper II).

Figure 11. The TADS-computer inside the tower of the monitored wind turbine. Photo: Mark Desholm/NERI.

I would characterize Paper VII, that deals with our predictive collision model, as the finale of my PhD study with the six other papers leading up to it. First we presented the framework for our predictive collision model as a deterministic version in Paper II and after its further development to a stochastic model, that takes the variability of input data into account, it is used in Paper VII for a stochastic model analysis of the collision risk at the study area. The conceptual diagram of the model can be seen in Paper VII and shows the different state variables and the external variables and how these components are interrelated by mathematical formulations of processes. During every iteration of the model a wind direction was sampled since it influenced both the orientation of the rotor-blades and the probability of passing safely the sweeping area by chance (Tucker 1996). The model estimated the number of autumn migrating Common Eiders colliding with the 72 turbines in the study wind farm. The rationale behind the modelling approach is that we, besides producing an estimate of the number of collision casualties (like in carcass collection studies), also gain insight in to the factors and processes that govern the collision pattern experienced at a given wind farm. The latter information is of added value since this is the kind of knowledge that is needed for developing mitigating measures if the anthropogenic impacts on the studied population turns out to be significant and we therefore face the challenge of counteracting any adverse effects.

1.2.2 Results

General migration pattern

Already after the first autumn seasons it became apparent, as shown in Paper IV, that the geese and Common Eiders were showing very different migration patterns when passing our study area. The Common Eiders were funnelled in a southern direction by the Gedser Odde peninsula to its southern tip were they performed a more or less 90-degrees turn directly towards the proposed wind farm area in the western direction (Fig. 3). In contrast, the geese had a more broad-fronted migration pattern extending over the land of Gedser Odde and with a general heading towards south-west. The causal factor governing this difference in migration pattern is most likely the marked difference in flight altitude with the geese flying generally higher compared to the Common Eiders, and hence, the geese were less influenced by the topography of the coast. Again, Common Eider was an obvious candidate as our focal species due to its concentrated migration pattern heading directly towards the proposed wind farm area and in heights also occupied by the sweeping rotor-blades of the turbines.

One of the first questions that came to us, when sitting in our radar tower mapping the migration trajectories of the waterbirds, was why some flocks tended to fly in a zigzag-like pattern rather than on a straight path? And could it inflict on the collision rate estima-

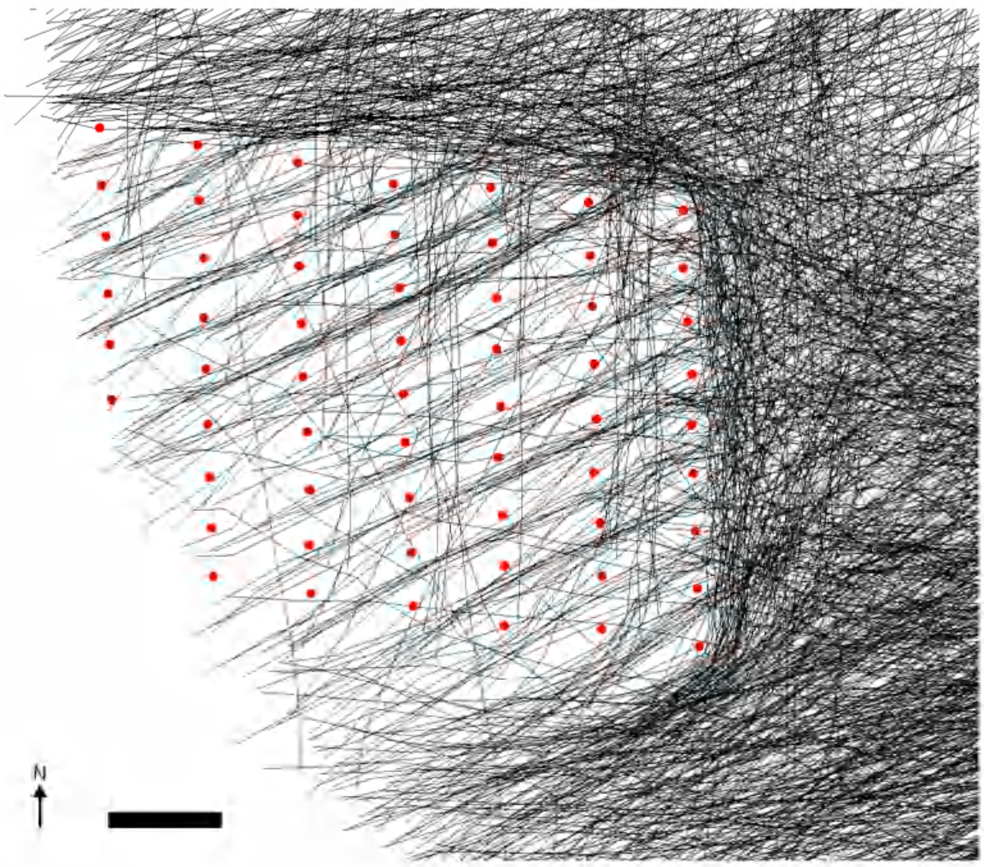

Figure 12. Map showing the south-west orientated flight paths of autumn migrating waterbirds during the period of initial operation (Adopted from Paper V).

tion by making the angle of approach, in relation to the orientation of the rotor-blades, more or less unpredictable? In Paper IV, I analysed the radar trajectories and found that flight paths were remarkably similar to straight lines in general and that this zigzag-like behaviour observed in some flocks was most probably caused by the birds compensating for wind drift. Hence, the conclusions from Paper IV did not change the framework of the collision model however certainly questioned the hypothesis that birds change their heading (orientation of the body) when compensating for wind drift (Richardson 1990, Liechti 2006). This very interesting topic of avian navigation, interesting at least to me, will be one of my near future scientific challenges which I am looking very much forward to study into further detail.

Avoidance behaviour

After the first year of the post-construction period (also named initial operation) we decided to publish the first preliminary results of our radar study (Paper V). This was because we judged that our findings could help researchers in the process of designing pre-construction studies at the many proposed offshore wind farms throughout Europe. First, we found that the percentage of flocks of waterbirds entering the wind farm area decreased significantly by a factor of 4.5 from pre-construction to initial operation. Second, it turned out that a significantly higher proportion was entering the wind farm area at night-time compared to day-time but that the night migrating individuals counteracted the higher collision risk when flying in the dark by maintaining greater distances to individual turbines. However, statistics were not at all necessary for convincing the public and the scientific community that the waterbirds passing the Nysted offshore wind farm indeed were, to a very high degree, avoiding the wind farm as a whole and that those birds passing the wind farm area in general were doing so by flying down the corridors between turbines (Fig. 12). I guess this figure speaks for it self.

Since the vast majority of the bird-wind turbine collision studies has relied on searches for casualties only very few studies have produced proper estimates of avoidance rates (Winkelman 1992, Paper VII). In fact, most studies using collision models has used indirect estimates of avoidance rates from the literature. However, this approach is heavily constrained as shown in Paper VI where we critically examined three case-studies dealing with the estimation and use of avoidance rates in conjunction with collision risk models. We showed that the sensitivity of predicted mortality to errors in estimated avoidance rates is far higher than any other variable of the models. Even when all other parameters were changed simultaneously by 10%, the predicted mortality increased only by 52%, compared to a 2613% increase when only the avoidance rate was lowered by the same proportion (10%). In Paper VI, we suggested that the value of the current models in estimating actual mortality rates is questionable until such time as species-specific and state-specific avoidance probabilities can be better established.

Model analysis of collision risk

In Paper VII we pulled together all available information on the migration pattern and avoidance behaviour of Common Eiders in the study area and adopted some variables from external sources and constructed a stochastic collision model. The aims of this paper were three-fold: 1) to compile information to build a stochastic predictive collision model for avian migrants that includes avoidance behaviour, 2) to validate this model by measuring the number of collisions directly using a thermal imaging system, and 3) to assess the importance of the avoidance factor in collision predictions.

One of the challenges of estimating the collision rate was how we should obtain measures for the migration altitude and the potential vertical avoidance reaction by the Common Eiders. Flight altitudes were estimated by the use of horizontal TADS video sequences showing flocks of birds passing in between the turbines. Flight altitudes were estimated from the distance and vertical angle to each flock of birds by trigonometry. The Common Eiders were flying lower inside the wind farm compared to outside with the percentage of flocks flying below the rotor-blades (<30m) of 84.2% and 55.7% inside and outside the wind farm, respectively.

Another interesting and new insight into the avoidance behaviour of avian migrants was the discovery that Common Eiders tended to minimise the number of rows of turbines crossed when passing through the wind farm by taking the shortest route out of the wind farm. This reduced the number of rows they crossed, from a mean of 6 rows pre-construction compared to 4 rows post-construction. Obviously, this additional and unexpected avoidance behaviour was factored in during the construction of the model.

The model analysis estimated an average (±SD) number of 47.1 (±46.2) migrating Common Eiders colliding during each autumn season (Paper VII). The vast majority of the modelled autumn seasons had less than 100 casualties but as can been seen in figure 13 the variation between seasons are substantial ranging from 0 to 321 casualties. Hence, the general risk of collision for Common Eiders passing the study area at Nysted was estimated to lie between 0.020% and 0.021%. The model analysis revealed that 94.6% of the birds, that would collide in the hypothetical situation without any avoidance behaviour, do actively avoid a collision in the real world. Finally, leaving out the avoidance factor at all spatial scales resulted in a 1749% increase in estimated collision numbers with complete avoidance of the wind farm having the highest impact alone (270% increase).

Sixteen thermal video sequences were triggered automatically by animals passing the field of view of

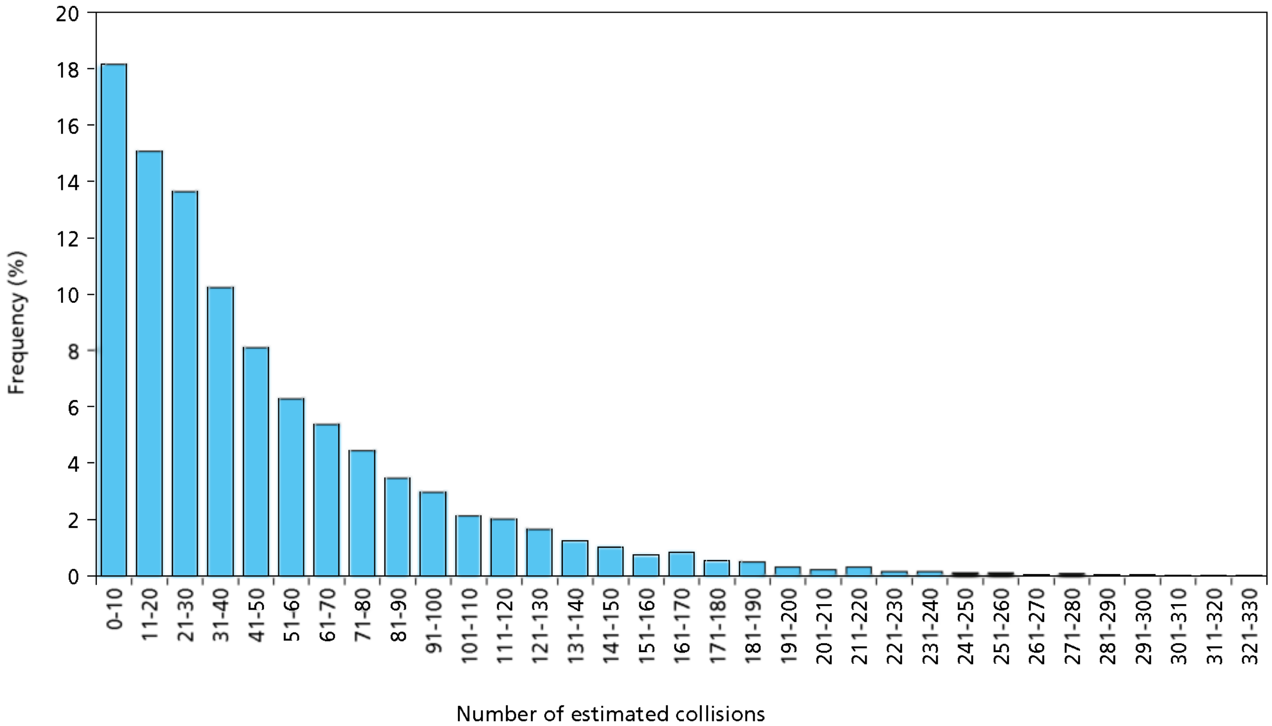

Figure 13. Frequency distribution showing the number of estimated collisions per autumn season for the Nysted offshore wind farm. A total of 10,000 iterations of the stochastic collision model were applied (Adopted from Paper VII).

the TADS during the slightly more than 2000 hours of collision monitoring and only one proved to show a collision event of a bird or bat (Paper VII). The remaining 15 non-collision sequences could be ascribed to 10 birds/flocks of birds, two bats, one moth and two birds/bats. The bat observations are especially interesting since bats have, until now, been very rarely observed at sea. Because of the low overall collision rate and the restricted TADS-coverage (only one operational set-up covering c. 1/3 of the area swept by the rotor-blades of one turbine) a thorough validation of the predictive collision model proved difficult. However, a comparison of the results of the stochastic collision model and the TADS monitoring scheme confirmed each other in concluding that the average number of collision per turbine per autumn lies in the order of magnitude of less than 10 casualties.

1.2.3 Conclusions & discussion

Prioritization between species

One of the important conclusions from this study is the importance of prioritization among species when designing a bird-wind farm study. Trying to embrace all species is simply not a feasible option and now we have a relatively easy-to-use prioritization framework (Paper III) to help informing this prioritization process. The outcome of the prioritization work for the Nysted wind farm data (Paper III) came as no surprise since many scientists in general have agreed that large and slow reproducing species like e.g. raptors and large bodied sea ducks are the most vulnerable to wind farm related mortality. Even though passerines might be present in very high numbers at individual migration "hot spots", the birds present very often represent insignificantly small segments of huge reference populations that, from a demographic point of view, are relatively insensitive to wind farm related adult mortality (Sæther & Bakke 2000). However, now managers and scientists have yet an other tool for their environmental study tool-box, and thus, now we can base our prioritization on an objective scientific basis instead of intuition.

We can now, based on a substantial amount of remote sensing data, draw conclusions on waterbirds in general and on Common Eiders in particular. However, I would like to emphasize here that before solid conclusions can be obtained, complementary studies at other sites are needed to confirm our findings, to include possible habituation behaviour over the years to come, to look at the effects of other wind farm designs, and to cover other focal species such as other sea birds and land-birds.

Wind farm related mortality

Our modelled estimate of 47.1 Common Eiders colliding per autumn equals 1.4 collision per turbine per year if we assume that the collision risk is equal during the two migration seasons. This figure lies within the published collision estimates for other wind farms worldwide which in general are low, i.e. between 0 and 54 casualties (Karlsson 1983, 1987, Langston & Pullan 2003). Our results are valid for one species only, so the overall collision rate would be highly elevated if all species migrating through our study site were taken into account.

A very high proportion of the published studies predict less than 1 casualty/turbine/year (e.g. Winkelman 1985, SEO/BirdLife 1995, Osborn et al. 2000, Lucas et al. 2004, Pettersson 2005), a little less in the intermediate interval with 1-10 casualties/turbine/year (e.g. Still et al. 1996, Johnson et al. 2002), and only very few at the upper interval with more than 10 casualties/turbine/year (e.g. Everaert et al. 2002, Drewitt & Langston 2006). Erickson et al. (2001) estimated the overall national collision rate to be 2.19 casualties per turbine per year for the whole US.

Although providing a helpful indication of collision rates, annual average collision rates per turbine must be viewed with some caution as they are often cited without variance and can mask significantly higher rates for individual turbines or groups of turbines (Drewitt & Langston 2006). A low average can be the result of a very high number of turbines as is the case with some of the best known cases with significant impacts on raptor species from the Altamont Pass in the USA (Orloff & Flannery 1992) and Tarifa in Spain (SEO/BirdLife 1995). Here, the average annual number of fatalities per turbine were generally low, ranging from 0.02 to 0.15, but the overall collision rates were high because of the large number of turbines involved (more than 7,000 at Altamont, Drewitt & Langston 2006). Furthermore, the annual collision rate per turbine is a very site specific figure, which means that result from one study site very rarely can be used as a predictive tool in a pre-construction situation at another site unless conditions (species composition, topography, design of turbines and wind farm) are very similar. It is my hope that the alternative predictive stochastic collision model with avoidance rate, as presented in Paper VII, will be implemented as a standard management procedure also at land-based wind farms because it in addition to the collision estimate also provides us with the causal relationships governing the observed collision patterns.

Avoidance factor

The ability of birds to avoid a collision is a very complex issue. First of all, it is almost certain that the avoidance factor to be used in predictive collision models will have to be species specific at least between species groups. This is because different species or groups of species have different eyesight, vigilance range, manoeuvrability (important only for last second avoidance behaviour), and perception of risk. These species specific characteristics may themselves be dependent on other external factors like the weather conditions (e.g. visibility and wind), turbine design (colour and size), wind farm design, the flock size (may influence risk perception among individuals) and age. However, at present it is premature to subject the avoidance factor to such a detailed level of analysis since very few studies have actually provided robust and directly measured estimates of the avoidance rates. The present thesis (Paper VII) provides an average avoidance rate estimate for Common Eiders and shows how the evasive behaviours at the different spatial scales result in the observed high avoidance rate.

Estimates of avoidance rates on land have been derived from the ratio of mortality (estimated from corpse searches) to the estimated number of birds flying in the risk area. However, both of these estimates are subject to considerable error, which will have a large effect on the precision of mortality estimates (Paper I, VI). As more and more wind farms are proposed for offshore areas, researchers will face the challenge of measuring avoidance rates directly as we have done in our study. Nevertheless, even though the challenge may seem overwhelmingly large the present thesis (see Paper II) provides advice on the use of remote applications, which extend the capabilities of the researcher (acting as her/his own extended arms and eyes), to collate the necessary data. For my part, using radar and thermal imaging proved to be one big adventure. Suddenly, I could follow my beloved flocks of birds for miles and miles even after sun-set when the bird ecologist had normally gone home to sleep. The TADS (Thermal Animal Detection System) was my remotely controlled "eye" within the wind farm for more than two years and its heat sensible detectors ensured me that the darkness of the night did not constrain my research.

So now after showing the importance of the avoidance factor and demonstrated how relatively easy it can be estimated through the use of remote technologies, I would like to emphasise, as we have done in Paper VI, that avoidance rate studies should be carried out as a matter of urgency. The value of the pre-construction prediction models presented by Band et al. (In press) and Tucker (1996) in estimating actual mortality rates is questionable until such time as species specific and state-specific avoidance probabilities have been better established.

The issue of lights

Offshore wind farms require navigation lights under legislation relating to maritime and airborne traffic and at the Nysted offshore wind farm red flashing or red continues light are mounted at the nacelle of each turbine. In conditions of poor visibility, passerines especially tend to be drawn towards continuous lights, which may substantially lower avoidance rates and thereby elevate collision rates (Hansen 1954, Kerlinger 2000, Jones & Francis 2003). On the positive side, our study shows that avian migrants can benefit from the lighting of the turbines when migrating during the darkness of the night. They can see the turbines when illuminated and therefore they also have the possibility of avoiding them.

According to Kerlinger (2000), no studies have documented the difference in collision risk caused by various lighting systems, although several researchers stated that white strobes were likely to be less risky than white or red blinking lights. This topic of avian migration research offers an obvious choice for a future study where our knowledge of the application of radar and thermal imaging could easily provide us with data on the effects of the different light system (e.g. contrasting colours and strobe frequency).

Cumulative impacts

Whilst this thesis has shown that it is possible to estimate collision rates at turbines using a combined remote sensing and model approach it is also essential to undertake population modelling (incorporating different strengths of density dependence) to assess the impact of those collision rates at the population level for the different species of interest. This is especially important to enable the assessment of the potential cumulative impacts of more than one wind farm development along the flyway corridor of a given population. This can be achieved by using modelling tools and the skills available to hand at present. For example, by using Leslie matrix models (Caswell 2001; as done in Paper III). The structure of such models will have to be much more complex to embrace population specific demographic data, including density dependence. Unfortunately, these kind of data exist for very few species and if data have to be collected before the analyses can be performed, such studies will be highly time consuming. This because the collection of robust demographic data, especially if the important stochastic dynamics are to be known as well (Lande et al. 2003), is a very time consuming process, at least for long lived species such as my focal species, the Common Eider. To my knowledge, the only study so far to produce a thorough population model analysis of the impact from wind farm related mortality is that on Golden Eagles at the Altamont Pass Wind Resource Area by Hunt (2002).

The environmental vulnerability index presented in Paper III could play an important role in deciding which potential species to focus upon in future population impact studies and the remote sensing and collision model approach presented in Paper VII could then inform the decision process as to whether such a population modelling exercise is actually necessary.

To put the estimated annual collision rate of 94 (2x47) Common Eiders (Paper VII) into perspective a comparison with other anthropogenic mortality factors seems appropriate. It would take 745 wind farms with the same local mortality as at the Nysted offshore wind farm to equal the c. 70,000 Common Eiders bagged annually by the Danish hunters (Asferg 2005). In fairness, it must be concluded that the mortality impact from the Nysted offshore wind farm on the population of Common Eider is relatively low and this is also why no such complex population modelling study has yet been performed.

Future challenges

The area of bird-wind farm collision research and monitoring is a very urgent priority for the future, both with regard to identifying the limits of collision risk models during the EIA stage and to gather data on actual collision rates post-construction, to test the validity of the predictive methods.

I recognize a tendency for proposed offshore wind farms to be sited further and further ashore. From a bird's point of view this is a positive development since this in variably means that the food items of diving ducks will be well beyond their normal range of diving depths (i.e. the birds will not forage in these distant areas) and because migration density generally seems to decrease with distance from the shore (because no topographical features exist in exclusive offshore areas to funnel or concentrate migrants). Thus, I expect the collision risk to be lower as the wind farms move further offshore in the future. However, the long distances to land also means that future EIAs will be constrained by the absence of suitable observation platforms. It will be essential, despite cost implications, to gather adequate pre-construction data (e.g. by the use of radar and TADS) to support well-founded EIA development. In Germany, the FINO 1 research platform is an excellent example of such an approach where researchers get access to the study area in due time for conducting a proper pre-construction study (Dierschke 2004). Other mounting solutions for radar and thermal imaging devices could be the frequently used weather masts (data must either be transferable to an anchored vessel or to land via optic fibres) or a jack-up barge (stable but will always be limited by their availability or high costs of hire; Paper II). Thus, I would strongly urge that due consideration is given to the establishment of observational platforms at the sites of future offshore wind farms.

The radar ornithology work presented in the present thesis was conducted with an "off-the-shelf" marine surveillance X-band radar (for a detailed review of radar hardware see Paper II). Several companies are selling modified marine radars for ornithological research and some have even integrated a vertical operated X-band and a horizontal S-band radar in one single unit. However, it has proved very difficult to integrate the two systems fully to adequately track all flight trajectories of birds detected in all three dimensions (Desholm et al. 2005, Paper II). Just like in the early 1970's when rapidly increases in the frequency of collisions between birds and aircraft attracted a great deal of attention on avian migration (Alerstam & Ulfstrand 1972) the rapid development of wind power production today has significantly increased the interest for radar ornithology. The time is right to fund the development of a dedicated bird radar targeted exclusively at detecting flying birds and aimed at obtaining streamed data collection on three-dimensional trajectories and wing beat frequency (Desholm et al. 2005).

In the near future strategic and larger-scale studies will be initiated in Europe (in Denmark such a study by NERI was initiated in 2006) and the US, aimed at gathering information on the general migration patterns in different regions, enabling a more strategic, scientific planning process for the future siting of large off-shore wind farms. The high-powered tracking and Doppler radars might prove to be the best option for such generic studies (Eastwood 1967, Alerstam 1990, Gauthreaux & Belser 2003).

Another methodological issue could be the development of a low cost sensor-system for detecting the impact from bird-turbine collisions for large-scale implementation in every turbine within future wind farms (see a discussion of this topic in Paper II). It could be based on the piezoelectric technology that can detect acoustic vibrations in materials like vibrations arising from the impact of birds hitting the rotor-blades, nacelle or tower construction. This could give the ecologist a spatial and temporal description of collisions over the course of several years. Of course it would not tell us anything about species composition and avoidance rates but used in combination with visual observations, radar and thermal imaging it would be a powerful tool for the wind farm ecologist tool-box.

It could be of great value to perform terrestrial validation tests of the TADS, so that the collision measures from this remote technology could be verified by carcass collection on the ground. Such a test study would also provide us with data on the avoidance and attraction behaviour of land-birds in relation to wind turbines which could be of high value for pre-construction predictions of land-bird collision risk in the future.

Last but not least, the many proposed mitigation measures has to be verified before they can be relied on in pre-construction management plans. Thus, well designed research programmes must be initiated as soon as possible to ensure that the mitigation tools are available for the expected near coming extensive off-shore wind power development in Europe and the US.

1.3 EIAs, SEAs and the role of applied science

Clean renewable electricity from offshore wind power offers some relief from our energy addiction to fossil fuels, but must we pay a high cost to maritime birdlife to save the planet? There is no reason why we should. Statutory safeguards exist under European Union Directives on Birds (79/408/EEC) and Strategic Environmental Impact Assessments (2001/42/EC). Even if we know less about offshore birds than most terrestrial species, recent experience from Denmark shows that we increasingly possess the tools to provide adequate environmental impact assessment (EIA) of marine wind farms (Paper I, Petersen et al. In press).

By always following the avoidance, mitigation and compensation hierarchy (Langston & Pullan 2003) when managing the wind power development in European waters we can ensure both the production of green energy and a healthy and sound avifauna simultaneously. First, on a national or regional level proper strategic environmental assessments (SEA) should inform the process of spatial planning of large developments like offshore wind farms to deal with the first step of the hierarchy, the avoidance of conflicts. These SEAs should include large-scale radar mapping of main migration corridors (Gauthreaux & Belser 2003) and aerial or ship transect-based surveys (Garthe & Hüppop 2004, Petersen et al. In press) of main staging areas for sea birds. Such distributional maps of birds are the prerequisite for a solid scientific-based site selection procedure that can ensure that important bird areas are avoided. Unfortunately, such SEAs are very rarely performed and almost never on a scientific basis. On a smaller scale the EIAs can also help avoiding sites within avian migration "hot spots" by offering advice on optimal sitings from several proposed locations within a SEA designated larger wind development area. Second, if post-construction monitoring programmes reveal significant negative impacts on bird life, despite the efforts to accommodate the most sensible siting, mitigating actions should be initiated to lower the level of impact. However, without knowledge of the behaviour of birds interacting with offshore wind farms such measures has to be based on intuition only. I would like to emphasise the important role of applied science in delineating which of the many proposed mitigating measures actually do lower the impact level. Finally, if the impact level cannot be lowered sufficiently by the mitigating measures the third step of the hierarchy must be applied. Now the wind farm related mortality must be counteracted through compensation which, though rather controversial, can ensure the sustainability of the wind power production at least for some species. An adverse collision mortality could be compensated for by lowering the mortality of the species of interest. This could be done through additional hunting regulations or more indirectly via habitat restoration (e.g. by decreasing the human exploitation of bivalves which is the food base of many sea ducks). This three step hierarchy should not be dealt with on an ad hoc basis, but rather through a detailed management plan developed on a site specific basis during the EIA process.

To date, several marine wind farms are operating world-wide. However, few enough have provided adequate case studies upon which to base current advice relating to impacts on birds of offshore wind farms (Langston & Pullan 2003). With so many more planned in the immediate future the demand for science-based assessments of their effects on migratory birds is obvious. For this very reason, it is essential that European common standards are agreed for data collection, as has been achieved, for example, in the case of aerial and ship-based bird survey methodologies in the UK (Camphuysen et al. 2004). The time is also right to establish a European or world-wide forum to exchange experiences and share information on the displacement of locally feeding birds, the extent of flight avoidance, collision rates with, and cumulative effects of, marine wind farms under a range of different circumstances. Co-ordination of specific offshore studies of bird-wind farm collisions will be of decisive importance if we are to effectively assess the consequences of wind turbines at sea, and ensure that such renewable energy developments are compatible with international conventions and legislations that protect migratory birds.

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Information needs to support environmental impact assessment of the effects of European marine offshore wind farms on birds

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European legislation requires Strategic Environmental Assessments (SEAs) of national offshore wind farm (OWF) programmes and Environmental Impact Assessments (EIAs) for individual projects likely to affect birds. SEAs require extensive mapping of waterbird densities to define breeding and feeding areas of importance and sensitivity. Use of extensive large scale weather, military, and air traffic control surveillance radar is recommended, to define areas, routes and behaviour of migrating birds, and to determine avian migration corridors in three dimensions. EIAs for individual OWFs should define the key avian species present; as well as assess the hazards presented to birds in terms of avoidance behaviour, habitat change and collision risk. Such measures, however, are less helpful in assessing cumulative impacts. Using aerial survey, physical habitat loss, modification, or gain and effective habitat loss through avoidance behaviour can be measured using bird densities as a proxy measure of habitat availability. The energetic consequences of avoidance responses and habitat change should be modelled to estimate fitness costs and predict impacts at the population level. Our present ability to model collision risk remains poor due to lack of data on species-specific avoidance responses. There is therefore an urgent need to gather data on avoidance responses; energetic consequences of habitat modification and avoidance flights and demographic sensitivity of key species, most affected by OWFs. This analysis stresses the importance of common data collection protocols, sharing of information and experience, and accessibility of results at the international level to better improve our predictive abilities.

INTRODUCTION

Clean renewable energy from offshore wind power offers the prospect of some relief from reliance upon fossil fuels. Offshore wind power avoids some of the problems presented to landbirds (e.g. raptors Orloff & Flannery 1992, 1996, Thelander & Rugge 2001, Barrios & Rodriguez 2004) and is free from 'Not In My Back Yard' protests on land. Since the first European marine wind farms were constructed in the early 1990s (Larsson 1994), at least 13 000 offshore wind turbines are currently proposed (ICES 2003), potentially making a major contribution towards achieving national targets for sustainable development under the Kyoto Protocol of 1997. This constitutes Europe's most dramatic marine industrial development to date. Current plans to develop offshore wind resources will require an area of 13 000 km^2 by 2030 in German marine waters alone (BMU 2001, Garthe & Hüppop 2004).

By virtue of their aerial mobility, high public profile and the existing international and national legal frameworks relating to the specific protection of migratory species, birds feature prominently in the environmental impact assessment (EIA) process associated with wind farm developments, both on land and at sea. There is a burgeoning literature relating to the interactions between land-based wind turbines and birds (Anonymous 2002, Langston & Pullan 2003, Hötker *et al.* 2004, Percival 2005). However, with only nine offshore wind farms currently operational in European waters, few case studies exist upon

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which to develop well-founded EIAs for future marine developments. Only four of these projects (Tunø Knob, Nysted and Horns Rev in Denmark and Kalmar Sound in Sweden) have provided good quality data on the effects on birds, since post-construction investigations are far from standard. In this review, we present the Danish experience of developing EIAs and results from post-construction monitoring in the context of the existing international legislation. We attempt to establish ideal objectives for offshore wind farm (OWF) EIAs in terms of assessing local effects (defined as proximate local changes in abundance and distribution) and large-scale impacts (defined as ultimate changes at the population level). In addition, we assess the constraints on achieving such objectives. It is necessary to distinguish between local effects and population impacts, to assess cumulative consequences for long-distance migratory birds. Finally, we provide guidance on the methods currently available, and make recommendations for improving data collection, collation and analysis.

BACKGROUND AND THEORETICAL FRAMEWORK

Factors associated with offshore wind farms affecting birds

Wind turbines simply exploit natural airflow to create mechanical energy that is converted to electricity. Offshore turbines are constructed of three-blade rotors driving encased generators perched on narrow cylindrical towers with internal maintenance access from an external landing platform above sea level. Structural size varies; recent OWFs have used 2.3 MW rated turbines, and there are already plans for 5 MW turbines. Rotor sweep (y, measured in metres) and hence tower height increase with power output (x, measured in MW) according to a power function ($y = 53.999x^{0.437}$, $r^2 = 0.998$; Danish Wind Energy Association 2003). Present typical 3.6 MW offshore wind turbines have a tower height of 77 m, a rotor sweep diameter of 100 m (clearance height of 27 m and total height of 127 m) and working speeds of 8–16 revolutions/min. It is generally assumed that the rotor sweep area represents the greatest risk of collision to flying birds and this clearly overlaps with the 0–50 m altitude range within which most seabirds commonly fly (Dierschke & Daniels 2003).

Despite a very broad range of opinions, there is a general consensus that the factors affecting birds resulting from the construction of OWFs can be distilled into three broad classes (shown in the uppermost row in Fig. 1). These comprise:

(1) a behavioural element, caused by birds avoiding the vicinity of the turbines as a behavioural response to a visual stimulus;

(2) a physical habitat element, where birds respond to destruction, modification or creation of habitat associated with turbine/ infrastructure construction; and

(3) a direct demographic element, resulting from mortality arising from physical collisions with the superstructures.

As we shall see below, there are problems associated with the direct measurement of the effects and, indirectly, with the assessment of the impacts of each one of these factors. Legislation requires that an assessment be made of the proximate effects of a new wind farm on birds. In this sense, the EIA must account for predicted changes in the local abundance and distribution of avian species; and in local biodiversity as a consequence of its construction and operation. Increasingly, however, there is a requirement for some assessment of the effects at greater spatial scales, including an assessment of the 'cumulative impacts' of several such developments. This of course necessitates an understanding of individual and additive impacts at the population level. For this reason, it is helpful to briefly review the legislative framework to identify specific ideal objectives to meet the requirements for EIAs with regard to OWFs.

Obligations under European Union legislation

In European Union (EU) states, all wind farm developments require some level of planning screening. Under Directive 2001/42/EC, national governments are required to undertake a strategic environmental assessment (SEA) of national wind energy plans and programmes that have the potential for an adverse impact on wildlife. Where there are potential transboundary effects regarding placements of OWFs, international co-ordination and collaboration should be sought. Specific projects also require a formal EIA (under Directive 85/337/EEC and amended by Directive 97/11/EC). This considers effects at local geographical scales (i.e. project level), assessed with regard to the individual avian populations involved, in contrast to the more strategic view of the SEA. However, the Directives also require some assessment of the cumulative effects and impacts arising from

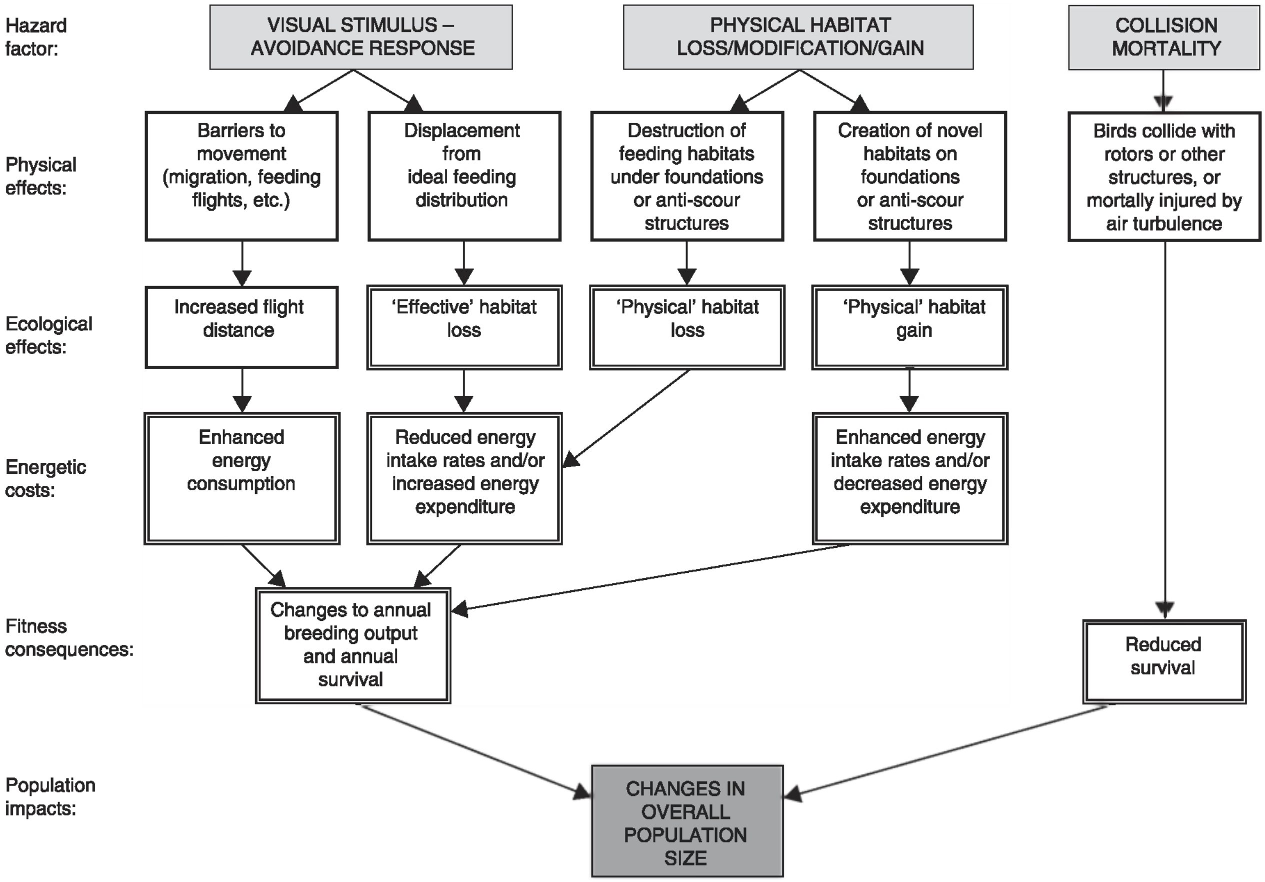

Figure 1. Flow chart describing the three major hazard factors (light shaded boxes) presented to birds by the construction of offshore wind farms, showing their physical and ecological effects on birds, the energetic costs and fitness consequences of these effects, and their ultimate impacts on the population level (dark shaded box). The boxes with a heavy solid frame indicate potentially measurable effects, the double framed boxes indicate processes that need to be modelled (see text for details).

each proposal (including associated on- and offshore infrastructure development, such as road improvements, power lines, transformer stations, under sea cables, etc.). Cumulative impacts also need to be considered in conjunction with other projects (which may include both other wind farms and other relevant human development projects), that impact upon the same flyway populations.

Measuring proximate local effects and ultimate population impacts

Unfortunately, the Directives and domestic legislation provide little guidance or case law to shape the precise requirements of SEAs or EIAs associated with OWFs. A major challenge is therefore to achieve some harmonization of approach, giving a general agreement on the overall aims and objectives of the process. Very few (effectively only two Danish and one Swedish) operational OWFs have provided long-term comprehensive case histories upon which to base an impact assessment. Hence, there is a need to define best practice in base-line studies: to inform upon sensitive siting of turbines to minimize deleterious effects on birds; and post-construction monitoring: to enhance predictive performance, based on feedback monitoring to improve our abilities to model effects. The information accumulated in these studies needs to address a range of issues, which will inevitably be species-, site- and season-specific when considering effects and impacts upon migratory birds. In terms of the behavioural and habitat elements, these studies need to specifically:

(1) assess the distribution and abundance of all locally feeding and migrating birds using a potential area;
(2) predict the extent of avoidance response; and
(3) report on the observed post-construction effects against predictions.

The assessment needs also to take into account the degree of habituation that may occur, whereby the strength of a particular response is moderated over time. Assessments of collision mortality should:
(1) assess the volume, direction, altitude and nature of all flying birds in the vicinity of a proposed wind farm area;
(2) predict the numbers of collisions under a variety of seasonal, environmental and weather conditions; and
(3) report on measured post-construction levels against predictions.

Such investigations enable an objective assessment of the potential effects on birds locally, but there remains a requirement to consider cumulative impacts. Hence, in both cases, these assessments need to take into consideration the local, regional and global sensitivity of each population involved and other factors affecting the population at a far greater spatial scale. Assessment of impacts at the population level therefore, poses a considerable challenge to the SEA and EIA processes. In all these cases, investment in post-construction monitoring, although initially expensive, will increasingly improve our ability to make predictions about, for example, habituation and collision rates.

Background to the Danish experience

Denmark lies centrally on the East Atlantic flyway and supports very high concentrations of migratory, staging and moulting waterbirds: 5–7 million birds of more than 30 waterbird species in winter. In several cases these constitute more than half of the wintering populations of some north-western Palearctic species (Laursen *et al.* 1997, Rose & Scott 1997, 2002). As a consequence, Denmark has special obligations under both the Ramsar and Bonn Conventions and the EU Birds Directive to protect and maintain these populations.

The Danish Government's energy action plan 'Energi 21' established a national target for a 50% reduction in carbon dioxide (CO_2) emissions by 2030 (as compared to 1988 levels). With limited opportunity for further erection of land-based wind farms in Denmark, a strategic 4000 MW capacity objective was established for OWFs and an overall assessment of marine waters (including environmental and economic interests) undertaken to identify potential locations. In 1997, an action plan for OWFs in Danish waters was published for consultation, concluding by proposing that five 'stage-one' demonstration projects should be undertaken to assess the technical, economic and environmental feasibility of large scale offshore wind electricity generating projects. In February 1998, the Danish Ministry of Environment and Energy gave permission for the construction of five offshore demonstration wind parks in Danish inshore waters. Of these, two have since been constructed, at Rødsand (Nysted) in south Denmark and at Horns Rev on the west coast of Jutland, completed in 2003 and 2002, respectively. Permissions were granted on condition that a programme of environmental studies would be undertaken to support the preparation of EIAs. The environmental studies were designed to cover the construction area (wind park and cable link areas), the impact area (the area during construction and operation in which there was expected to be an effect), and a reference area (a comparable area, free of wind turbine development). Particular emphasis was placed upon waterfowl and migrating bird species. The EIAs were to include proposals for a dynamic programme, monitoring positive and negative impacts on the environment, in both the construction and the operational phase, to continue 2–3 years post-construction.

One major objective of the monitoring programme was to enable a comparison between the predicted effects arising from the initial EIA, and the observed effects post-construction. An important element in the design of the programmes was to ensure that base-line monitoring was of sufficient duration to rule out 'natural variability' masking the effects that the programme was designed to detect during the operational phase.

DATA REQUIREMENTS AND COLLECTION METHODS

Supporting a Strategic Environmental Assessment

Despite the imperative presented to national governments to attain their Kyoto targets, development of offshore energy resources requires an international, national and regional SEA of the most suitable areas for such exploitation. Ideally, the first strategic level approach should determine the relative avian nature conservation interest of European marine waters, to establish a core overview of differential importance and therefore sensitivity. After this, the economic constraints on the suitability of different potential OWF sites to deliver power into the national grid can be considered in order to provide a 'wish list' of potential development sites, to compare against known avian distributions and assess the likely impacts on birds. From the industry side, this wish list would be compiled based upon the available wind resources in relation to the costs of offshore developments in the best areas. Constraints upon this would include, for example: water depth; substrate type; distance to shore; suitability of grid connections; and costs of transmission to distant centres of population etc. Such a ranking of feasible and cost-effective sites for development would then offer up a first level list of proposed sites for the consideration and assessment of potential consequences for, and interactions with, a range of other stakeholders and user-groups. Some of the issues necessitating wide consultation with appropriate stakeholders and statutory bodies (which lie outside the scope of this review) would include: conflicts with shipping lanes, military, fisheries, oil and gas industry, telecom linkages and many others. However, the first level of screening and consultation would include an assessment of the nature conservation values of the site, with regards to the statutory obligations directed by domestic and European legislation. From the avian conservation viewpoint, it is essential that the bird interest of a particular proposed wind farm site can be assessed in the international, national and regional context. This necessitates at least some idea of the distribution of resting and feeding birds in all sea areas during critical periods of the annual cycle (taken here to be wintering areas, spring staging areas, nesting and breeding feeding areas, moulting areas and autumn staging areas).

In Denmark, extensive data on the relative distribution of birds at sea were available from aerial census data supplemented with boat-based surveys available since the 1970s (e.g. Joensen 1973, 1974, Durinck *et al.* 1994, Laursen *et al.* 1997). These data formed the basis upon which to make a preliminary assessment of the favoured sites for development of wind energy in the sea. Such extensive knowledge enabled a first level assessment of the relative suitability of the five proposed wind farm sites in Denmark.

In most European states, such extensive knowledge of resting and feeding bird distributions at sea are generally lacking. Notable exceptions include those areas covered by the European Seabirds at Sea (ESAS) database (and associated analyses, e.g. Blake *et al.* 1984, Tasker *et al.* 1987, Carter *et al.* 1993, Mitchell *et al.* 2004) and/or subject to special monitoring (e.g. designated Special Protection Areas notified under the EU Birds Directive). However, ESAS coverage can be patchy, especially in shallower waters inshore. It is then neccessary for some phase 1 level survey of extensive areas of marine waters in order to make proper assessments of the relative importance of proposed sites. The ideal objectives of such a survey would be: to cover as large an area as possible in the time available; to sample as simultaneously as possible; use the greatest level of spatial precision possible; and to use observation platforms that create the least disturbance to abundance and distribution patterns. Suitable methods for achieving this, using transect grid coverage by aerial surveys, have been described by Camphuysen *et al.* (2004). Transect sampling of bird abundance based on counts from moving platforms, corrected for detectability using distance sampling approaches (Buckland *et al.* 2004) offers a very powerful tool for generating bird density surfaces. This is especially so when using spatial modelling techniques (such as generalized additive and mixed modelling) to incorporate environmental parameters as covariates to explain bird distributions and abundance (e.g. Hedley *et al.* 1999, Clarke *et al.* 2003). Such approaches offer the possibility to sample bird distributions using sparse transect coverage to interpolate modelled densities with confidence as a phase 1 survey (Camphuysen *et al.* 2004). These methods offer the opportunity for an objective ranking of 'hot spots' of high bird concentrations at particular times during the annual cycle or at least identify areas in need of more intensive survey.

Whilst such survey is ideal for defining the distribution of birds exploiting the sea for feeding or resting, instantaneous sampling is poor at defining avian migration intensity over large areas of open sea. Flight movements of birds between areas (especially during long distance migration and foraging flights between breeding sites, feeding areas and roosting sites) are by definition intense and of very short duration at various different altitudes, heavily dependent on season and weather. However, assessments of bird movements at local, small spatial scales (but set in a national or regional context) are required for the effective assessment of, for example, collision risk probabilities. Where terrestrial birds, as well as waterbirds, can be shown to migrate in very low densities, the local collision risk can be considered very much lower than in cases where large densities of birds migrate at turbine height through a proposed site. It is well known, for example, that migrants collect at the tips of peninsulas throughout the world prior to crossing the sea (e.g. Foy 1976, Alerstam 1990). Waterbirds are also concentrated by topography (e.g. Common Eiders *Somateria mollissima* at Nysted, Kahlert *et al.* 2004) or gather at sea prior to crossing the land

(Bergmann & Donner 1964, Bergmann 1974). Hence, it is likely that topography shapes migration routes out at sea, at least in near shore areas. Similarly, it is known that migrating birds crossing the sea may lose or gain height upon approaching land (e.g. Richardson 1978, Alerstam 1990). Any knowledge of the migration corridors and patterns of flight in three dimensions across the open sea (especially in near shore areas where wind farm development is most likely) is highly desirable to support effective siting of wind farms to avoid high collision risk areas.

Unfortunately, such data are not extensively or readily available in Europe. Only military, air traffic control or meteorological radars can currently provide sufficient coverage of mass migrations of birds over time at large spatial scales (i.e. 1–200 km), over a range of altitudes (Gauthreaux 1970, Desholm *et al.* 2005). Some species specific radar studies have been undertaken in Europe (e.g. Alerstam *et al.* 1974) using weather radar (e.g. in Finland & Koistinen 2000) or military radar (e.g. in Sweden, L. Nilsson *pers. comm.*, and Germany, O. Hüppop *pers. comm.*). However, the results have not been fully published and because the quality of data on bird migration altitude is variable, are generally not in a form suitable to support SEAs. There are a number of problems associated with using such radars, not least the conflict of interest, given that meteorological, air traffic control and military radars frequently filter out the signals reflected by birds. The operational lack of capability to distinguish bird migration at low (i.e. turbine sweep) altitudes is frequently another disadvantage of using such technology (Desholm *et al.* 2005). Nevertheless, the use of these existing sources of data and the development of specific bird radar equipment has the potential to deliver vital information in the future. Both could potentially be used to support the identification of migration corridors (e.g. those associated with promontories and peninsulas where birds tend to arrive and depart from) and the flight behaviour of birds (especially flight altitude) in the vicinity of proposed wind farm sites. This information is needed both to inform the SEA process and influence the local siting of turbines as pre-construction mitigation during the EIA process.

At present, there have been very few attempts in Europe to undertake a SEA associated with OWF development, despite the fact that the legislative framework requires this to be undertaken. Many of the specific environmental issues associated with a development will be addressed at site level by a project-specific EIA. A strategic assessment of where best to locate OWFs in national waters, to avoid specific conflict with resting and feeding waterbirds has only been undertaken in Denmark, Germany (the MINOS project, 'Marine warm-blooded animals in the North and Baltic Seas: foundation for assessment of offshore wind farms') and regionally in the UK. To the best of our knowledge no strategic national assessment of avian migration routes has been undertaken in this connection, with the exception of current studies in Germany (see Exo *et al.* 2003).

Developing a site-specific Environmental Impact Assessment

What species are involved? What is their distribution in time and space?

From the outset, it is essential to define the range of bird species occurring within the area of a proposed wind farm, whether these birds exploit the site during the breeding, moulting, staging or wintering periods, or simply pass through on migration. Useful historical data are likely to exist in a variety of forms. For example, shore-based sea-watching observations of passing birds have been compiled at migration watch points to give a picture of general bird migration in the vicinity of the Horns Rev OWF (Noer *et al.* 2000). Much seabird distribution data is held in archives (such as ESAS) or result from specific surveys of limited spatial scale. Although such sources of information are valuable, these data are often collected using different methods at a geographical or temporal resolution that does not provide a basis for impact assessment or a rigorous base-line for post-construction comparisons. A site-specific assessment of the species composition and abundance of birds in the area of a wind farm should also be undertaken. This should encompass a geographical area that includes construction, impact and reference areas; an assessment of the conservation status of the species or specific populations involved; and the conservation status of sites protected for their nature conservation interest in the immediate vicinity of a development.

Hazard factors and measurement of effects/impacts

The approach taken in the Danish model has been to attempt to quantify the physical effects of each of the three major factors on bird behaviour, abundance or distribution (Fig. 1). This helps to identify measurable parameters that can contribute to the measurement of local effects and feed directly into the local EIA process. However, although this tells us a great deal about how birds are likely to react locally, it is hard to translate the effects of changes in distribution or displacement, to the specific consequences for an individual bird and its lifetime fitness, or for the population as a whole. This is important if we are to determine the cumulative impacts of many such wind farms in a given area or along a species flyway corridor. It is even more important if we are going to assess the relative impacts of OWFs in comparison to other anthropogenic factors affecting that population. Such comparisons and assessments of impacts from a combination of developments necessitate the measurement of impacts using a common currency. The ultimate measure to understand changes in population is that of fitness, namely changes in vital processes of birth and death rate (see Fig. 1), which ultimately affect annual changes in overall population size. However, with the exception of collision deaths, it is difficult to directly relate displacement of an individual bird from its ideal feeding position, to its reproductive success or to its survival probability. For this reason, it becomes necessary to use the measurable local effects to model ultimate population impacts.

Given the physical effects that arise from each of the factors shown in Fig. 1, the rationale has then been to attempt to determine the ecological effects on the birds, and in some cases translate these effects directly into additional energetic costs incurred as a result of post-construction conditions. In some circumstances, changes in these energetic costs can be incorporated in individual behaviour-based models to determine the potential fitness consequences at the individual level, which can then provide a basis for impacts at the population level (as is being done for Common Scoter *Melanitta nigra* see Kaiser *et al.* 2006). At the population level, it becomes possible to incorporate and/or model other cumulative impacts to start to address the issue within the EIA process.

Avoidance response – barriers to movement

Initial observations suggest that some birds chose to fly outside an offshore wind turbine cluster rather than fly between the turbines (Desholm & Kahlert 2005). Such behaviour reduces collision risk, but means that OWFs might represent a barrier to movement, either to local feeding and roosting flights, or to longer migratory flights (Dirksen *et al.* 1998, Tulp *et al.* 1999, Pettersson & Stalin 2003, Kahlert *et al.* 2004, Desholm & Kahlert 2005). The extent to which such avoidance constitutes a problem depends on the species, the size of the OWF, the spacing of the turbines, the extent of extra energetic cost incurred by the displacement of flying birds (relative to the normal flight costs pre-construction) and their ability to compensate for this degree of added energetic expenditure. Very large-scale developments could ultimately have a disruptive effect on linkages between feeding, nesting and roosting areas and perhaps finally create a barrier that birds will not cross at all, completely re-routing the flight trajectory – although no such effect has been reported to date.

The ideal objective therefore, is to construct a frequency distribution of individual bird and flock trajectories (identified to species during day and night) in three-dimensional space through a defined corridor of air space in and around the proposed OWF prior to its construction. This necessitates consideration of the spatial scale of the migration area to be monitored, dependent upon the distance over which the OWF is visible to birds and the range of the remote sensing technology equipment to be used (see Desholm *et al.* 2006). Gathering such data provides a basis for comparisons of the frequency distributions through the same area post-OWF construction in a manner that accounts for differences in weather conditions. These requirements are rigorous and difficult to attain, but continuing improvements in the field of remote sensing offer increasing opportunities to use radar and thermal imaging equipment to construct such frequency distributions (see Kahlert *et al.* 2004 and Desholm *et al.* 2005 for review of methods and techniques).

Given radar studies of pre- and post-construction flight volume, direction and tracks, it is possible to quantify the level of avoidance shown amongst bird trajectories that result following wind farm construction (Desholm & Kahlert 2005). Mechanical models (e.g. Pennycuick 1989) can then be used to assess the relative additional costs of these flights. Such local avoidance by migrating birds is likely to be relatively trivial in energetic terms, since avoidance of present scale OWFs consisting of 80–100 turbines is likely to incur additional flight costs of less than 20 km to completely avoid the structures. At the local scale, such a limited extension to a migration flight of several hundred kilometres, is likely to contribute very little to extra energy expenditure compared to, encountering strong and unfavourable winds, for example. Such extra energy costs are likely to be compensated for by slightly enhanced feeding rates. Under these circumstances, at the local single OWF level, the additional energetic costs are unlikely to be significant. However, this may not be the case for birds commuting daily between feeding and other areas used in the daily cycle. These would include, for example, Common Scoter and Long-tailed Ducks *Clangula hyemalis*, moving daily between feeding and roosting areas on their wintering grounds. Breeding gulls (Laridae) or terns (*Sterna* spp.) also move between marine foraging and terrestrial nesting areas, where additional flight costs may increase normal energy expenditure and/or survival of nestlings may be affected if provisioning rates decrease. At a greater spatial scale, construction of OWFs along the migration corridor of a long-distance migratory waterbird may begin to have a greater cumulative energetic cost. In this context, it is important that such additional costs that arise from this source of barrier effect be incorporated into modelling of overall annual energy budgets to assess the effects on fitness and ultimately the potential for impacts at the population level. This approach also means that some comparative assessment of population impacts can be made when considering the effects of OWFs vs. other forms of human activities.

Displacement from ideal feeding distribution

Following construction of a wind farm, waterbirds may show a spatial response to the new constructions in the sea. Waterbirds may avoid the vicinity of novel, man-made structures; may be disturbed by the visual stimulus of rotating turbines; or be displaced by the boat/ helicopter traffic associated with maintenance. Whatever the cause, the result is that birds are displaced from a preferred feeding distribution, which results in effective habitat loss in the vicinity of the turbines. Apart from the relatively small area of seabed habitat lost under the foundations (and any surrounding associated antiscour constructions), the habitat and associated food resources are likely to remain physically intact. However, if birds of a given species are hesitant to approach to within half of the distance between adjacent turbines of a single project, the entire wind farm area, and an avoidance strip around the outer turbines, will become effectively lost as a feeding area.

The objective here, therefore, is to assess the degree of habitat loss that results for a given population of birds by the creation of the OWF. This should be based on as large a sample gathered during as many base-line years (at least 3) as possible to account for year to year variation in bird abundance and distribution (Camphuysen *et al.* 2004). Such direct assessments of habitat extent and quality are costly and time consuming, so effective and actual habitat loss can be measured using bird densities as a proxy measure of bird habitat. To this effect, aerial survey has proved a valuable tool for sampling bird distributions using distance sampling techniques to correct bird densities for the declining detectability of individuals with increasing distances from the observer (Buckland *et al.* 2004, Camphuysen *et al.* 2004). Spatial modelling techniques can then be used to generate bird density surfaces with confidence intervals over large areas of open sea based on transect samples to compare pre- and post-construction distributions and abundance (see above). The aim is to assess the density of birds throughout the proposed OWF area and a control area around this, prior to construction to predict the degree of habitat loss liable to occur post-construction, assuming different avoidance scenarios. In addition to informing the EIA process, this approach also offers the opportunity to undertake statistically robust comparisons of pre-construction base-line densities with post-construction observations (Fig. 2). This enables an assessment of the extent of total habitat loss and the extent of any graded avoidance response (Fig. 2). Furthermore, with sequential post-construction monitoring over a series of years, it will be possible to introduce a temporal element into the modelling to take account of year to year variation in displacement and the extent to which habituation may occur.

It is important to stress the need for adequate base-line and post-construction sampling. A base-line period must be long enough to discern some degree of natural variation pre-construction, matched by a similar period post-construction. Since the construction of the Øresund Fixed Link and Nysted OWF, three year base-lines have defined current practise in Danish bird studies (Noer *et al.* 1996, Kahlert *et al.* 2004). In relation to the erection of German offshore wind farms, a minumum of 2 years were proposed for base-line studies, with 3–5 year post-construction monitoring (Hüppop *et al.* 2002). Although these are long (and expensive) time frames for data collection, this is important to account for the natural variability in bird abundance. For instance, in the case of the Long-tailed Duck distribution at Nysted in south Denmark, using data from only 2 (and consistent) base-line years in 2001 and 2002 would suggest a dramatic displacement of birds from the OWF in 2003 out to almost 15 km. However, the baseline data from 2000 showed that the bird distribution during 2003 fell within the variability of the baseline sampling (Fig. 3).

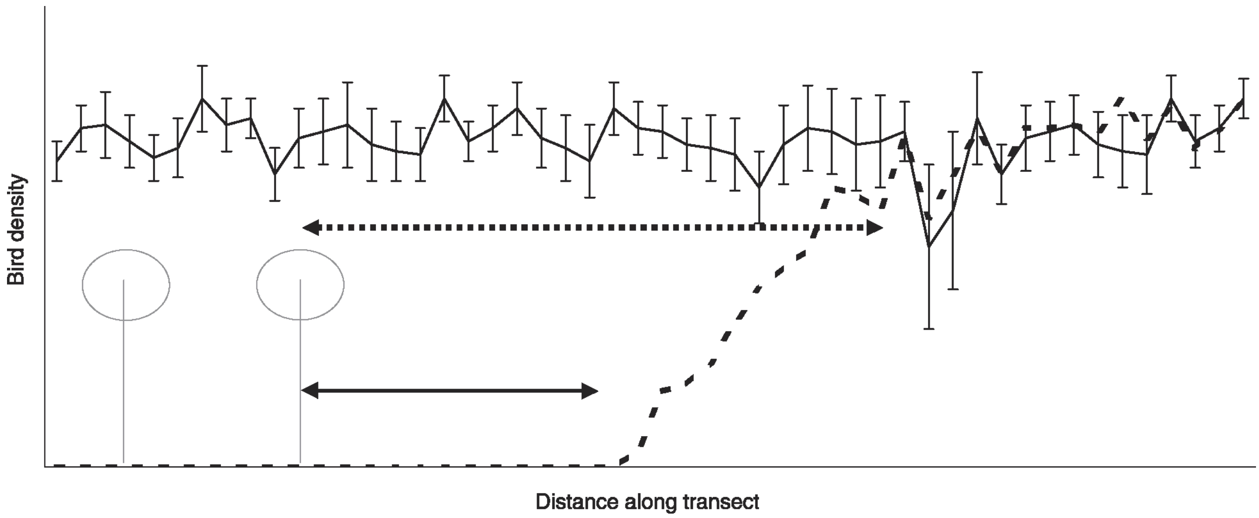

Figure 2. Theoretical two-dimensional representation of the modelled bird densities generated by spatial modelling as described in the text. The solid plotted line identifies the bird densities in grid cells modelled from aerial survey counts prior to the construction of the offshore wind farm (represented by two wind turbine symbols), the vertical bars indicate confidence intervals around these estimates. The dotted plotted line indicates the observed modelled bird densities post-construction (without confidence intervals for clarity), demonstrating complete avoidance of the area within the offshore wind farm. Note also an avoidance zone outside the turbines (solid arrow), and a surrounding area which experiences reduced bird densities as a result of avoidance and a graded avoidance response (dotted arrow). The integrated area between the two curves represents the difference in bird density resulting from the construction of the wind farm.

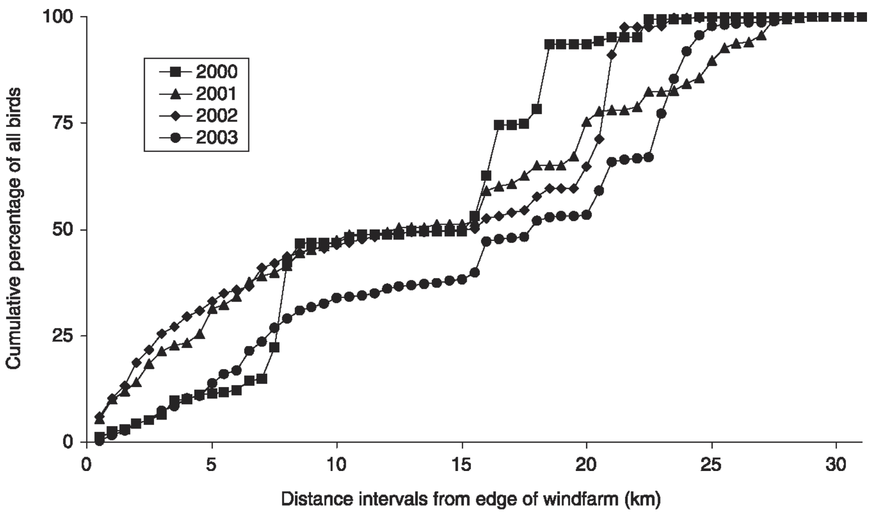

Figure 3. Cumulative percentage distribution of Long-tailed Ducks *Clangula hyamelis* at 500 m intervals from the periphery of the Nysted offshore wind farm, based on all aerial survey data in 2000, 2001 and 2002 (pre-construction), and post-construction in 2003. See Kahlert *et al.* (2004) for full explanation and methods.

Where food supply is limiting, displacement from ideal foraging opportunities will have an effect on the displaced individuals. Birds may be forced to move elsewhere, with an associated energetic cost with that movement. Following the construction of the Øresund Bridge, Common Eiders displaced by associated habitat destruction showed a graded response. Post-construction, bird numbers increased at other sites more than 7 km from the original foraging area, presumably because there were no alternative feeding sites in the vicinity of the construction site (Noer & Christensen 1997). Hence, the size of any monitored reference area must take account of the potential scale of spatial rearrangement post-construction. For some particularly critical periods in the avian life cycle (e.g. moulting sites used by waterbirds), there may be such specific requirements on habitat characteristics that no alternative sites physically exist, exposing the birds forced to use other unsuitable sites to elevated fitness costs (e.g. enhanced predation risk whilst flightless).

Displaced birds may be forced to move elsewhere to feed in potentially less suitable (i.e. energetically profitable) conditions (e.g. diving in deeper water, or foraging in areas with reduced prey densities). They may also experience increased competition from higher densities of birds in areas to which they are displaced. To determine the effects of such processes requires a fundamental knowledge about feeding opportunities throughout the migratory range of the population concerned, a detailed knowledge of the feeding ecology of the species and some assessment of the behavioural implications for feeding at different prey and predator densities (West & Caldow 2006, Pettifor *et al.* 2000). For a restricted range of critical species, it may be possible to gather such data to construct individuals-based spatially explicit population models to test for the effects of such 'effective habitat loss' on energy intake and ultimately on fitness consequences (i.e. breeding success and annual survival). This approach is already being developed for the assessment of the effects of disturbance and habitat loss from wind farms on Common Scoter (Kaiser *et al.* 2006). This species is of critical importance throughout the western Palearctic because of its selection of sandy substrates in shallow coastal waters which were initially the preferred situations for the development of OWFs because of nearness to shore and the ease of ramming foundations into the soft substrates (Fox 2003).

Destruction and/or modification of feeding habitat

The extent of physical loss to turbine foundations and to antiscour protection provision has never amounted to more than 2% of the total area of a wind farm in the Danish experience. For this reason, physical habitat loss has been considered under disturbance loss, since these two effects cannot be distinguished, not withstanding that the area of habitat affected is small. In relation to the creation of new habitats and food resources associated with the novel substrates provided by the turbine towers and antiscour protection, these have tended to be considered as trivial in terms of the overall EIA, on the basis of the restricted area involved. Nevertheless, where boulder protection is introduced to reduce scour to purely sandy substrates, such artificial reef structures may attract fish species (e.g. Jensen *et al.* 1994) that were previously absent (and hence piscivorous birds). Certainly gulls (especially Herring Gull *Larus argentatus*) and terns showed increased abundance at the Horns Rev wind farm post-construction compared to the base-line pre-construction. However, it was not clear if this resulted from birds being attracted to the turbines as loafing structures or to the associated boat traffic as potential food sources (Christensen *et al.* 2003, Petersen *et al.* 2004). Cormorants (*Phalacrocorax carbo*) are attracted to turbine maintenance platforms simply to use them as loafing structures (Kahlert *et al.* 2004), and potentially also because of enhanced feeding opportunities associated with the wind farm. Hence, wind farm construction may both remove and add structures and habitats that affect the abundance, distribution and diversity of the local avifauna. To date, because these modifications affect habitat areas that constitute less than 5% of the total wind farm area, and because the bird species associated tend to be abundant, widespread and those of little conservation concern, these effects have not been considered of great importance. Nevertheless, such changes in habitat can be measured using bird density measurements as outlined above and this may be an issue that will merit greater attention in the future.

Collision rates

Birds can be injured or killed by interactions with wind turbine structures in three ways: by hitting the stationary superstructure, the stationary or rotating rotors, or by being caught and injured in the pressure vortices created in the wake of the rotor blades. Birds, especially night-migrating passerines, are well known to collide with stationary objects, both on land and at sea, such as towers (e.g. Evans 2000, Kerlinger 2000), especially those with certain types of illumination (e.g. Gauthreaux & Belser 2000, Manville 2000). OWFs require navigation lights under legislation relating to maritime and airborne traffic. In conditions of poor visibility, birds tend to be drawn towards continuous lights, which may substantially lower avoidance rates. Equally illumination may enhance avoidance and light safe potential resting places at sea during adverse conditions. Disorientated and unconscious birds are also more likely to die (as a result of drowning) offshore compared to those on land (Tingley 2003).

Collision mortality is often considered to be the most important hazard presented to birds by wind turbines constructed in the sea because the impact of such additional mortality can be seen as having an immediate consequence at the population level. It is axiomatic to state that deaths occurring through collision with the turbines (or by the turbulent airflow associated with the blades around the sweep area) will reduce population size. However, the population dynamics of some avian species give them a greater resilience to extra mortality over several generations than other species. For this reason it is very important to estimate collision rates to determine the extent of this source of mortality and interpret this in the context of the population concerned.

Our aim would be to measure the rate of flight movements through the area of a proposed OWF and from this explain the collision risk frequency expected post-construction. In other words, we need to model the deterministic probability of birds hitting the turbines corrected for the ability to avoid them. But how do we estimate collision risk and especially bird avoidance rates pre-construction as a contribution to an EIA? Radar can be used to track the altitude and trajectories of birds in the vicinity of a proposed OWF prior to construction. This is important to measure the volume of bird movement that occurs through the area at different altitudes under a range of annual, seasonal and meteorological conditions (e.g. Christensen *et al.* 2003, Kahlert *et al.* 2004, but see Desholm *et al.* 2006 for limitations on data collection). Furthermore, there exist statistically sound models to predict collision risk of birds within the sweep area of the turbine rotors (e.g. Tucker 1996, Band *et al.* 2005) based on these frequency distributions (Chamberlain *et al.* 2005, 2006). Sensitivity analyses show that the probabilities of collision provided by such approaches show little change in response to bird size, but are reliant upon accurate flight altitude measurements to determine collision risk. The final calculation of avian mortality incorporates the parameter $(1-\alpha)$, where α represents the probability of avoidance, multiplied by collision probability and the bird numbers at risk entering the turbine sweep area. The very few measures of avoidance rates that do exist in the literature are high (> 0.90, see Chamberlain *et al.* 2005, 2006) creating large-scale adjustments in mortality rates. Hence, small errors in avoidance rates have very large effects on percentage changes in predicted mortality rates, dwarfing the effects of changes in other fitted parameters in the model. Yet avoidance rates of individual birds and the factors affecting these remain poorly known.

Estimates of avoidance rates on land are derived from the ratio of mortality (estimated from corpse searches and collection) to the estimated number of birds flying in the risk area. However, both of these estimates are subject to considerable error, which will have a large effect on the precision of mortality estimates (Chamberlain *et al.* 2005, 2006). Given the species-, site- and weather-specific variations in avoidance rates, it is deemed unacceptable to use avoidance rates from other studies without clear and rigorous justification. For this reason, there is a very clear and urgent need to gather extensive and better quality data on state specific avoidance rates of different bird species to turbines to enable effective parameterization of bird avoidance rates to incorporate into collision risk modelling. At Nysted OWF in southern Denmark, radar studies showed that Common Eiders modified their flight trajectories (in response to the visual observation of the turbines) at an average distance of 3 km during daylight (less by night) compared to pre-construction flight patterns (Kahlert *et al.* 2004, Desholm & Kahlert 2005). Similar adjustments to flight orientation of other species have been recorded at the Horns Rev OWF (Christensen *et al.* 2003). Furthermore, from one single TADS sequence, it is known that passerines exhibit the ability to apparently stop still in space in very close proximity to the turbine rotor sweep and avoid collision by flying away from the danger area (Desholm 2003, 2005). It must be stressed however, that case studies of this type are extremely few in number. Such a range of responses at very different spatial scales requires much development of radar and thermal imaging hardware (e.g. Thermal Animal Detection System, [TADS]) and gathering of more extensive data on relatively rare events (Desholm *et al.* 2005). It must be remembered that the extent of data available on such encounters between offshore wind turbines and birds remains very limited, and one must remain extremely prudent in drawing general conclusions from such observations made under specific circumstances associated with relatively few wind farms.

This area of research and monitoring is a very urgent priority for the future, both to identify the limits of collision risk models during the EIA stage and to gather data on actual collision rates post-construction, to test the validity of the predictive methods. It is known that birds collide with a variety of man-made objects (e.g. lighthouses, bridges, tower blocks, communication towers; Avery *et al.* 1976, 1980, Kerlinger 2000, Manville 2000, Jones & Francis 2003) under conditions of poor visibility. It is likely that the same will occur at OWF occasionally although the rarity of such events makes it difficult to determine their frequency with accuracy and precision. However, were it possible to correlate high collision rates with particular meteorological conditions at critical times of the year, this would offer a basis for mitigation measures. For example, it may be possible to shut down turbines during those rare events when poor weather and heavy migration conspire to create unusually high collision risk, if stopping turbines proves to be an effective mitigation measure to reduce collision rate.

So far, such measurement of actual collision rates post-construction at OWFs has proven difficult, with the only effective method using infra red thermal imagery technology to gather data from sampled sections of the turbine sweep area, triggered by warm-bodied objects entering the field of view (Desholm 2003). Such equipment is expensive and costly to operate, so there remains a need for a cheap equipment solution that provides time specific records of avian collision on an extensive scale to better understand the conditions under which collision risk is elevated (Desholm *et al.* 2006).

Whilst it may be possible to estimate collision rates at turbines using this type of approach it is also necessary to model the effects of such mortality over longer time periods to assess the impacts of such mortality on different populations exhibiting different sensitivities. Short-lived species (such as passerines) tend to be highly fecund, and in situations with strong density dependent effects, it may be that the high reproductive potential of a population can replace lost individuals relatively quickly to maintain population size. In contrast, this is not the case for relatively long-lived species (such as divers *Gavia* spp., and many raptors) which raise very few young throughout their lifetime. These species are less able to replace lost numbers over short time intervals (dependent also upon the extent of available breeding habitat and the pool of non-breeding sexually mature individuals), such that additional mortality is more likely to cause sustained declines in numbers over time. It is therefore essential to establish the level of collision rates associated with turbines at sea, the species and populations involved and to undertake population modelling (incorporating different strengths of density dependence) to assess the sensitivity to the levels of observed collision mortality. This is especially important to enable the assessment of the potential cumulative impacts of more than one wind farm development along the flyway corridor of a given population.

DISCUSSION

What is clear is that we still have a long way to go before we can consider our toolbox complete for obtaining the necessary data for the development of effective EIAs for OWFs. This review emphasizes the need for the collation and analysis of data at different spatial and temporal scales, in order to address the strategic impact of a wind farm (in terms of the siting on an international, national and regional level) as well as the local effects of the construction of a specific wind farm and ultimately its impact on populations. The challenges are many and varied, but this gap analysis shows that we require more studies which involve before/after and control/impact comparative studies to validate the data from our existing OWF EIAs, to enable improved predictions to support future EIAs.

One of the most important guiding principles is the need for the adoption of common (preferably international) agreed best practice standards to enable standard collation of data and to ensure the most effective cross comparison of experiences.

At present, there exist good before, during and after construction monitoring data for resting, feeding and migrating birds relating to the two Danish OWFs described above. However, these are ultimately species-, season- and site-specific experiences from just two sites with only 2 (potentially atypical) post-construction years of observations. In the UK, the COWRIE (Collaborative Offshore Wind Research into the Environment) Steering Group has funded strategic research initiatives. It has also taken the lead on the development of recommended survey and monitoring methods as industry standards for UK OWF developments (e.g. marine bird survey methods and remote sensing technologies; Camphuysen *et al.* 2004, Desholm *et al.* 2006). It is increasingly important that adequate monitoring be put in place to see how predictions made in EIAs for OWFs perform against reality post-construction; without such feedback monitoring, we shall not be in a position to improve our ability to make effective EIAs in the future. We also increasingly need a centralized data handling facility to collate and curate data and ensure common experiences are made available to all the stakeholders and professionals involved with the development of OWFs. Again, this forms the basis of a new COWRIE initiative, which has been awarded after tender. Plans are also in hand to develop mechanisms to share experiences at the

European Union level, currently under development by the European Commission (M. O'Briain, pers. comm.).

It would seem that many national European programmes to develop offshore wind resources are progressing without undertaking full SEAs. This process requires the extensive mapping of resting and feeding waterbird densities throughout national waters at all critical periods of the annual cycle to define areas of differing levels of importance and sensitivity. Such a strategic assessment would aid in zoning extensive sea areas in terms of their suitability for development. It would also avoid the unfortunate discovery of further hitherto unknown concentrations of resting and feeding waterbirds during the EIA process (*cf.* concentrations of Common Scoter in Liverpool Bay and of Red-throated Divers *Gavia stellata* in the Thames). The methods for undertaking such extensive phase 1 survey using aerial survey techniques are now well established at the finer scale for supporting EIAs of individual OWFs. Although the mapping of important migratory routes at sea (incorporating all important altitude data) has not been undertaken to date, new use of extensive large scale weather, military, and air traffic control surveillance radar is recommended in the immediate future. Such techniques could prove useful to define areas, routes and behaviour of migrating birds to effectively describe the most intensively used migration corridors in three-dimensional space to provide large-scale spatial data for migrants. Such layers in an environmental GIS database would provide an invaluable tool for preplanning assessment of the potential nature conservation issues associated with development of offshore wind resources in particular areas.

Given the logistical difficulties of working at sea in a harsh marine environment, we still face many challenges in our ability to determine even the effects of the construction of wind farms at sea on birds. This is especially the case as the proposed sites for turbines move further from shore, where our ability to observe birds from land is considerably lessened. The use of aerial survey to map avian densities, remote techniques such as radar (to track increases in flight distances and avoidance responses) and infra-red thermal imagery (to measure collision rates) has greatly enhanced our ability to measure the local effects by pre- and post-construction data comparisons. We would strongly urge that due consideration is given to the establishment of observational platforms at the sites of offshore wind farms in the future. It is essential, despite cost implications, to gather adequate pre-construction remote sensing data (such as radar and TADS imagery) to support well-founded EIA development.

In addition, we need to invest greater efforts in modelling tools because our greatest challenge remains the conversion of these measurements of local effects into impacts at the population level. This can be achieved by using modelling tools and the skills available to hand at present. However, this process needs to be undertaken quickly and effectively for those species and populations whose flyway corridors and geographical ranges overlap most with the areas scheduled for development. Such modelling is vital to establish the likely fitness consequences for the populations concerned of all the effects of constructing OWFs so we can establish a common currency in terms of population impacts. This is especially important given that environmental impact assessment procedures Directive 85/337/EEC as amended by Directive 97/11/EC require that some assessment is made of the cumulative impacts of multiple wind farms and other developments scattered throughout the flyway of migratory populations. Such approaches are essential in order to offer mechanisms for assessing the cumulative impact of many wind farms and the combined effects of other anthropogenic factors that affect population processes in migratory birds.

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II

Remote techniques for counting and estimating the number of bird-wind turbine collisions at sea: a review

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Remote techniques for counting and estimating the number of bird–wind turbine collisions at sea: a review

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Since the early 1990s, marine wind farms have become a reality, with at least 13 000 offshore wind turbines currently proposed in European waters. There are public concerns that these man-made structures will have a significant negative impact on the many bird populations migrating and wintering at sea. We assess the degree of usefulness and the limitations of different remote technologies for studying bird behaviour in relation to bird–turbine collisions at offshore wind farms. Radar is one of the more powerful tools available to describe the movement of birds in three-dimensional space. Although radar cannot measure bird–turbine collisions directly, it offers the opportunity to quantify input data for collision models. Thermal Animal Detection System (TADS) is an infra red-based technology developed as a means of gathering highly specific information about actual collision rates, and also for parameterizing predictive collision models. TADS can provide information on avoidance behaviour of birds in close proximity to turbine rotor-blades, flock size and flight altitude. This review also assesses the potential of other (some as yet undeveloped) techniques for collecting information on bird flight and behaviour, both pre- and post-construction of the offshore wind farms. These include the use of ordinary video surveillance equipment, microphone systems, laser range finder, ceilometers and pressure sensors.

BIRDS AND OFFSHORE WIND FARMS

Migratory bird species enjoy a high public profile and are protected by international and national legislation designed to protect shared natural resources. Hence, migrant birds figure prominently in the environmental impact assessment (EIA) process associated with most wind farm development projects. The coastal and offshore waters of Europe are of global importance for several species of resident and migratory birds. The hazards posed to birds by the construction of offshore wind farms can be summarized under three broad headings:

(1) Displacement and flight avoidance responses (birds are displaced from an ideal feeding distribution by the presence of turbines, or avoid flying near to them on migration);

(2) Habitat loss/modification (physical habitat loss under foundations, or the creation of novel feeding and resting opportunities that actively attract birds to the turbines); and

(3) Collision risk (the probabilities of individuals of different species being struck by turbines).

Of these, collision risk will have the most direct impact at the population level, because it elevates the normal mortality rate of species (Johnson *et al.* 2002). This review will mainly focus on the risk of collisions. However, this does not imply that the other effects are trivial, especially when the cumulative effects of, for example, habitat loss are considered in the light of the construction of many offshore wind farms along the length of a migratory bird species' corridor (Fox *et al.* 2006).

DEFINING THE ROLE OF REMOTE TECHNOLOGIES

To support an adequate assessment of the risk presented by each hazard, and subsequently to monitor the actual effects or impacts of each hazard, EIAs need to predict the effect of each hazard and measure the potential effects each may have at the individual site

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level. These assessments are extremely time consuming or near impossible to achieve through direct human observation and increasingly, rely upon remote techniques to observe bird behaviour in a way which can provide robust objective data for modelling. For example, it is difficult for a human observer to physically watch and map the trajectories of migrating birds as they cross an area of open sea prior to the construction of a wind farm and make comparisons with post-construction observations in assessing the barrier effect (birds changing their flight path due to an obstacle) of the development. Such work requires the use of remote techniques, such as radar (Lack & Varley 1945, Eastwood 1967, Cooper 1996, Bruderer 1997a, Bruderer 1997b, Gauthreaux & Belser 2003), to accurately plot migration trajectories prior to and post-construction. Furthermore, counting the number of avian collisions directly or through carcass collection, as has been conducted at land-based wind turbines, will be constrained to a very high degree by the often harsh conditions in remote offshore areas. Such studies again require the use of remote video techniques, e.g. the Thermal Animal Detection System (www.praetek.dk; Desholm 2003b, Desholm 2005) which is an infra red-based technology developed as a means of gathering highly specific information about actual collision rates, but also for parameterization of input data for collision models.

The remote techniques need to be able to record multiple observations in order to assign probabilities under a range of parameters relating to prevailing environmental conditions and the birds involved. These remote techniques require a platform for mounting and preferably a stable platform. The most appropriate areas suitable for the application of remote technologies to collect data for the EIA process associated with offshore wind farms would seem to be the following:

(1) to provide a broad pre-construction phase description of the movements of birds within a study area, for the purposes of: (a) collision risk assessment and (b) as a base line for post-construction comparisons of flight pattern;

(2) to quantify probability models estimating the number of colliding birds; and

(3) to provide validation of **(2)** by measuring actual collision rates of birds hitting the turbine superstructure, or being killed in the vortices encountered in the wake of the turbines.

Researchers are already applying these remote techniques to the gathering of data to support pre- and post-construction studies of offshore wind farms in Denmark (Kahlert *et al.* 2000, 2002, 2004, Desholm *et al.* 2003, Christensen *et al.* 2004), the Netherlands (Sjörd Dirksen *pers. comm.*), Germany (Dierschke 2004, Hötker *et al.* 2004), and Sweden (Pettersson 2005). This experience, although limited, offers promise of comparable utility in other European waters. This review paper will assess the degree of usefulness and the limitations of different existing remote technologies for studying bird behaviour in relation to wind farms and provide recommendations for further methodological development to increase utility.

RADAR SYSTEMS

Hardware

The various commercially available types of radar can be classified in different ways. Firstly, the radar operating frequency can be subdivided into frequency bands, with the most frequently used radars in ornithological studies being the X-band (3 cm; 8–12.5GHz), S-band (10 cm; 2–4GHz) and L-band (23 cm; 1–2GHz). Second, the peak power output differs with regard to the strength of the radar signal (most commonly ranging between 10 kW and 200 kW), which determines the operational range for a given target size. Finally, classification based on mode of operation, most commonly grouped as (a) surveillance radar (b) doppler radar, and (c) tracking radar.

Surveillance radar systems

Surveillance radars are most often used for surveillance of ships (know as ship radar or marine radar); aircraft (airport surveillance radar); or precipitation (meteorological radar or weather surveillance radar [WSR]). These are characterized by a scanning antenna often shaped as a 'T-bar' or as a parabolic disc (conical or pencil beam). Surveillance radars can be used to map the trajectories of moving targets and the echo trail feature makes each echo visible for a given amount of time. Low-powered surveillance radars can detect individual birds (size of ducks) within a range of a few kilometres and flocks of birds up to 10 kilometres. These antennas can be mounted on a tripod, observation tower, or vehicle. High-powered surveillance radars can detect birds within a range of 100–240 km (Gauthreaux & Belser 2003) and are applied as stationary air route surveillance radars, airport surveillance radars, WSRs (Koistinen

2000) or military surveillance radars. Some of the high-power L-band radars are equipped with a Moving Target Indicator (MTI) that prevents stationary or slow moving echoes from being displayed on the monitor (in radar terms, Plan Position Indicator, or PPI).

Surveillance radars can also be configured to use a fixed beam collecting data along a predefined line of interest. Often these systems are modified marine surveillance radars where the 'T-bar' antenna has been substituted with a fixed parabolic disc. Whilst increasing detection range and providing data on flight altitude, the disadvantage of narrowing beam widths is that spatial coverage is reduced and, hence, the ability to obtain data over a wide area is reduced.

Doppler radar systems

These systems are used in a variety of applications from large scale WSRs to small portable low-powered traffic speed control doppler radars (Evans & Drickamer 1994). The identifying characteristic of these systems is their ability to detect small differences in target position between consecutive pulses of radiation, and generate information on the velocity of the target.

The new-generation weather doppler-radar (WSR-88D) used for weather forecasting throughout the US (159 individual radars) produce pictures showing the base-reflectivity (density of targets), base-velocity (radial velocity), and vertical wind profile (movement of small particles). The WSR-88D operate in the S-band with a peak power output of 750 kW and a scanning pencil beam from a large parabolic disc (diameter of *c.* 9 m), detecting birds at distances of up to 200 kilometres (Diehl *et al.* 2003).

Tracking radar systems

Tracking systems are made mainly for military applications and can only track a single target at a time (Fortin *et al.* 1999). They often have a high peak power output and are of relatively large size. The radar beam is of the narrow pencil type and operates often in the X-band. Most often the air space has to be scanned manually by the operator before locking the radar on to the target, however pre-programmed automatic scanning for targets can also be applied, after which the radar locks onto the target and follows it. The returned signal can be used to describe the three-dimensional movements of the target and provide data on ground speed, heading and modulations of reflectivity. Tracking radars are capable of analysing wing beat signatures (Renevey 1981). It requires the radar to dwell at a single bird for at least the period of a series of wing beats. However, if a flock of birds is illuminated with an incoherent radar, the amplitude fluctuation of the individual birds will destroy the echo signature for potential wing beat frequency analysis. A coherent tracking radar can measure the doppler spectra of individual birds and, in principle, can still provide useful wing beat information for a flock of birds. This is a new measurement technique for bird signature analysis which, as far as the authors are aware, has not yet been practically implemented. As with surveillance radars, the tracking radar can also be operated in a fixed beam mode where data are collected at predefined lines of interest.

RADAR STUDIES IN WIND FARMS

So far only X-band and S-band surveillance radars have been used in ornithological research in relation to wind power production facilities. Surveillance radars are designed for scanning 360° of azimuth to monitor spatially moving targets. However, in order to collect data on flight altitude, systems have been modified to incorporate vertical scanning modes or substituted the scanning 'T-bar' antenna with a fixed parabolic disc.

In Denmark, four bird studies have been conducted using marine surveillance radars. Pedersen & Poulsen (1991) used a 10 kW (Furuno FR-1500; www.furuno.com) surveillance radar with a scanning 'T-bar' antenna to study bird migration routes around an inland wind turbine. They showed that the birds changed direction by 1–30 degrees when passing the turbine, irrespective of whether the turbine was operational or not.

Tulp *et al.* (1999) used a 10 kW X-band ship radar (Furuno FR2125) to study the avoidance behaviour of wintering Common Eiders *Somateria mollissima* to an offshore wind farm comprising 10 turbines. In this study, a marked effect was noticed up to a distance of 1500 meters, with reduced flight activity in the vicinity of the wind farm.

At the Nysted offshore wind farm (Kahlert *et al.* 2000, 2002, 2004, Desholm *et al.* 2003) a before-and-after study is currently in operation, using a 25 kW Furuno FR2125 ship radar. This radar study concerns migrating birds, especially waterbirds. Owing to the relatively long distance between the radar observation tower and the wind farm area, it was difficult to map migration trajectories of landbirds, although larger bodied water birds were easier

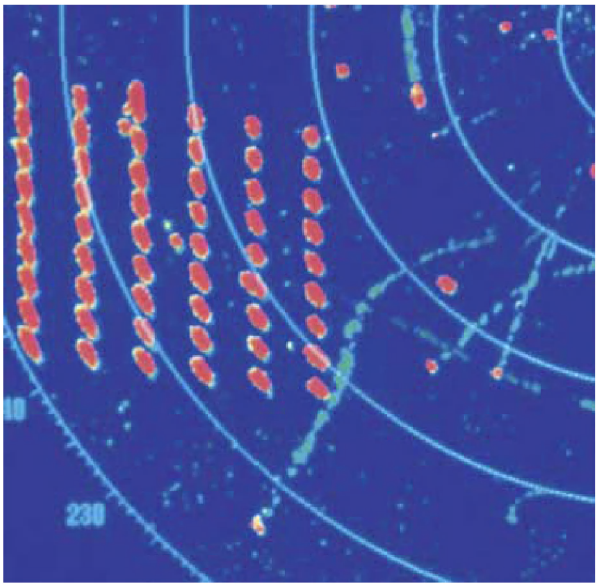

Figure 1. Photo showing the echoes of migrating waterbirds (red echoes with green tails) in the vicinity of the wind turbines (red echoes without tails) at the Nysted offshore wind farm, Denmark.

to track. Profound avoidance behaviour was recorded in a large proportion of the waterbirds in the vicinity of the wind farm (Fig. 1). Those entering the wind farm showed a high tendency to fly in the corridors between individual turbines (Desholm & Kahlert 2005).

At the Danish Horns Reef offshore wind farm in the North Sea, the same radar as that at the Nysted study has been used (Christensen *et al.* 2004), supplemented by a Furuno 10 kW ship radar. The difference in peak power output resulted in a marked difference in performance: the 25 kW radar detected flocks of birds much more easily and at longer range than the smaller 10 kW radar. In this study, avoidance behaviour by wintering and moulting Common Scoters *Melanitta nigra* and by migrating waterbirds was observed.

In the Netherlands, Winkelman (1989) used radar to monitor the nocturnal migration volume at a small land-based wind farm. Recently, a radar study in the Dutch part of the North Sea has been initiated (Sjoerd Dirksen *pers. comm.*). In 2003, Bureau Waardenburg contracted DeTect Inc. (Florida, USA) to install a custom-engineered environmental radar system 'Merlin' on Meetpost Noordwijk: a government owned research platform, situated 10 km off the Netherlands shoreline. The project is set up as a baseline study for the impact assessment for the Dutch Near Shore Wind farm (NSW). The NSW project is a 36 turbine wind farm to be erected 12–18 km off the Dutch coast at Egmond. 'Merlin' consists of a vertically operated X-band and a horizontally operated S-band radar, connected to computers running algorithms on the raw radar data. The system allows for automatic registration of signals of flying birds into a database. Simultaneous measurements by radar and by field observers provide a detailed picture of species and flight patterns. Results of the fieldwork are expected to be published in summer 2005.

In the US, a similar type of system called the Mobile Avian Radar System (MARS) has been used in the environmental impact assessment of the proposed Cape Cod wind farm in the Nantucket Sound (Geo-Marine Inc. 2004). The report of the work specifically mentioned that the X-band radar was particularly sensitive to rain which can provide signals that appear similar to bird echoes, making automatic detection of birds in rain unreliable.

Tracking radars have not so far been used in a wind farm context. To some extent, this can be explained by the way this system locks onto targets. Locking a tracking radar onto a migrating bird/flock approaching a wind farm would provide a good trace of the movement, until such time as the bird(s) passed in front of a moving turbine. The radar would then lock onto the first turbine passed by the bird, since the rotating blades reflect a much stronger pulse of energy than small flying birds. Thus, the risk of adopting such an approach is that only the approach part of the flight trajectory would be mapped, leaving the researcher with no information on the flight pattern of birds in the immediate vicinity of the wind farm – the main objective of the study.

Design of radar studies

The radar needs to be sited in such a way that the observer can view the approach of birds towards the wind farm (which may differ between seasons) to see the volume and direction of movements.

Platform deployment methods

Marine surveillance radars can be used to collect data on both the spatial and vertical distribution of migrating birds if the equipment can be mounted in both vertical and horizontal operating modes. This has to be considered when designing the study, involving either a flexible switching mounting device or preferably two independent radars.

Placing the radar on land will inevitably necessitate the use of long operational ranges if the bird trajectories within true offshore wind farms are to be studied. The advantages of working onshore are: stability; ease of deployment; readily available power supply; use of mobile laboratory; low cost; rapid repair and maintenance; and flexibility to choose height to minimize radar clutter.

Using a ship or fishing vessel as a radar platform will have the one major advantage of the very flexible positional possibility. However, the instability of any but a large (> 40 m) ship at sea will often make radar observations using horizontally mounted surveillance radar of birds more or less impossible due to sea clutter. The use of jack-up barges or oil-rigs as stable radar platforms will always be limited by their availability or high costs of hire. The normal procedure associated with the construction of an offshore wind farm is the erection of a meteorological mast several years in advance of the turbines. These masts will almost certainly have limited space for the radar and a human operator but often will be located conveniently close to the site of the future wind farm. One possibility would be to mount the antenna on the mast and the PPI, power generator and operator on a ship at anchor. Perhaps more preferable would be an adequate platform on the mast for both the radar and its operators.

Data handling

Bird flight trajectories (in all three dimensions) can be stored in a geographical information system (GIS) platform (Fig. 2) which makes further analysis very efficient (Desholm 2003a, Christensen *et al.* 2004, Kahlert *et al.* 2004).

Observed flight speed can be used to group the echoes into different groups of birds (Bruderer & Boldt 2001, Larkin & Thompson 1980, Larkin 1991), since small birds tend to fly slower than larger birds. Radars produce estimates of ground speed which need to be converted to air speed. By accounting for the tail wind component, air speed can be calculated from ground speed, and thus, be used to discriminate between different groups of bird species (e.g. water birds and passerines). Species recognition based on either simultaneous visual observations or on recorded air speed has to be noted in the GIS database of flight trajectories. To our knowledge, the two present studies from Denmark (Kahlert *et al.* 2000, 2002, 2004, Desholm *et al.* 2003, Christensen *et al.* 2004) and the study by Tulp *et al.* (1999) have been the only ones to fully integrate visual observations, radar and GIS to analyse data on avian migrants at offshore wind farms.

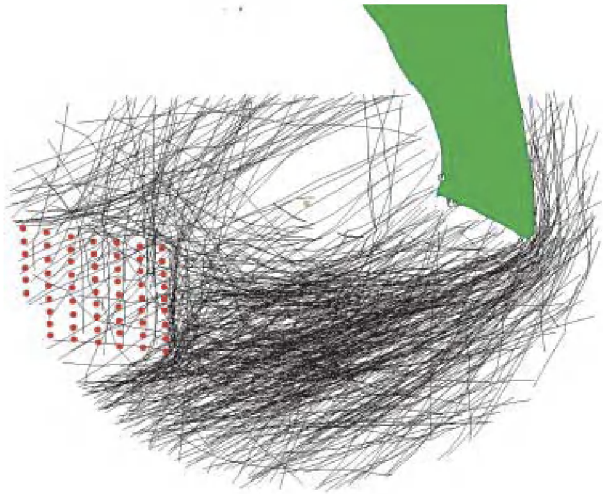

Figure 2. Radar registrations from the Nysted offshore wind farm applied on a GIS-platform. Red dots indicate individual wind turbines, green area the land, green dot the siting of the radar, and black lines migrating waterbird flocks determined visually at the Nysted offshore wind farm. Adopted from Kahlert *et al.* 2004.

Environmental factors are known to modify migration patterns at a given site (Zehnder *et al.* 2001, Alerstam 1990, Baranes *et al.* 2003). In a 'before and after study' these effects needs to be taken into account as covariables, so the possible effects of weather can be excluded as explanatory variables for any sudden change in migration pattern after the erection of a wind farm. Furthermore, if the influence of weather is known to be significant, a range of probability models, describing the probability of entering the wind farm for a given bird flock, should be produced in order to account for the changing risk of collision due to natural variability.

INFRA RED CAMERA SYSTEMS

Early generation hardware

Image intensifier devices (e.g. first, second and third generation night scopes and night vision goggles) are dependent on detecting and amplifying small amounts of ambient light present.

The earlier generations of true infra red cameras were dependent upon an external infra red source to light up a scene (active detectors) and illuminate the object of interest. In a wind farm context, Winkelman (1992) used two such infra red cameras to measure bird migration intensity between wind turbines.

A collision detection system is at present being developed based on microphones for impact detection and active infra red camera for species identification (Verhoef *et al.* 2004).

New generation hardware

The new generation equipment is generally categorized as forward-looking infra red thermal imagers (FLIR). These are true thermal imaging devices (passive detectors) that create pictures based on the heat energy (infra red spectrum of wavelengths between 2 and 15 μm) emitted by objects within the viewed scene rather than from small amounts of reflected light. As the heat radiation passes through the atmosphere, it is subject to a degree of attenuation due to particulate matter, water vapour and the mixture of gases in the air.

The radiation finally reaches the detector within the thermal camera via a lens, typically made of germanium (as IR-radiation is fully absorbed by conventional glass). The camera lens focuses the heat radiation onto elements called infra red detectors that transform the received radiation into an electrical signal. This is then amplified and transmitted to an array of light-emitting diodes that create a visible image, i.e. the thermal image (Hill & Clayton 1985). The long wave cameras (8–13 μm) are less susceptible to absorption by the atmosphere than the short wave (2–5 μm) applications (Desholm 2003b). The ability of a thermal imager to detect a given object is constrained by the optical resolution and the focal length of the lens used (Boonstra *et al.* 1995). Critical to object definition is the thermal resolution, which is defined as the minimum thermal differential between two objects (in this case, the heat signature of the body of a flying bird compared to its background environment).

Thermal imagers have been used extensively in industry (e.g. to detect electrical defective circuit boards and other electrical problems), and in physiological studies using thermography to detect heat differentials in the body (Klir & Heath 1992).

Thermal imagers offer several ways to identify observed birds to species or group level. Although plumage colouration is not distinguishable on a thermal image (birds appear white against a dark background; Fig. 3), body shape, wing beat frequency, flock formation, 'jizz' (often indefinable combinations of species characteristics) and flight pattern can all contribute to species identification by experienced observers. In the study by Desholm (2003b), the thermal imager was calibrated in order to relate a given body length – measured as the number of pixels at the monitor – to a real life body length at a given distance.

Figure 3. Thermal image recorded by TADS and showing a flock of Common Eiders passing the field of view at a distance of *c.* 70 meters.

In southern Sweden, the passerine migration pattern was studied using thermal imaging equipment with a relatively large telephoto lens of 1.45° (Zehnder & Karlsson 2001, Zehnder *et al.* 2001). A 'video peak store' was applied which superimposed several hours of recordings, so that birds passing the field of view appeared as individual lines of dots. This equipment could detect small passerine birds at a distance of up to 3 km. The same thermal imaging device has been used in conjunction with radar to calibrate the moon watching method (see below; Liechti *et al.* 1995).

Infra red studies in relation to wind farms

In a wind farm context, only two studies have been published so far using thermal imagers. The first study was conducted in Holland (Winkelman 1992) where a thermal camera was used to detect avian collisions at a land-based wind farm. The second study is still ongoing in Denmark and involves the development and use of Thermal Animal Detection System (TADS) for collision monitoring and collision model parameterization at an offshore wind farm (Desholm 2005a, 2005b). In the Dutch study by Winkelman (1992) in the 1980s, one thermal camera was used for detecting collisions between land-based turbines and migrating birds. A bird the size of a duck could be detected out to a distance of 50–250 m, 600 m, and 3 km for 15°, 5° and 3°

Figure 4. Photo showing the TADS mounted in the vertical mode on one of the wind turbines at the Nysted offshore wind farm, Denmark.

lens, respectively. In total, 65 birds were observed trying to cross the area swept by the rotor-blades of which 15 collided. Collisions did not always result in death and, in four cases, birds recovered after colliding and continued their flight. In six of the 14 nocturnal accidents, the birds were swept down by the wake behind the rotor and not by the rotor-blades themselves.

During the last 3 years, the TADS has been developed in Denmark for automatic detection of avian collisions at offshore wind farms (Desholm 2003b, 2005). The TADS could cover *c.* 30% of the area swept by the 42 m long turbine blades and detect individual waterbirds and passerines at distances of up to *c.* 150 m and 30 m, respectively. Thermal sensor software triggers the downloading of video sequences onto the hard disk, only when at least one pixel in the field of view exceeds an operator-defined threshold temperature level. This ensured a minimum number of recording events, so that mostly sequences of birds passing the field of view were recorded, avoiding arduous viewing of many hours of empty video sequences.

TADS has been used at the Nysted offshore wind farm in Denmark for measuring the number of collisions between waterbirds and wind turbines (Fig. 4). The collision monitoring programme has so far been running for one spring (Desholm 2005a) and one autumn (Desholm 2005b) migration period. To date, no collisions have been registered, which reflects the general avoidance behaviour of waterbirds towards the wind farm as a whole, and to the individual turbines as shown by radar studies of flight trajectories (Desholm & Kahlert 2005). Both TADS and radar data from that study support this conclusion, as does the study by Hansen (1954). It must be stressed here that only one thermal camera has been applied in this relatively short study of only 3 months and that collisions could have occurred at some of the other 71 turbines within the wind farm.

Design of thermal monitoring studies

When designing a thermal imaging monitoring programme, it is advisable to bench- and field test the equipment well in advance of initiating the study. Getting to know the effects of changing camera settings on the image appearing on the monitor is crucial, especially with regard to achieving sufficient contrast between bird and background (e.g. water surface or the clear background of a full clouded sky). Secondly, the trade-off between focal length (i.e. strength of the telephoto lens) and area of the field of view at a given distance should be taken into account when deciding the distance between thermal detector and monitoring area, and lens size. The consequence of a reduced monitored area (when using telephoto lenses), will be a reduced amount of accumulated data, if the number of monitoring devices or time spent on monitoring is not increased accordingly.

Collision monitoring

When dealing with the direct measurement of bird collisions, a monitoring programme must be the subject of careful design. The aim of such a programme will be to compile enough information to form the basis for a sound statistical analysis. Thus, the appropriate temporal scope and hardware volume of such investigations will be dependent on the actual number of collisions and on the spatial and temporal distribution of these at the wind farm. If several collisions occur daily at all the turbines, a single camera would be sufficient for a data collection protocol. However, if the annual collision rate amounts to 1–5 birds per annum within a 80 turbine wind farm, many more devices will be needed in order to provide reasonable precision on collision risk estimates. This means that low collision risk necessitates a large-scale monitoring programme (both in terms of number of devices and monitoring time).

The process of running a collision-monitoring scheme consists of operating the camera system over a given period. The degree to which the system is capable of running automatically will, to a high degree, determine the investment of man-hours needed. In the absence of automation, the operator will need to operate the camera and subsequently visually process all the recordings. Processing recordings can be made more efficient in two ways. Firstly, by fast-forward viewing of the recordings. Second, by the use of a video peak store to superimpose several hours of recordings onto a single frame (Zehnder & Karlsson 2001, Zehnder *et al.* 2001). If the image of the bird is represented by a very few pixels, the risk of missing an event during rapid visual viewing of the recordings increases significantly. Similarly, using the video peak store method, there is a risk that birds passing close to the camera will not be visible on the superimposed picture, because the time taken for the bird to pass out of the field of view will be less than the time interval between two consecutive frames. To date, TADS is the only system that merely records images when birds are either passing or colliding with the turbine blades (Desholm 2003b, 2005). However, the limited field of view is a drawback in terms of assessment, particularly when the cost of the appliance is taken into account. When running an avian collision detection programme, it is advisable to log all activities in a logbook. This ensures that data relating to monitoring efficiency, number of bird flocks passing per unit time, the influence of time of day and of the natural viability induced by weather on the collision risk can be analysed after the field season.

Collision monitoring can be either designed as a high intensity programme using a large number of thermal cameras for measuring the low daily collision frequency, or as a low intensity programme with only one or two thermal cameras for detecting periods with a high number of collision casualties under rare and unusual situations. Such mass mortality events have been reported in studies of illuminated land-based super-structures (Lensink *et al.* 1999, Nilsson & Green 2002) and of offshore platforms (Müller 1981). High death rate events may occur at offshore wind farms under conditions where a relatively uncommon combination of factors result in high collision events (e.g. high migration volume and a sudden decrease in visibility).

Collision model parameters

If the direct measurement of avian collisions turns out not to be feasible (economically, technically or for other reasons), an indirect approach of modelling the avian risk of collision can be applied. This approach necessitates the construction of statistical models that can forecast the number of potential future collisions that may occur at a given wind farm site. For this modelling work, radar data describing the three dimensional avoidance response and migration trajectories will be essential. However, the infra red monitoring device can also contribute with important data to these models, especially by providing estimates for the following parameters:

(1) near turbine blade avoidance behaviour;
(2) flight altitude;
(3) flock size (especially at night); and
(4) species recognition (especially at night).

Other techniques

Visual observation

During daylight, long-range spotting scopes (e.g. × 30 magnification) can be used to identify avian migrants to species, to a distance of at least 5 km for larger birds such as ducks and geese (Kahlert *et al.* 2000, 2002). This detection distance depends on the height above sea level at which the observer is sitting and the weather specific visibility. The fact that this method cannot be used in darkness and in periods with dense fog is its predominant shortcoming, since these are the very periods when one would expect the highest number of collisions to occur. For this reason, visual observations alone can never be the only mode of assessment. However, this 'low-tech' method can supplement the more sophisticated approaches using radar with very important specific data on migration volume, flock size and species identification (least during the daylight). Thermal cameras can provide these data during both day and night, but are constrained by a restricted data volume resulting from the smaller field of view and relatively fixed viewing direction. Light sensitive recordings suffer similar limitations as spotting scopes with regard to poor visibility. Nevertheless, a video camera can be operated remotely and can therefore potentially collect offshore data for long periods. The drawback of this system is the many hours of recordings, which have to be visually viewed, although this could be done remotely at the office and may be be simplified by the use of automatic pattern recognition software if developed in the future.

Avian acoustic monitoring

Detecting bird sounds using microphones in the vicinity of turbines offers sources of information to tackle two different issues. Firstly, monitoring of bird calls for species recognition (Larkin *et al.* 2002) and second, monitoring the sound of birds colliding with wind turbines as a means of measuring collision rate. The technique of acoustic monitoring by sensitive microphones of avian night flight calls is a way of producing a list of bird species migrating over a given site at night. Dierschke (1989) reported that very few species were calling intensively over the North Sea, and hence, that the acoustic monitoring was highly biased towards a few species. Additionally, this method will be biased towards species migrating at low altitudes which is likely to differ between areas. The relative volume (detection rate) at the species level can be obtained (Farnsworth *et al.* 2004), but such data will always be biased towards species using contact calls during nocturnal migration and towards birds migrating at lower altitudes. From studies in the US, some 200 species are known to give calls during night migration, of which roughly 150 are sufficiently distinctive to identify with certainty (Evans 1998). The remaining species can then be lumped into a number of similar-call species groups. The acoustic data on tapes can either be processed by ear or analysed by sound analysis software (Evans 1998).

At the time of this review, the ECN (Energieonderzoek Centrum Nederland) in the Netherlands is developing a bird–turbine collision detection system based on microphones linked to a video camera (Verhoef *et al.* 2004). The system aims to detect the acoustic signal created by birds hitting the turbine structures. The microphones are placed on the inner side of the turbine tower and the acoustic data are continuously analysed by sound analysis software. The system is not operational at present and some major problems remain unsolved. For example, the background noise of larger turbines far exceeds original expectation, and hence, the signal from avian collisions cannot be separated from background mechanical sounds. Furthermore, there are several shortcomings associated with the camera, because the quality of the night time images have been insufficient for species recognition, necessitating excessively long exposure times (Verhoef *et al.* 2004)

Acoustic monitoring could be used in combination with radar or TADS in order to determine the species detected by these other methods.

Laser range finder

A laser range finder can be used to measure the distance and vertical angle to an object and thereby estimate the height. Furthermore, the horizontal angle also can be obtained in some devices which, in combination with the distance to the object and the geographical position of the observer, can give a three-dimensional position of the object (Pettersson 2005). Several consecutive positions of an object, e.g. a migrating bird flock, can be used to describe the migration trajectory of the bird. The drawback of this method is that it can be operated only in daylight, the spatial resolution is relatively restricted, and it is also hard to hit a small and fast moving object. However, it offers an alternative to radar measurements of flight trajectories at short distances from the observer and during daylight periods.

Ceilometers

Ceilometer surveys involve direct visual observation of night-migrating birds using a high-powered light beam directed upward from a study site (Able & Gauthreaux 1975, Bruderer *et al.* 1999, Williams *et al.* 2001). Birds will appear as white streaks as they pass through the beam and must be viewed through a spotting scope or binoculars. In general, this method enables birds as small as thrushes to be detected and counted up to a distance of up to 400 m from the observer. Data can be collected on total number of birds passing the beam and can be used to estimate an overall passage rate for the site. Furthermore, the approximate heading of the migrating birds can be assessed. At wind farms, this method can be used to describe the species or groups of species composition during night-time migration. One of the biggest drawbacks is the necessary night-time siting of a human observer on an offshore platform.

Moonwatching

Moonwatching is a similar technique to the ceilometer where the light beam is exchanged by the full or nearly full moon (Liechti *et al.* 1995). Otherwise this technique follows the procedures used in ceilometer surveys. Moon-watching can be a useful adjunct to ceilometer-based studies, since ceilometer beams are difficult to see on bright moonlit nights.

Carcass collection

The practice of collecting dead and injured collided birds at offshore wind farms is believed to be untried and is judged to be unrealistic due to the currents moving corpses away from the collision site and due to an unknown scavenger rate. Construction of floating bunds and/or nets to retain corpses is expensive and impractical and would not overcome problems associated with predator scavenging over longer sampling periods.

FURTHER METHODOLOGICAL DEVELOPMENT

The wind industry is in its initial stage of exploiting the European waters, and hence, only few studies on wind farms have so far been conducted in offshore areas. As a consequence, only a limited amount of experience has been acquired regarding the use of radar and thermal imaging technologies in this specific context. Some promising methods are still to be developed and some of the existing technologies could benefit from a further development or bird-turbine specific adjustments.

So far only horizontal surveillance radar have been used in effect-studies of offshore wind farms (Kahlert *et al.* 2000, 2002, 2004, Desholm *et al.* 2003, Christensen *et al.* 2004), so even though the combined set-up of both a vertical and horizontal radar are being used in offshore areas, the results are not yet published.

It could be of great value to perform terrestrial validation tests of the TADS, so that the collision measures from this remote technology could be verified by carcass collection on the ground. The amount of data generated from TADS monitoring is still very limited, and hence, further collection of data could enhance our understanding of this passive infra red technique and its future application possibilities.

Another possibility could be the development of a low cost sensor-system for detecting the impact from bird-turbine collisions for large-scale implementation, i.e. at every turbine in a wind farm. It could be either a further development of the WT-bird microphone system (www.ecn.nl; Verhoef *et al.* 2004) or could be based upon a system using the piezo-electric technology that can detect acoustic vibrations in materials (e.g. vibration waves arising from the impact of birds hitting the rotor-blades, nacelle or tower construction). This approach necessitates collation of information on background vibration of turbines in order to detect vibrations from colliding birds.

COLLISION MODELLING

When constructing collision prediction models we have to discern between models for EIA studies (pre-construction) and models for effect studies (pre- and post-construction) since only the latter offer the opportunity to include avian avoidance response to wind turbines. This is because data on species-specific avoidance manoeuvring is very scarce. Consequently, such data need to be collected at the study site of interest before proper estimates of the number of collisions (including avoidance behaviour) can be estimated through quantitative predictive modelling (Chamberlain *et al.* 2006). Nevertheless, it is recommended to build non-evasive-type models as part of the EIA studies as a first crude assessment of the potential risk of collision for any proposed wind farm.

Framework for a collision model

Risk of collision is defined as the proportion of birds/flocks exposing themselves to collision by crossing a collision conflict window. The risk of collision (r_i) is assessed at four levels of conflict windows: Level 1 relates to the study area, level 2 the wind farm, level 3 the horizontal reach of rotor-blades, and level 4 the vertical reach of rotor-blade (Fig. 5). The value of r_i can be measured directly for each level post-construction as the transition probability distribution, or be estimated pre-construction by multiplying the pre-construction proportion of birds/flocks (p_i) passing the level specific conflict window with the assumed (published estimates) proportion of birds (a_i) not showing any evasive manoeuvres at the given level. After level 4, a factor describing the by-chance-probability (c) of not colliding with the rotor-blades must be incorporated to account for those birds safely passing the area swept by the rotor-blades by chance (Fig. 5; Tucker 1996, Band *et al.* 2005). An overall risk of collision (R) can be obtained by multiplying the four probability risk values:

$$R = r_1 \times r^2 \times r_3 \times (r_4 \times (1-c)) \qquad [1]$$

The simple deterministic way of estimating the overall number of collisions at the wind farm ($n_{collision}$) would be to multiply R with n_1 using mean values for transition probabilities and for the *c*-value. The more profound way of estimating $n_{collision}$ would be by simulating the migration event from n_1 through $n_{collision}$ in accordance to the collision prediction model by resampling transition probabilities from field data-based probability distributions and applying the re-crossing loop (flocks passing more than one row of turbines; Fig. 5).

This model can be applied for different scenarios such as:

(1) day and night;
(2) head-, tail-, and cross-wind (especially r_3 and c may be affected by wind direction (Liechti & Bruderer 1998, Tucker 1996)); and
(3) rotor-blades, foundation and turbine tower.

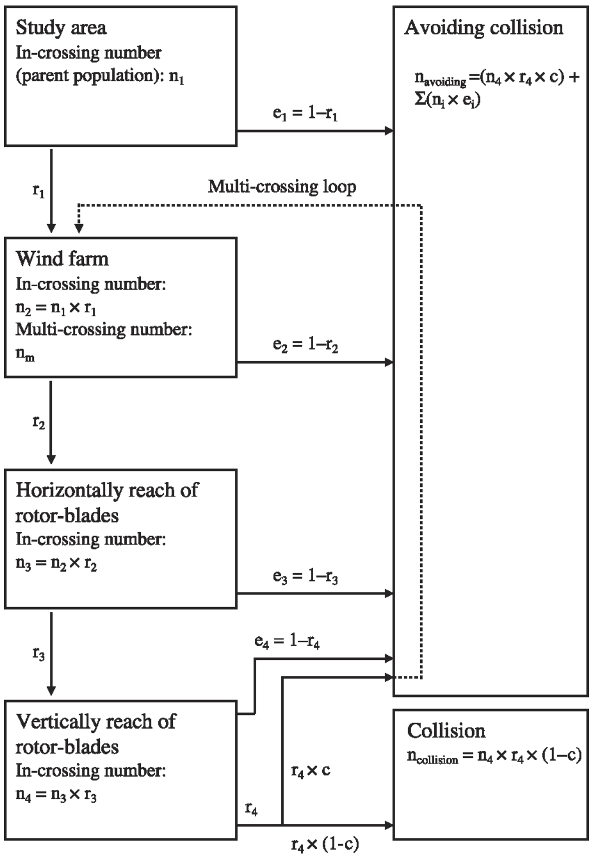

Figure 5. Schematic presentation of the collision prediction model where the boxes to the left represent the four scale-specific conflict windows and the boxes to the right the non-colliding and colliding segments of the migrants. The six values of n_i denote the number of birds/flocks which enter each box and can be calculated in accordance to the equations presented in the boxes. The migration volume in the study area is represented by n_1. The r_i-values represent the transition rates of birds exposing themselves to a conflict window and the e_i-values represent the transition rates of birds performing an evasive behaviour and thereby avoid colliding with the rotor-blades of the wind turbines. The n_m-value denotes the number of turbine rows passed, $n_{avoiding}$ the number birds avoiding a collision, $n_{collision}$ the number birds colliding with the rotor-blades of the turbines, and c the theoretic non-evasive probability of passing the area swept by the rotors by-chance.

Finally, the results from these partial models can be combined in an overall estimate of number of collisions at the wind farm under study. Parameterization of the collision prediction model can be done by applying radar, TADS and visual observations in the data collection protocol as follows for each of the four spatial levels (Fig. 5):

Level 1. n_1 represents the overall number of birds/flocks passing the study area during a migration event (i.e. spring or autumn migration season);

Level 2. For this part of the analysis radar data defining the probability distribution/proportion of migrants passing the wind farm is needed (r_1);

Level 3. Radar data defining the distance to the nearest turbine is needed for those flocks that pass through the wind farm. From the compiled frequency distribution of distance to nearest turbine, the proportion (r_2) of the migrating flocks that pass within the horizontal risk distance (equal to the length of the rotor-blades) of the turbines can be calculated for day and night. Desholm & Kahlert (2005) has recently recorded such diurnal difference in mean distance to turbines for waterbirds; and

Level 4. In order to estimate the proportion (r_4) of birds flying within the vertical reach of rotor-blades, a height distribution is needed. Depending on the level of information on migration altitudes the height distribution can be based either on theoretic values or preferably on directly measured altitude data collected at the study site. Altitude data on migrating birds can be collected by operating surveillance radar vertically or by applying the height data collection protocol by TADS (Desholm 2005b).

At this stage, n_4 (number of birds/flocks passing the area swept by the rotor-blades) is estimated and the final transitions to birds colliding with ($r_4 \times (1-c)$) and avoiding the rotor-blades ($e_4 + (r_4 \times c)$) must be executed. For inclusion of the near rotor-blade avoidance rate (e_4), which must be collected during both day and night, infra red detection systems (e.g. TADS) should be applied. So far, only Winkelman (1992) has reported avoidance behaviour using a thermal camera. Finally, an avoiding-by-chance factor (c) must be implemented after level 4 for those birds crossing the rotor-swept area safely, without performing any avoidance actions. Procedures for calculation of 'c' can be found in Tucker (1996) and Band *et al.* (2005) and can be directly incorporated in the collision prediction model.

The end product of the collision prediction model will be the predicted number of birds colliding with the turbines:

$$n_{collision} = n_4 \times r_4 \times (1-c) \quad [2]$$

and the predicted number of birds that avoid (either by chance or by evasive actions) colliding with the turbines:

$$n_{avoiding} = (n_4 \times r_4 \times c) + \Sigma(n_i \times e_i) \quad [3]$$

where n_1 (overall number of birds passing the study area) equals the sum of $n_{collision}$ and $n_{avoiding}$.

CONCLUSIONS

It must be emphasized that, due to the immature state of the offshore wind power generation and the relating environmental studies, both pre- and post-construction studies are of the utmost importance. Only by post-construction collection of data on avoidance response, can future pre-construction EIAs properly assess and predict the future impact from proposed wind farms.

Radars

It is concluded that, at present, the low-powered marine surveillance radars or modified avian research laboratory radars are the most appropriate radars for use in bird studies relating to a single wind farm. Economically, these relatively low cost systems are more feasible than both the tracking and doppler weather radars, if these are to be used specifically for a wind farm EIA. At present, all radars used by ornithological researchers have been constructed for detection of objects other than birds, and hence, their performance within this field is likely to be sub-optimal. Plans exist for developing a dedicated bird radar targeted exclusively at detecting flying birds and aimed at data collection on three-dimensional trajectories and wing beat frequency at relatively long range (Desholm *et al.* 2005).

It must be stressed here that in the near future strategic and larger-scale studies will most probably be initiated in Europe and the US, aimed at gathering information on the general migration patterns in different regions, enabling a more strategic, scientific planning process for the future siting of large offshore wind farms. The high-powered tracking and doppler radars might prove to be the best option for such generic studies.

Infra red camera systems

In general, it can be concluded that the thermal imaging products available can provide data on nocturnal bird behaviour that is difficult to obtain in any other way. For fast processing of data three options exist so far:
(1) fast viewing of recordings;
(2) trigger software that excludes the non-bird observations (Desholm 2003b, 2005b); and
(3) video peak store which superimposes several hours of recordings on to a single frame (Zehnder & Karlsson 2001, Zehnder *et al.* 2001).

The operational distance is much less than for ordinary video equipment due to the relatively low optical resolution in thermal imaging devices, but can in part be overcome by the use of large telephoto lenses. However, the trade-off between operational distance and the size of the field of view at a given distance should be considered, since the area monitored by the infra red device will affect the amount of data (number of birds passing the field of view) that can be collected by one thermal camera within a given amount of time.

Only one type of hardware arrangement (the TADS) has so far been used as a remotely controlled system for monitoring the collision frequency in offshore areas. However, since this kind of remote controlled software is comprised of standard components for any operational system, there are no constraints on its use besides the necessity for an optic fibre linkage between land and wind farm. TADS is the only system adapted for offshore use under harsh and corrosive (especially salt) conditions. No severe problems have been encountered with regard to its offshore use and the fact that the prototype of TADS has been operating continuously under these extreme conditions for more than 2 years clearly shows that these possible constraints can be easily resolved.

Before designing a thermal imaging programme it is important to consider several aspects of the study. Firstly, the physical structures available as potential mounting platforms (turbines and transformer platform, weather measurement towers) must be considered, since these and (especially) the distance between them can constrain the data collection because of the limited resolution of such thermal imaging devices. Second, it is necessary to consider the species of interest (or at least the size of the key focal species) and whether single individuals or flocks of birds form the focus of the study. If small birds are the main target and single individuals need to be detected (if collisions are to be measured directly) a telephoto lens is needed, and thus, the field of view will be highly restricted. A small field of view will necessitate greater replication (i.e. more TADS devices) if reliable collision estimates are to be produced. A low migration volume will also require a larger number of devices in order to increase the sample size of the data set.

Impacts on the population level

This review deals exclusively with the local effects from single wind farms, but more interesting in a biological and ecological perspective is the impact on the population level of the bird species involved.

A fly-way population of a specific species may not be impacted by 80 2 MW turbines erected at a single site, but if we are dealing with a long-distance migratory bird species, they might have passed several other utility structures along their migratory corridor. Thus, from a conservation management perspective, all the potential local effects must be assessed in combination. Such population level assessments cannot be expected to be dealt with at every single wind farm, but must be handled at a more strategic level, perhaps co-ordinated by governmental institutions. If negative effects are occurring at the site level, governments must provide best practice guidance for local EIAs, with the purpose of more strategic population assessments in mind. However, since avian migrants, by their very nature, cross national boundaries, a forum like the EU might be a suitable level for developing such strategic guidelines.

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III

Avian sensitivity to wind farm-related mortality: a general framework for setting management priorities for migrating species

DESHOLM, M.

Submitted

Title:
Avian sensitivity to wind farm-related mortality: a general framework for setting management priorities for migrating species

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Summary

1. Wind power production will become one of the greatest human physical exploitation activities of European marine areas in the near future. International obligations and great public concerns exists for the many millions of avian migrants that every spring and autumn must pass these man-made obstacles. Yet some bird species are more vulnerable to bird-wind turbine mortality than others.
2. In this study, a simple and logical framework for ranking bird species with regard to their relative vulnerability to wind farm related mortality was developed. To exemplify its use, a data set comprising 38 species of avian migrants at the Nysted wind farm in Denmark was processed. I chose two indicators believed to characterize the vulnerability of each individual species: 1) relative abundance and 2) demographic vulnerability (elasticity of population growth rate to changes in adult survival).
3. Common eider and rough-legged buzzard showed the highest values in relative abundance and the 15 species showing the highest values of relative abundance were either (excluding hirundines) birds of prey or waterbirds.
4. Bewick's swan and barnacle goose shared the top ranking position as the species showing the highest elasticity and the 19 species showing the highest values were all birds of prey or waterbirds.
5. Birds of prey and the waterbirds exclusively dominated the group of species of high conservation priority. Besides goshawk and merlin, only passerines were represented by low levels in one or in both of the indicators of the priority framework.
6. *Synthesis and applications.* In general, it is recommended that future bird-wind farm studies should allocate resources to the study large bodied and long lived species like birds of prey and waterbirds. Even though passerines might be present in very high numbers, the affected birds very often represent insignificant segments of huge reference populations that, from a demographic point of view, are relatively insensitive to wind farm related adult mortality. It will always be important to focus attention and direct the resources towards the most vulnerable species if the wind power production shall maintain its reputation as being sustainable from a nature conservation point of view.

Introduction

During the last decade, the first marine wind farms have been constructed in European waters and the potential for further development seems almost unlimited in the many shallow offshore areas of the world. This renewable electricity from wind power can contribute to achieving national Kyoto targets for sustainable energy development. However, the green image of wind power may be jeopardized if the local wildlife is adversely affected.

Migrating birds will inevitably collide with offshore wind turbines (Barrios & Rodriguez 2004). However, the impacts at population level of a given number of casualties will depend greatly on population size and life history traits (Fox et al. 2006). Long-lived bird species are highly sensitive to very small changes in annual adult survival (Sæther & Bakke 2000). By contrast, many small passerines have lower annual adult survival, but produce many young in successive broods making them more robust to replace lost adults, potentially through density dependent changes in reproductive output. For this reason, population modeling and simulation most be an integral part of the assessment of the likely cumulative impact of observed collision rates on the different geographically defined avian populations.

In accordance to European Union legislation the development of such large offshore installations needs careful planning through Strategic Environmental Assessments (SEA) at the national or regional level and Environmental Impact Assessments (EIA) at the local area level to ensure that environmental consequences of projects are identified and assessed before authorisation is given. Finally, the results from an EIA can be used when designing further investigations, like for the Effect Studies (ES) undertaken pre- and post-construction at the two Danish offshore demonstration wind farms (Christensen et al. 2004; Desholm & Kahlert 2005; Desholm et al. 2006; Fox et al. 2006).

However, many different migrating bird species can potentially pass proposed future wind farm site and in very different numbers. In EIA- or ES-studies, tools for focusing attention on the most vulnerable species must be developed. Only in this way we can ensure that limited available resources can secure sustainability of future wind power developments with suitable emphasis upon

the most vulnerable bird species. Identifying these species is a problem that depends upon many different biological factors such as the site specific migration volume, population size, flight altitude, avoidance behaviour, and demographic vulnerability to wind farm related mortality.

The main aim of this study was to develop a general framework for setting management priorities by categorizing species according to their relative vulnerability to wind farm-related mortality. To do this, I developed an Environmental Vulnerability Index (EVI) composed of an abundance and a demographic vulnerability indicator, two indicators believed to characterize the vulnerability of migrating birds to wind farm related mortality. Finally, the EVI was applied to the Nysted offshore wind farm, situated at one of the major avian migration bottlenecks in the Baltic Sea, in order to categorise the bird species with regard to their local conservation concern, and thus, inform the process of priority setting between species.

Methods

INDICATORS OF VULNERABILITY

Many factors can be argued to influence the species specific vulnerability to wind farm related mortality and consequently the challenge lies in limiting the number of different currencies to be compared with each other in a multiple-factor EVI. My approach has been to design a general framework that can be used at all levels of information. Thus, it can be applied from the lower end of a continuum, where ecologists know only the species and their numbers passing a given study area, to the upper end where a detailed knowledge on the species specific local spatial migration pattern and the species specific avoidance behaviour is available.

I chose two indicators describing the species specific sensitivity to wind farm related mortality, first, the indicator of relative abundance, and second, the indicator of demographic vulnerability. This means that the resulting EVI will end up with only two uncomparable currencies which can be plotted against each other for visual presentation, and thereby, avoiding reliance upon arbitrary weightings of incompatible multiple factors.

(1) Relative abundance

Relative Abundance (RA) is defined as

$$RA = \frac{\alpha}{\beta} \times 100\% \qquad \text{eqn 1}$$

Were α is the number of individuals passing a given risk window (see below) and β is the number of individuals within a geographic reference population. Thus, the indicator of relative abundance is based on two factors describing each species and sharing "number of individuals" as the common currency.

The definition of risk window, used for assessing α, depends on the available information on migration volume:

Level 1) local study site,
Level 2) proposed wind farm area,
Level 3) collision zone (static turbine structures and rotating blades) without avoidance behaviour, and
Level 4) collision zone with avoidance behaviour.

In the pre-EIA situation, the level of available information on avian migrants may be close to none if no ornithological studies have ever been performed at the given study site, which will not support any priority setting between species. However, if the proposed wind farm site lies close to an avian migration corridor, the chance that either migration counts or bird ringing has taken place and at minimum a list of the species and numbers passing the study area may therefore be available (this referred to information level 1). This situation allows focusing on vulnerable focal species even before the EIA study, which in practical terms may influence the design of the study. In a post-EIA situation, when priority setting with regard to focal species for a following ES is desirable, the amount of information will most likely cover either level 2 or 3. Consequently, a more robust assessment can be made of the vulnerability of the different species or groups of species. As more data on species specific avoidance behaviour gets published the use of information level 4 will be possible. At present avoidance data across species are not available from the literature, and hence, the ecologist must support the species priority setting procedure at a maximum information level of 3.

Reference population (β) is here defined as the size of the breeding population (individuals) from the breeding area occupied by the birds passing the migration study site. To define the reference population more specifically the ecologist must run through each species or group of species to delineate their migration flyways and breeding distribution. For this delineation process the many published flyway atlases, ringing atlases, and population assessments is of great value (for examples see references in Appendix S1). This novel definition of reference population is not the only one existing and the present framework for priority setting aims at potentially covering all possible scales, and hence, can be used by authorities to cover the spectra from small local breeding populations of national interests to large bio-geographic defined global migration flyways.

(2) Demographic vulnerability

This indicator is based on the elasticity value e_{s2} describing the proportional change in growth rate (λ) resulting from a proportional change in adult survival (s_2) for each species (Benton & Grant 1999; De Kroon et al. 2000; Caswell 2001). In other words, e_{s2} is an indicator of the vulnerability of a species to relative changes in mean adult mortality, here represented by bird-turbine collisions. Species specific elasticity values are estimated for 25 hypothetical bird species by the use of simplified stage-classified Leslie matrix models (Caswell 2001) where theoretic values of immature survival (s_1), adult survival (s_2), and annual adult fecundity (f_2) were applied.

I constructed the matrix population models and estimated the elasticity values using the ULM software (Legendre & Clobert 1995; Ferriére et al. 1996; Legendre 1999). The female-based projection matrix includes two stage classes (pre-breeding and breeding), has pre-breeding census, a projection interval of one year and assume a balanced sex ratio:

$$A_i = \begin{bmatrix} f_1 & f_1 \\ S_1 & S_2 \end{bmatrix} \qquad \text{eqn 2}$$

Were female fecundity (f_1) is set to 0 which makes sense since f_1 refer to the fecundity of pre-breeding females, and were s_1 is chosen to give $\lambda = 1$ which have been shown (Sæther & Bakke 2000) not to influence the distribution among species of the elasticities of the fecundity rate and of adult survival. The whole population modelling rationale is female-based meaning that population size, adult survival, and fecundity (number of offspring) refers to females only. The models were run using the different combinations of f_2 (range: 1-5) and s_2 (range: 0.1-0.9). An elasticity landscape was generated showing the relationship between s_2, f_2 and e_{s2} (Fig. 2) and for each of the five values of adult fecundity a linear regression analysis was performed generating the equation and coefficient of determination (r^2; see legend to figure 2). In practical terms, these equations can then be used to estimate e_{s2}, representing the indicator of demographic vulnerability in the EVI, by the use of already published values of s_2 and f_2. For many species the available amount of demographic data is rather sparse and in these situations values can be used from similar closely related species. Such generalised and relatively simple population Leslie matrix models have been shown to capture the essentials of full age-classified Leslie matrices (Braut & Caswell 1993; Levin et al. 1996; Heppell et al. 2000), and they may therefore represent a useful tool for a first assessment of the relative vulnerability to wind energy related mortality for different bird species.

FRAMEWORK FOR PRIORITY SETTING

The avian migrants can be ranked in accordance to the two indicators separately or they can be grouped in to different levels of conservation priority on the basis of both ranking lists. Here I assign the species to three different levels of conservation priority: 1) high, 2) medium, and 3) low (for definitions see figure 3).

NYSTED OFFSHORE WIND FARM AS A CASE-STUDY

To exemplify the use of the framework, a data set based on autumn migrating birds at the Gedser Odde peninsula, Denmark (Fig. 1) was applied. This area now holds one of Denmark's two large offshore wind farms, the Nysted offshore wind farm. The data comprise species composition and number of day-time migrants (Appendix S1) and are adopted from the Nysted offshore wind farm EIA-study (Christensen & Grell 1989; Skov et al. 1998; Kahlert et al. 2000).

Additionally, data on species specific size of reference population and annual adult fecundity and survival was compiled from the literature for all the species listed in the EIA-study (Appendix S1).

Defining the reference population will inevitable rely on a combination of objective population estimates and a more of less subjective judgement of the geographic breeding origin of the birds migrating through a specific study area. Ideally, a sub-sample of all species migrating through the study area should be ringed at the site and their breeding range analysed before assessments of the reference population size should be performed. However, this would be a very time and resource demanding operation that, in reality, may not even be feasible. Here, I chose to make some general definitions of breeding origin for the different species groups. Passerines are known as broad-fronted migrants with a general south-westerly orientation during autumn migration, and hence, their breeding origin was defined as the birds breeding to the north and north-east of the study area, or more specifically, birds breeding in Sjælland (i.e. eastern part of Denmark), Sweden and half of the Finnish population. The reason for only including half of the Finnish population is that Finnish passerines are known to also migrate southward along the eastern side of the Baltic Sea. For twite *Carduelis flavirostris* (Linnaeus), half of the Norwegian population was included due to its very northern distribution and because the Swedish and Finnish populations are relatively small. The breeding origin for waterbirds (divers, swans, geese, ducks, crane *Grus grus* (Linnaeus), shorebirds, skuas, gulls and terns) was generally defined as birds breeding along the Baltic coast, Swedish and Finnish inland, west Siberia, and Russian arctic. Smaller adjustments were made for some of the waterbird species because their special migration patterns are well known, e.g. the common eider *Somateria mollissima* (Linnaeus) reference population is based on the Baltic/Wadden Sea population only, since birds from northern Finland and from costal west Siberia are known to migrate westward to Norway during autumn migration. Within the group of birds of prey the general definition of breeding origin was Sjælland, Sweden and Finland. Again smaller adjustments were performed for some of the species, e.g. the Finnish buzzard *Buteo buteo* (Linnaeus) population was left out from the reference population estimate because this segment of the population is known to migrate solely along the eastern Baltic Sea coast (Hagemeijer & Blair 1997). Annual adult survival and fecundity values were compiled from the literature and used to estimate the elasticity values of adult survival in accordance with figure 2 (Appendix S1).

Results

ELASTICITY LANDSCAPE

The 25 modelled hypothetical bird species showed strongly different elasticity values especially between groups with different values of adult survival which is apparent in the elasticity landscape (Fig. 2). The contribution from adult fecundity to the variation of elasticity was more moderate but increased exponentially with increasing adult survival ($y = 0.0003 \cdot e^{0.4822x}$; $r^2 = 0.9694$), i.e. that the increase in e_{s2} with increasing adult fecundity was most pronounced among groups with high annual adult survival rates (Fig. 2).

THE CASE-STUDY AT NYSTED

Relative abundance

The 15 species showing the highest ranks were all, except for hirundines (sand martin *Riparia riparia*/barn swallow *Hirundo rustica*/house martin *Delichon urbica*; Linnaeus; rank no. 9), belonging to the groups of birds of prey or waterbirds.

Within the waterbirds, relative abundance varied from 0.29% in divers *Gavia stellata* (Pontoppidan)/*Gavia arctica* (Linnaeus) to 33.8% in common eider. Ten out of fourteen waterbird species occurred in numbers representing more than 1% of their reference population.

Among birds of prey the relative abundance varied from 0.01% in goshawk *Accipiter gentilis* (Linnaeus) to 22.8% in rough-legged buzzard *Buteo lagopus* (Pontoppidan) with a general trend showing that species with a more southerly distribution (e.g. red kite *Milvus milvus* (Linnaeus) and marsh harrier *Circus aeruginosus* (Linnaeus)) and species known as soaring migrants (e.g. red kite, honey buzzard *Pernis apivorus* (Linnaeus), buzzard, and rough-legged buzzard) in general had the highest values of relative abundance. Eight out of eleven species of birds of prey occurred in numbers representing more than 1% of their reference population.

Amongst the passerines, the relative abundance varied from 0.03% in coal tit *Parus ater* (Linnaeus) and tree pipit *Anthus trivialis* (Linnaeus) to 4.11% in hirundines. Besides hirundines only the two largest species of non-birds of prey landbirds, wood pigeon *Columba palumbus* (Linnaeus) and jackdaw *Corvus monedula* (Linnaeus), appeared in numbers representing more than 1% of the their respective reference populations.

Elasticity

Bewick's swan *Cygnus columbianus* (Ord) and barnacle goose *Branta leucopsis* (Bechstein) ranked highest amongst elasticity values and the lowest values of elasticity were estimated for hirundines and siskin *Carduelis spinus* (Wilson; Appendix S1). The 19 species showing the highest elasticity values (i.e. the upper half of the list of 38 species) were either birds of prey or waterbirds, and only the three smallest birds of prey species merlin *Falco columbarius* (Linnaeus), sparrowhawk *Accipiter nisus* (Linnaeus), and kestrel

Falco tinnunculus (Linnaeus) and the three smallest duck species pintail *Anas acuta* (Linnaeus), wigeon *Anas Penelope* (Linnaeus), and scaup *Anthya marila* (Linnaeus) occurred in the lower half of the elasticity ranking-list.

Amongst waterbirds, elasticity varied between 0.37 (scaup) and 0.78 (bewick's swan and barnacle goose), among birds of prey from 0.44 in kestrel to 0.75 in goshawk and amongst passerines from between 0.20 and 0.57 in hirundines and wood pigeon, respectively.

Setting species priorities

No correlation was found between relative abundance and elasticity of adult survival (Fig. 3; $R^2 = 0.067$; $F = 2.590$; $P = 0.116$; $N = 38$). The distribution pattern of all the species in a plot of the two indicators of relative abundance and elasticity are exclusively dominated by birds of prey and waterbirds as the groups of species of high conservation priority (Fig. 3 and Appendix S1). This group of high conservation priority species comprised 24% (9 out of the 38) of all the species (5 species of birds of prey and 4 species of waterbirds). The species of medium conservation priority accounts for 34% (14 out of 38) of all the species with three, nine and two species of birds of prey, waterbirds and passerines, respectively. This leaves the remaining 40% (15 out of 38) of the species in the group of low conservation priority species with three species of birds of prey (27% of the species within this group), one species of waterbird (7% of the species within this group) and eleven species of passerines (85% of the species within this group). Thus, besides goshawk and merlin, only passerines showed a low level in one or in both of the indicators of the EVI.

Discussion

EVALUATION OF THE GENERAL FRAMEWORK

Ranking only by the indicator of relative abundance it becomes apparent that, across species groups, species known to be especially susceptible to the funnel effects of topography during migration appear in relatively (to the reference population) high numbers at the Gedser Odde peninsular. This phenomenon is well known for waterbirds that try to avoid crossing land (e.g. common eider), and hence, fly around islands and other land bodies that they encounter en route, and for soaring birds of prey that prefer to fly over land and cross water bodies where these are most narrow (Kjellén 1997). At the Nysted offshore wind farm EIA-study area, Gedser Odde acts like an avian migration funnel especially for both waterbirds and soaring migrants. However, high concentrations of up to nearly 100,000 individuals annually within a single group of passerines (Appendix S1) have been counted during one autumn season. Such dense numbers of passerines at single migration hot spots must be put in to perspective with regard to the corresponding huge reference populations they represent. The indicator of relative abundance takes this into account and therefore also rank passerines at the lower end of the list. At the bottom of the list we find goshawk and coal tit that both represent a more or less non-migratory strategy (for coal tit at least in most years) and therefore can be characterised as well ranked. Finally, the indicator of relative abundance support the findings from Kjellén (1997), who showed that species with more southerly distribution (i.e. near to the study site), such as marsh harrier are occurring in relative high numbers compared to a more northern species like hen harrier *Circus cyaneus* (Linnaeus). So, the indicator of relative abundance seems to capture the known fundamentals of the occurrence of the different migration species (e.g. that soaring birds of prey are most subjected to the land funnel effect, that passerines are parts of huge reference populations, the almost absence of non-migratory species, and the latitudinal differences in breeding origin), and hence, is concluded to be highly suitable for the present priority framework.

The term "reference population" is most often defined as the entire flyway population or as the national population. The present definition, as the breeding population from the breeding area occupied by the birds passing the migration study site, have to my knowledge never been used before. It's use provides novel utility, since this is the geographic population that potentially may be affected by the wind farm. In the context of cumulative impacts, which in accordance to the EU legislation (under Directive 85/337/EEC and amended by Directive 97/11/EC) must be assessed in all wind farm EIAs, this novel way of defining the reference population could be an option, since it deals with a clear unit that can be practically managed. Furthermore, it is flexible and can be adapted specifically to either a single or a whole array of wind farms.

For various reasons, strange rankings of different species may occur when using this kind of prioritisation framework and it is highly advisable always to look for peculiar outcomes. This can be exemplified by the Nysted case-story where black tern *Chlidonias niger* (Linnaeus) was ranked as a high priority species in part due to the very high migration volume and relatively low size of the reference population. For this species, a combination of population decline over the last two decades and a time-lag between the estimation of the migration numbers and population size of the same period has biased the ranking of the black tern (Hagemeijer & Blair 1997; Svensson et al. 1999). This example shows how important the use of updated figures are in this kind of ranking processes, but also that a sound sceptical attitude towards the ranking lists is advisable.

It was expected that birds of prey and waterbirds dominated the highest conservation priority species when ranked in accordance to the demographic vulnerability indicator (elasticity values) alone, since these species in general are relatively long-lived, mature late and lay few eggs which are demographic characteristics known from species were adult survival contribute the most to the population growth rate (Heppell et al. 2000; Sæther & Bakke 2000). It must be stressed here, that not only reduction in mean survival can affect the growth rate, but also the annual variability in adult survival (even without affecting the mean) can reduce the growth rate (Lande et al. 2003). These stochastic effects can be modelled by more complex matrix population models for high priority focal species found by EVIs like the one presented in this paper.

However, not only did the elasticity ranking list capture the difference between the groups of species, but it also demonstrated that species within groups can show marked differences, e.g. the three small ducks (wigeon, pintail, and scaup) and the three small birds of prey (sparrowhawk, kestrel, and merlin) all showed much lower elasticity values than the other species within their respective species groups. Likewise, the passerines appearing highest on the demographic vulnerability ranking list were the three relatively large species (wood pigeon, jackdaw and fieldfare *Turdus pilaris* (Linnaeus); Appendix S1). Thus, applying simple Leslie matrix models seem to be a useful approach when comparing a long list of different species with regard to their relative vulnerability to wind farm related mortality, adding to the applications of elasticity analyses of matrix models, which for long have been mainstream of the applied conservation biology (Mills et al. 1998; Benton & Grant 1999). Because we do not have good demographic information for most populations (Heppell et al. 2000), it is useful to categorize species in accordance to their life history characteristics and related elasticity patterns as a first step in assessing the sustainability of the wind power development of the European waters.

Elasticity values may change within species as the growth rate change (Caswell 2001). Since the present way of assessing demographic vulnerability only accounts for stable populations the user of the framework must pay special attention to the conservation status of the different bird species. So, species like for example the Baltic/Wadden Sea common eider population that have declined dramatically over the last two decades (Desholm et al. 2002) or the red kite which is the only one of the 38 case-study species which is classified as "near threatened" by the IUCN (The International Union for Conservation of Nature; Baillie & Groombridge 1997) must be given special attention regardless of the outcome of the prioritization process.

Estimating the absolute demographic effects (e.g. the absolute impact on the reference population) of wind farm related mortality necessitate the use of much more complex and robust matrix population models (Hamilton & Möller 1995; Ferriere et al. 1996; Heppell et al. 2000). The predictive power of such models is determined by the degree to which the estimated input-parameters reflect the true mean values and their associated variance. Furthermore, details about density dependence, population age structure, age at first breeding, number of non-breeders and environmental and demographic stochasticity within survival or fecundity (may have greater impact on λ than the mean) must be in incorporated. Often such detailed data do not exist for the species of interest making the construction of such complex matrix population models a difficult task. One way of dealing with this would be to use the EVI for ranking the species and then develop standards for assessing the population impacts of estimated collision figures, for species of highest local conservation concern, by the use of complex Leslie matrix models. This is also the level of study where the topic of cumulative impacts should be dealt with.

In North America, three different avian conservation priority ranking systems have been applied with regard to the perceived endangerment and vulnerability of species (Beissinger et al. 2000; Carter et al. 2000; Mehlman et al. 2004). Although the three systems have different geographic and taxonomic scope, all systems identified approximately 20% of the species as being of conservation concern (Mehlman et al. 2004), which is in close agreement with the 24% of the species classified as high priority species in the present priority framework. Defining the boundaries of the low, medium, and high segments of the indicators will always be a subjective action, but ascribing about 20% of the species to the high priority group seems to be a balanced and often used approach.

As discussed by Beissinger et al. (2000), multiple factor ranking schemes may have the shortcoming of unintentional weighting because of multicolinearity (or correlations) among variables, which if present will limit the use of summed scores and force the scientist to consider the variables separately when assessing risk. The priority-setting framework presented in this paper shows no correlation among the two variables, and consequently, they can be used in combination to assess vulnerability for the different species. This is not the case for the vulnerability index developed for informing the spatial planning process for wind power development in the German marine areas (Garthe & Hüppop 2004) where strong inter-dependences between variables can be found, with 30.6% of the 36 different combinations of variables being significantly correlated ($P<0.05$), an only the factor "European treat and conservation status" showed no correlation with other variables. Strong correlation among priority variables will complicate interpretation of a summed scores (Beissinger et al. 2000) and it is therefore suggested that users of the German index do not base their assessment of area vulnerability solely on the summed scores but also try to consider the variables separately.

Performing effect studies on all the bird species migrating at an offshore wind farm are often not feasible for economical reasons, since both the scale and design of the study needs to be carefully chosen in accordance with the species of interest. Hence, some kind of prioritisation between species will always be mandatory and at least three reasons exist why the present framework for species priority seems well-suited for a bird-wind farm study. First, both indicators seem to capture known characteristics of the different species with respect to population dynamics and their significance of occurrence at migration sites. Secondly, the two indicators can cover all possible levels of information from the lowest level when we know only which species occur at the study area to the upper level when we know how many individuals of the different species are migrating annually through the area swept by the turbine blades. Thirdly, the logical and simple approach of using only two different indicators to characterize the vulnerability of migrating birds to wind farm related mortality, leaves us with only two currencies, reducing many of the difficulties inherent in combining different pattern and process factors in one single index (Williams & Araújo 2002; see below).

Finally, it should be considered that the present priority framework can be used for a variety of other bird conservation management issues, e.g. fixed links over water bodies, telecommunication towers, tall buildings, glide slopes at airports, and gas burning flares, and thus, is not restricted to deal with wind farms only.

COMPARING APPLES AND ORANGES

Many studies have tried to integrate multiple factors in the decision process of choosing the best and most efficient reserve network for the cause of nature conservation (Lambeck 1997; Wikramanayake et al. 1998; Cowling et al. 2003) and, as mentioned above, a German study has used this approach for assessing area vulnerability for sea birds to wind farm development on the basis of nine vulnerability factors (Garthe & Hüppop 2004). These studies are classical examples of the compensatory method which combine scores for multiple factors with different and incompatible currencies, and there is no uniquely justifiable way of weighting them against one another (Faith & Walker 1996). The fundamental problem in these cases is how to address questions like: how much of a decrease in percentage of time flying may legitimately compensate for a particular increase in adult survival rate? This has often been described as the problem of comparing apples and oranges to which no guidelines for optimizing the outcome exists (Margules & Pressey 2000; Williams & Araújo 2002). These kinds of problems could be avoided if certain ways of relating factors were shown to be more biologically robust, for example as suggested by Williams & Araújo (2002), by finding some of the underlying relationships among the many factors, and where possible, using these relationships to integrate factors within as few common currencies as possible.

The authors of the German paper are fully aware of the fundamental problems of using these kinds of indices, as they depend strongly on the factors selected and the way they are weighed against each other (Garthe & Hüppop 2004). For example, recent findings suggest that the avoidance factor (i.e. the species specific ability to avoid flying within the wind farm area or close to individual turbines) may be the most important factor when assessing the risk of wind turbine-bird collisions (Desholm & Kahlert 2005; Chamberlain et al. 2006). Present lack of this kind of data evidently justify its exclusion from indices but it should be kept in mind and be an integral part of future discussions and studies of bird-wind turbine collision risk.

The priority-setting framework presented in this paper tries to avoid the pitfalls of comparing apples and oranges by integrating all factors in to a very simple and easily comprehended two-indicator EVI. Furthermore, this framework is generalized in a way that makes it suitable also for the future, were hopefully our understanding of species specific avoidance behaviour is far better than today. So instead of assessing the indicator of relative abundance at information level 1 (number of individuals passing the study site) the ecologists can use a predicted value of the number of individuals passing the areas swept by the rotor-blades (level 2; based on pre-construction flight pattern and know species specific avoidance rates at different spatial scales).

In general, indices must be re-evaluated as we gain knowledge of the behaviour of the birds. For example, in the German index one of the factors assumes that species that spend a lot of time flying in the dark are more at risk than exclusive day-time flyers. However, recent findings suggest that this may in fact not be the case, at least not for migrating common eiders, since this species tend to maintain longer distances from individual turbines when flying at night compared to daytime (Desholm & Kahlert 2005). This is just one example of new-gained knowledge that should be integrated in priority frameworks and underline the importance of continuous re-evaluation of indices.

CONCLUSIONS AND MANAGEMENT IMPLICATIONS

Among the many species migrating at the Nysted offshore wind farm the present framework seems to rank the large waterbirds and large birds of prey as the species being most vulnerable to wind farm related mortality. It is important to stress, that the case-study used in this paper only deals with the information level available at the time when the EIA was written (Kahlert et al. 2000). Consequently, it was not known for sure how the migration pattern would differ between the different species groups. During the post-EIA radar studies it became apparent that the majority of the birds of prey and passerines were leaving land at the southern coast of the Gedser Odde peninsula and that most of the waterbirds (especially the many common eiders) were passing Gedser Odde very close to land and then heading westward towards the wind farm area (Kahlert et al. 2002; Desholm et al. 2003; Kahlert et al. 2004; Desholm & Kahlert 2005). This meant that the proportion of individuals migrating in the vicinity of the wind farm was several magnitudes higher for the waterbirds than for the birds of prey (Fig. 1). Using common eider as a focal species seems retrospectively to have been a very good choice. Not only because it is a large bodied bird flying in big flocks which therefore provide good radar targets, but also because it seems to be one of the most vulnerable species in study area.

In general, it is recommended that future bird-wind farm studies should allocate resources to the study of local effects and population impacts on especially the large bodied and long lived species like birds of prey and waterbirds. Even though passerines might be present in very high numbers at individual migration hotspots, they very often are insignificant segments of huge reference populations that, from a demographic point of view, are relatively insensitive to wind farm related adult mortality. It is my hope that priority frameworks, as presented in this paper, will be an integral part of future EIAs, SEAs and ESs at the many proposed wind farms world-wide. It will always be important to focus attention and direct the always limited resources towards the most vulnerable species, if the wind power production shall maintain it reputation as being sustainable from a nature conservation point of view.

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Supplementary material

The following supplementary material is available from http://www.blackwell-synergy.com.

Appendix S1. Table with summary data.

Figure legends

Figure 1

The area around Gedser Odde peninsula, Denmark and a schematic presentation of autumn migration pattern of waterbirds (bold arrows) and landbirds (thin arrows). The Nysted offshore wind farm is depicted as the striped area. Scale bar, 5000 m.

Figure 2

The distribution of the values of elasticity (e_{s2}) of population growth rate to changes in adult survival in relation to adult fecundity (f_2) and adult survival (s_2) for 25 hypothetic bird species. For each of the five values of annual adult fecundity least squares fit statistics were performed using species values between adult survival and e_{s2}. The linear regressions are represented by the following equations and coefficients of determination (r^2) for the f_2 values 1, 2, 3, 4, and 5, respectively: $y = 0.947x-0.090$, $r^2 = 0.974$; $y = 0.980x-0.097$, $r^2 = 0.971$; $y = 1.004x-0.101$, $r^2 = 0.970$; $y = 1.031x-0.106$, $r^2 = 0.968$; $y = 1.050x-0.110$, $r^2 = 0.967$.

Figure 3

A framework for identifying priority species of high local conservation concern on the basis of two indicators described by: 1) relative abundance and 2) elasticity of growth rate to changes in adult survival (e_{s2}). Relative abundance is presented in percentage on a log scale (due to very skewed distribution towards small values) and is divided by dotted lines in to a high (>1%), medium (>0.1% and <1%) and low (<0.1%) segment. Elasticity is divided by dotted lines in to a high (>0.67), medium (>0.33 and < 0.67), and low (<0.33) segment. Waterbirds are here defined as divers, ducks, geese, swans, cranes, shorebirds, terns, gulls, and skuas. For simplicity, wood pigeon is enclosed in the group of passerines. The species are grouped in to three levels of conservation priority: high priority species = high value in both indicators; medium priority species = high value in one and medium in the other indicator; and low priority species = the remaining species showing low value in one of the indicators or medium in both. Number at each data point refer to the species number presented in Appendix S1.

Figure 1

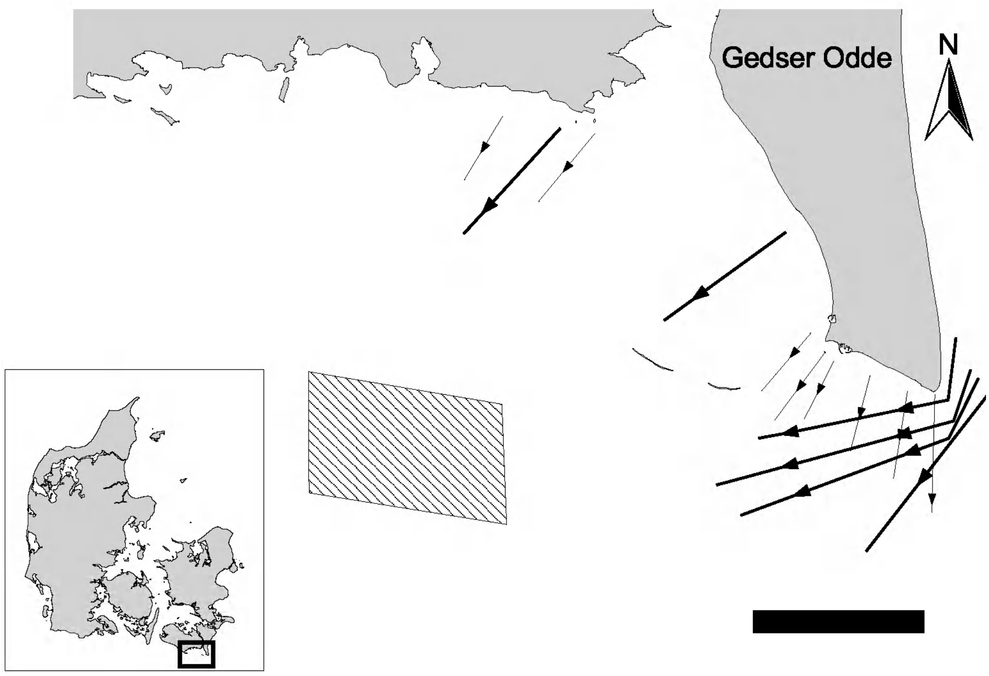
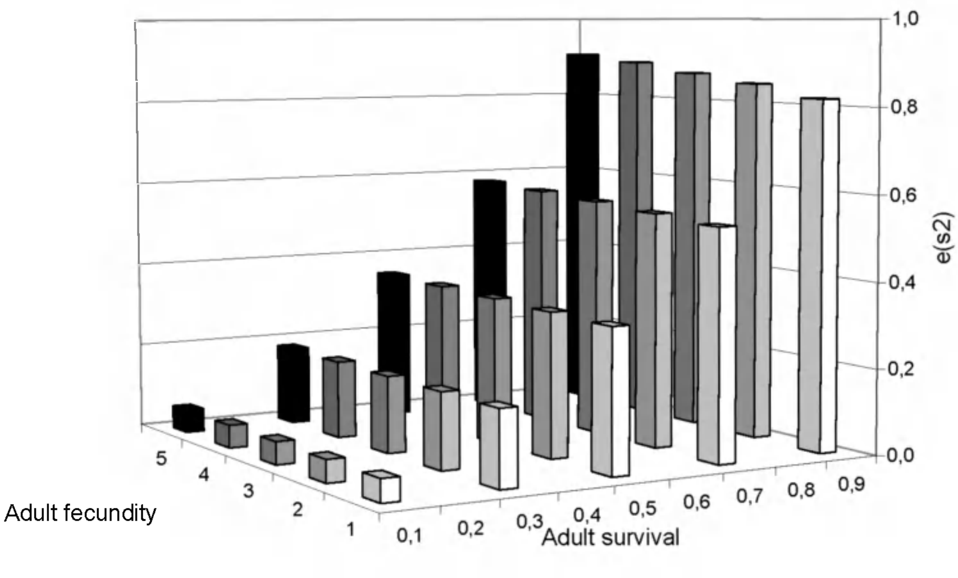
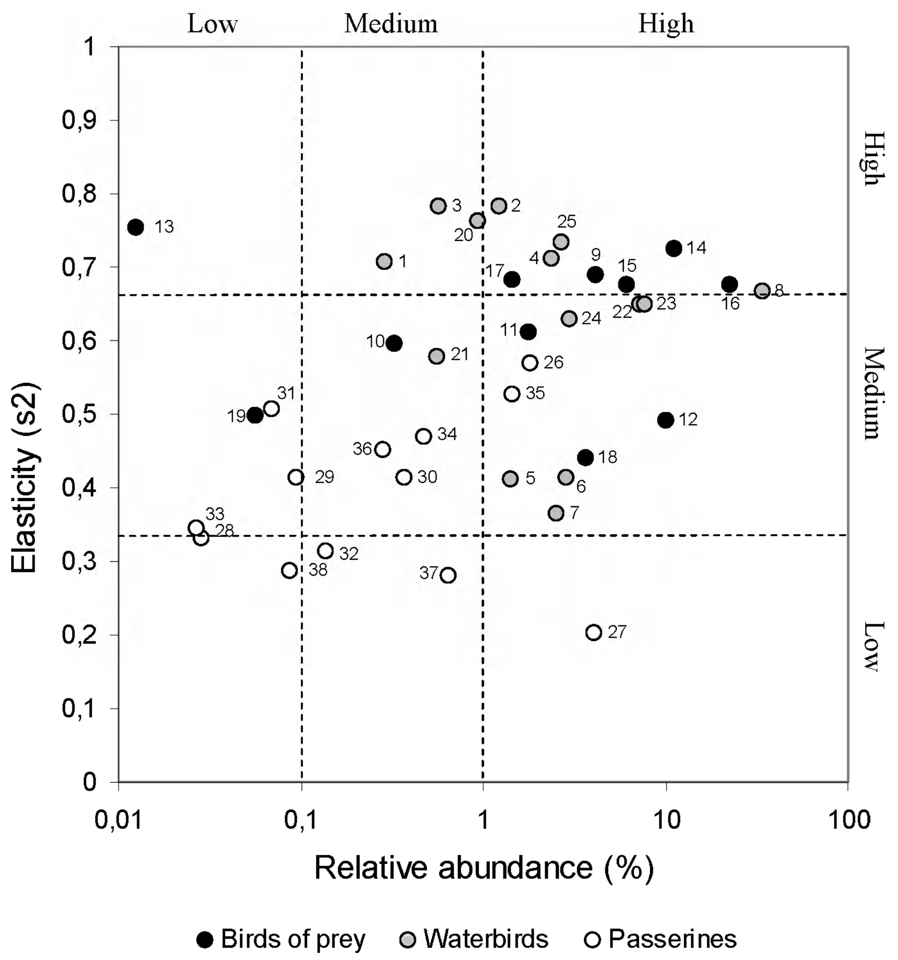


Figure 2



1,0
0,8
0,6
0,4
0,2
0,0
e(s2)
5
4
3
2
1
Adult fecundity
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
Adult survival

Figure 3


Low
Medium
High
High
Medium
Low
Elasticity (s2)
1
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
0,01
0,1
1
10
100
Relative abundance (%)
13
3
2
20
25
1
4
9
15
14
17
16
8
22
23
24
11
10
21
26
35
31
19
12
36
34
18
29
30
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6
7
33
28
32
38
37
27
Birds of prey
Waterbirds
Passerines

Appendix S1.

Summary data on the migratory bird species presented in the Nysted offshore wind farm case-study from Denmark (Kahlert et al. 2000). The identification number in brackets in front of each species name refer to the data points in figure 2. The number of asterixs following the species name indicates its level of conservation priority due to the preset EVI: *** = high priority species; ** = medium priority species; * = low priority species (see text and figure 3 for further description). Migration volume refers to the annual number of autumn migrating birds estimated to have passed Gedser Odde (Kahlert et al. 2000 and references herein) and the reference population refer to the breeding population that potentially pass the study site on autumn migration and is also presented as number of individuals. Species specific annual adult survival rate and annual adult fecundity (measured as number of females fledged per female) have been collated from the literature. Relative abundance is defined as the migration volume relative to the reference population in percent and Elasticity of adult survival is estimated in accordance to figure 1, and for the two indicators the ascending ranking number (low rank number equals relative high vulnerability) is given in brackets. See superscripts for references: 1) Hagemeijer & Blair (1997), 2) Delany & Scott (In press), 3) Desholm et al. 2002, 4) Svensson et al. (1999), 5) Grell (1998), 6) Hemmingsson & Eriksson (2002), 7) Nichols et al. (1992), 8) Larsson et al. (1995), 9) Cramp (1986), 10) Cramp (1980), 11) Tjermberg & Ryttman (1994), 12) Lieske et al. (2000), 13) Mathews & Macdonald (2001), 14) Cramp (1983), 15) Furness (1987), 16) Servello (2000), 17) Cramp (1985), 18) Cramp (1988), 19) Cramp (1993), 20) Cramp (1994).

Species name (English)	Species name (scientific)	Migration volume	Reference population	Adult survival rate	Fecun-dity	Relative abundance (rank)	Elasticity of s2 (rank)
(1) Divers **	*Gavia stellata/arctica*	1071	373,500[1,2]	0.84[6]	0.2[9]	0.29 (29)	0.71 (8)
(2) Bewick's Swan ***	*Cygnus columbianus*	247	20,000[2]	0.92[7]	1.2[9]	1.24 (21)	0.78 (1)
(3) Barnacle Goose **	*Branta leucopsis*	2398	420,000[2]	0.92[8]	1.1[9]	0.57 (24)	0.78 (1)
(4) Brent Goose ***	*Branta bernicla*	4735	200,000[2]	0.85[9]	1.3[9]	2.37 (15)	0.71 (7)
(5) Wigeon **	*Anas penelope*	21,057	1,490,000[1,2]	0.53[9]	1.5[9]	1.41 (20)	0.41 (31)
(6) Pintail **	*Anas acuta*	1663	58,000[1]	0.52[9]	2.4[9]	2.87 (12)	0.41 (28)
(7) Scaup **	*Anthya marila*	7763	304,900[1,2]	0.48[9]	0.3[9]	2.55 (14)	0.36 (32)
(8) Common Eider ***	*S. mollissima*	257,139	760,000[3]	0.80[9]	0.4[9]	33.83 (1)	0.67 (13)
(9) Red Kite ***	*Milvus milvus*	67	1600[4]	0.82[10]	0.7[10]	4.19 (8)	0.69 (9)
(10) Hen Harrier *	*Circus cyaneus*	26	8000[1]	0.72[10]	0.6[10]	0.33 (28)	0.60 (18)
(11) Marsh Harrier **	*Circus aeruginosus*	52	2900[5]	0.74[10]	1.2[10]	1.79 (17)	0.61 (17)
(12) Sparrowhawk **	*Accipiter nisus*	5917	59,000[1,5]	0.60[10]	1.7[10]	10.03 (4)	0.49 (24)
(13) Goshawk *	*Accipiter gentilis*	3	24,000[1]	0.89[10]	1.4[10]	0.01 (38)	0.75 (4)
(14) Honey Buzzard ***	*Pernis apivorus*	2702	24,000[1]	0.86[11]	0.7[10]	11.26 (3)	0.72 (6)
(15) Buzzard ***	*Buteo buteo*	2452	40,000[1,5]	0.81[10]	1.1[10]	6.13 (7)	0.68 (11)
(16) Rough-legged Buzzard ***	*Buteo lagopus*	4109	18,000[1]	0.81[10]	0.9[10]	22.83 (2)	0.68 (11)
(17) Osprey ***	*Pandion haliaetus*	93	6400[1]	0.82[10]	0.9[10]	1.45 (18)	0.68 (10)
(18) Kestrel **	*Falco tinnunculus*	257	7000[1,5]	0.56[10]	1.4[10]	3.67 (10)	0.44 (27)
(19) Merlin *	*Falco columbarius*	80	140,000[1]	0.62[12]	1.2[10]	0.06 (35)	0.50 (23)
(20) Crane **	*Grus grus*	303	32,000[1]	0.90[13]	0.5[10,13]	0.95 (22)	0.76 (3)
(21) Bar-tailed Godwit *	*Limosa lapponica*	674	120,000[2]	0.71[14]	0.4[14]	0.56 (25)	0.58 (19)
(22) Pomarine Skua **	*S. pomarinus*	144	2000[1]	0.78[15]	0.8[15]	7.20 (6)	0.65 (14)
(23) Arctic Skua **	*S. parasiticus*	155	2000[1]	0.78[15]	0.8[14]	7.75 (5)	0.65 (14)
(24) Little Gull **	*Larus minutus*	3652	123,000[2]	0.76[14]	0.1[14]	2.97 (11)	0.63 (16)
(25) Black Tern ***	*Chlidonias niger*	417	15,400[1,4]	0.87[16]	0.4[17]	2.71 (13)	0.73 (5)
(26) Wood Pigeon **	*Columba palumbus*	23,670	1,300,000[4,5]	0.70[17]	0.3[17]	1.82 (16)	0.57 (20)
(27) Swallows *	*Hirundines*	50,000	1,216,000[4,5]	0.30[18]	3.6[18]	4.11 (9)	0.20 (38)
(28) Tree Pipit *	*Anthus trivialis*	3893	13,500,000[1]	0.43[18]	2.8[18]	0.03 (36)	0.33 (34)
(29) Pied Wagtail *	*Motacilla alba*	2510	2,655,500[1,5]	0.52[18]	2.2[18]	0.09 (32)	0.41 (28)
(30) Yellow Wagtail *	*Motacilla flava*	3430	924,500[1,5]	0.52[18]	1.9[18]	0.37 (27)	0.41 (28)
(31) Fieldfare *	*Turdus pilaris*	2084	3,000,000[1]	0.63[18]	1.3[18]	0.07 (34)	0.51 (22)
(32) Redwing *	*Turdus iliacus*	7119	5,200,000[1]	0.43[18]	1.4[18]	0.14 (31)	0.31 (35)
(33) Coal Tit *	*Parus ater*	458	1,704,532[1,5]	0.43[19]	8.1[19]	0.03 (37)	0.34 (33)
(34) Nutcracker *	*N. caryocatactes*	110	23,332[1]	0.59[20]	0.8[20]	0.47 (26)	0.47 (25)
(35) Jackdaw **	*Corvus monedula*	4628	321,666[4,5]	0.65[20]	1.0[20]	1.44 (19)	0.53 (21)
(36) Chaffinch/ Brambling *	*Fringilla sp.*	97,000	34,070,000[1]	0.57[20]	1.0[20]	0.28 (30)	0.45 (26)
(37) Siskin *	*Carduelis spinus*	13,333	2,071,100[1]	0.39[20]	0.8[20]	0.64 (23)	0.28 (37)
(38) Twite *	*Carduelis flavirostris*	520	600,750[1]	0.39[20]	2.3[20]	0.09 (33)	0.29 (36)

IV

How much do small-scale changes in flight direction increase overall migration distance?

DESHOLM, M.

2003

Journal of Avian Biology 34: 155-158

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How much do small-scale changes in flight direction increase overall migration distance?

Mark Desholm

Desholm, M. 2003. How much do small-scale changes in flight direction increase overall migration distance? – J. Avian Biol. 34: 155–158.

During a radar study of autumn migrating waterfowl Denmark, individual flight trajectories of bird flocks were seen to show zigzag-like patterns, rather than exact straight lines. An analysis of these small-scale changes in flight directions, which are too small to be detected by satellite telemetry, showed that geese and common eiders *Somateria m. mollissima* were flying on average 0.7% and 1.6% longer distances, respectively, than if they would have flown along exact straight lines. Thus, it is concluded that the flight paths are remarkably similar to straight lines. A multivariate regression analysis suggested cross wind as a factor increasing flight distance, and hence, the small-scale changes in flight directions could in part be a result of birds trying to compensate for wind drift.

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Avian migration has attracted considerable research attention, not least for describing the general migration patterns of long distance migrants, e.g. routes and overall flight distances (Alerstam 1990, Berthold 1993, Alerstam and Hedenström 1998). Conventionally, the loxodromic or orthodromic distances (*sensu* Imboden and Imboden 1972) travelled by migrating birds have been calculated either at a large scale by joining ringing and recovery localities (Alerstam and Pettersson 1991, Elphic 1995, Alerstam et al. 2001, Bairlein 2001), or more precisely at a medium scale by measuring the distances between a series of satellite telemetry positions (Gudmundsson et al. 1995, Clausen and Bustnes 1998, Green et al. 2002). Thus, the total distance of a bird's flight path will always be a matter of scale, with overall distances becoming longer the smaller step lengths that are used for the measurements.

During a radar study in southern Denmark, flocks of autumn migrating geese (*Anser* and *Branta* spp.) and common eiders *Somateria m. mollissima* showed zigzag-like trajectories, rather than straight lines when analysed on a small scale (mean length of flight trajectories was ca 10 kilometers). These small-scale changes in flight directions, which are too small to be detected by the satellite telemetry technique, have been studied in the context of foraging flights of seabirds (Alerstam et al. 1993), but have never been used to estimate migration distances.

I had two main objectives with the present study. First, to investigate how much these small-scale changes in flight directions increase the overall migration distance, and second, through a multiple regression analysis, to see if these deviations from the straight-line approach could be related to: (a) flock size, since a large flock may include more old and experienced individuals, prone to lead the flock in specific directions, compared to a small flock, (b) amount of cross wind, since cross wind are known to drift the flocks away from their intended track, forcing them to perform corrections in order to keep track, or (c) ground speed, since fast flying flocks are less exposed to the drift effect of the wind.

Methods

The study was performed between 11 September and 23 October 2000 from an observation tower placed in the sea 6 km south-west of Gedser Odde in south-eastern Denmark (Fig. 1). The area is known to be passed by ca 250.000 eiders and tens of thousands of geese each autumn.

Data were collected using a X-band surveillance radar (Furuno FR2125, peak power 25 kW, variable pulse length/volume 0.3–1.2 μs, pulse repeat frequency 9410 ± 30 MHz, vertical beamwidth 20°, monitor resolution 1280 × 1024 pixels, each pixel represent a square of 23 m × 23 m). The radar range was set to 12 kilometres at which the accuracy, according to the manufacturer, of range measurements should be better

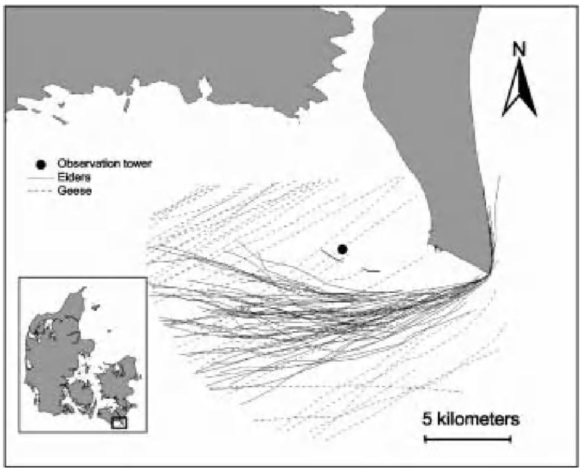

Fig. 1. Map of Denmark showing the location of the study area, the observation tower and the south-westward migration paths of 37 flocks of geese and the 50 flocks of eiders used in the stepwise multiple regression analysis.

than ± 1% (≤ 120 meters). Echoes from fixed targets (like the weather tower and the coast) were not displaced between the sweeps of the scanner due to radar inaccuracy, and thus, it is concluded that the spatial movements of targets (e.g. goose and eider flocks) have been monitored rather precisely by the radar.

Each flock of birds entering the detection area created an echo on the radar monitor, and by monitoring the movement of echoes, the precise migration trajectory of any given flock could be monitored. Start and end points of the migration tracks were defined as the point where a flock was first noticed and the point where it was lost from the monitor, respectively.

The migration routes were mapped by tracing the precise course of individual bird flocks (the centre of each echo) from the radar monitor in the Equidistant Azimuthal projection on to a transparency. Afterwards, the migration routes were transferred to the GIS-platform ArcView in the local datum of the UTM 32 projection before distance measurements were performed by using a continuous scale. Only migrating bird echoes for which the species identity and flock size was recorded visually were included in the present analysis. The 37 flocks of geese consisted of 25 flocks of dark-bellied brent goose *Branta bernicla bernicla* (67.6%), 4 flocks of barnacle goose *Branta leucopsis* (10.8%), one flock of greylag goose *Anser anser* and 7 unidentified goose flocks (18.9%). All goose and eider flocks were migrating over the sea. In the data for eiders, only parts of tracks more than 5.5 km from land were used in the analysis (thus excluding curved tracks, influenced by the coastline close to the peninsula; see Fig. 1). Tracks shorter than 2 kilometres were not included in the analysis to ensure the exclusion of local movements.

The deviation from a straight line between start and end points (D) was calculated for each migration track, expressed as the increase in distance (in percent):

$$D = \frac{t - s}{s} \times 100$$

where t = true distance and s = straight line distance.

The likely measurement error in D was estimated by digitising the same eider track 20 times, which resulted in a mean D of 2.16% and 95%-confidence limits of between 2.09% and 2.22%. The radar resolution did not contribute with any measurement error in D, since each pixel was at least five times smaller than the avian echoes.

Data on wind speed (at 7.9 m a.s.l.) and wind direction (at 25 m a.s.l.) were collected every 10 minutes at a weather tower 7 km south-west of the observation tower. Wind direction is defined as the direction from which the wind is blowing. More than 80% of the eiders migrating during autumn at Gedser Odde have been shown to fly at less than 25 m altitude (average: 10.9 m, maximum: 95.8 m, minimum: < 5 m, N = 89 flocks/2384 individuals; Kahlert et al. 2000). Thus, the height at which wind data were collected fits well to the height of migrating eiders in the study area. Cross winds are known to cause drift among migrating birds (Alerstam 1979a, 1990, Green 2001), and hence, the cross wind component (S) was computed (Liechti et al. 1994). The cross wind component was computed in relation to the migratory track vector:

$$S = V_w \cdot \sin\beta$$

where V_w = wind speed and β = the angle between the migratory track vector and the wind vector.

Table 1. Summary data on migration tracks and wind conditions. V_g denotes ground speed, AD angular deviation, SD standard deviation and CR circular range (Zar 1996). Note that conventionally flight directions of birds are given as the direction the birds are flying towards, while wind directions are given as the direction from which the wind is blowing.

	Geese	Common eider
Number of tracks (flocks)	37	130
Mean track length (± SD) (km)	10.3 (4.1)	10.5 (2.0)
Mean V_g (± SD) (m/s)	28.0 (1.6)	23.9 (3.6)
Mean flight direction (± AD; CR) (°)	244.7 (10.5; 48.7)	268.0 (12.0; 64.0)
Mean flock size (± SD)	140.0 (101.0)	49.6 (37.0)
Mean wind direction (± AD; CR) (°)	72.5 (30.2; 233)	97.3 (28.3; 138)
Mean wind speed (± SD) (m/s)	10.4 (2.3)	8.5 (2.4)

Table 2. The average deviation from a straight line, increase in distance (D) in percent. 95% C.I. = 95% confidence interval and N = sample size.

	D (%)	Maximum (%)	Minimum (%)	SD	95% C.I.	N
Geese	0.72	4.38	0.00	1.02	0.38–1.06	37
Eiders	1.57	10.10	0.00	1.57	1.31–1.86	130

The Wilcoxon Two-Sample Test was used to test for differences in mean deviation between groups and a stepwise multiple regression analysis was performed to test for combined relationships between variables.

Results

The mean track length for geese and eiders, respectively, were 10.3 km and 10.5 km with mean flock sizes of 140 and 49.6 individuals (see Table 1).

Average deviations (D) from a straight line of 0.72% and 1.57% were calculated for the geese and eiders, respectively (Table 2). The difference in D between geese and eiders was highly significant (Wilcoxon Two-Sample Test; $Z = -4.81$, $P < 0.0001$).

Only for eiders, sufficient data were collected to enable a stepwise multiple regression to analyse the possible effects of flock size, ground speed (V_g) and cross wind (W) on D. This analysis could only be conducted for the 50 flocks of eiders for which all three variables were available. The analysis showed that only W had a significant effect on D ($y = 0.31W + 0.76$, $F = 5.69$, $df = 48$, $r^2 = 0.106$, $P = 0.021$, $N = 50$; see Fig. 2).

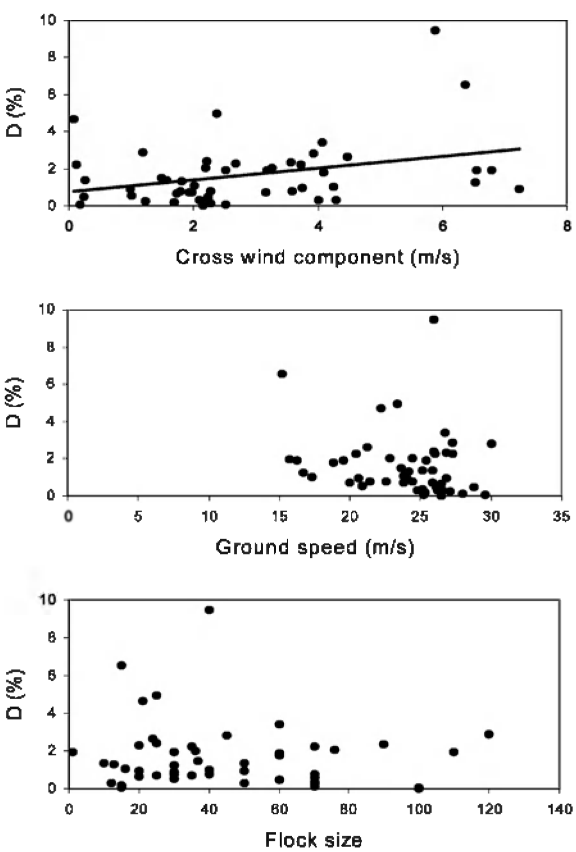

Fig. 2. The relationship between D (deviation from the straight line, %) and the cross wind component, ground speed and flock size. The cross wind component turned out to be the only factor showing a significant effect in the stepwise multiple regression analysis, and hence, the regression line is depicted for this factor only.

Discussion

The results show, as reported by Alerstam (1996), that migrating geese and eiders in general are capable of keeping relatively straight flight paths over a distance of ca 10 km. If a mean deviation from a straight line of 1% is applied, a satellite tracked dark-bellied brent goose migrating ca 5000 km from the Dutch Wadden Sea to the Taymyr peninsula (Green et al. 2002), will add 50 km to the total migration distance. On a temporal scale, this means an extra flight time of less than one hour. However, in some cases larger discrepancies from the straight line were found (Table 2). In the extreme, one flock of eiders was changing flight direction so often that the true migration distance was increased by ca 10%. Though this is not a general phenomenon it is important to keep these extreme records in mind, since they might contribute to explain discrepancies between empirical data on migration distances and predictions of maximum flight distances from flight energetic models.

The apparent difference in D between geese and eiders may be explained by (a) the geese are flying significantly faster than the eiders, and hence, being less exposed to wind drift and/or (b) the geese are flying at a higher altitude than the eiders and thereby gaining a better view of environmental cues, which could be the primary stimulus by which their movement is directed (Able 2000). Even though the measurement error in D constitute a insignificant part of the calculated deviations from straight lines, the D values should be regarded as maximum estimates since the plotting procedure from radar monitor to GIS-platform will never be perfect.

The multivariate regression analysis showed a significant increase in D with increasing cross winds (Fig. 2). This indicates that the small deviations from the straight line in part may result from birds trying to compensate for wind drift. Each phase of drift could be followed by a compensatory manoeuvre to get back on track, resulting in a series of small oscillations. This would minimise the wind drift, and if the amplitudes of the oscillations are not too large, also the total migration distance. Under certain circumstances, however, migrants may allow themselves to be drifted to gain the advantage of a higher ground speed towards their goal (Alerstam 1979a, b). Thus, the extent to which geese and eiders perform these compensatory manoeuvres during migration depends not only on the wind but also on the objectives of the birds; either minimising the distance travelled or the time spent flying. Since both the flocks of geese and eiders showed these small deviations from the straight line, it is likely to be a general phenomenon, at least among birds migrating by flapping flight.

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V

Avian collision risk at an offshore wind farm

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Avian collision risk at an offshore wind farm

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We have been the first to investigate whether long-lived geese and ducks can detect and avoid a large offshore wind farm by tracking their diurnal migration patterns with radar. We found that the percentage of flocks entering the wind farm area decreased significantly (by a factor 4.5) from pre-construction to initial operation. At night, migrating flocks were more prone to enter the wind farm but counteracted the higher risk of collision in the dark by increasing their distance from individual turbines and flying in the corridors between turbines. Overall, less than 1% of the ducks and geese migrated close enough to the turbines to be at any risk of collision.

Keywords: migration; radar; wind turbines; avoidance; collision; waterbirds

1. INTRODUCTION

Since the early 1990s marine wind farms have become a reality (Larsson 1994), and no fewer than 13 000 offshore wind turbines are currently proposed in European waters. At present, two large offshore wind farms operate in Denmark, one of which was the focus of the present radar study. Here, hundreds of thousands of waterbirds migrate annually between breeding and wintering grounds, and there is great public concern at the risk of bird–turbine collisions. The assessments to date of wind turbine collision risk for birds have mostly been conducted on land (Garthe & Hüppop 2004), and offshore investigations are expensive. However, the risk of collision at sea needs to be investigated as well, not in the least because long-lived waterbird populations are especially sensitive to additional mortality (Sæther & Bakke 2000). To help address this, we have investigated the avian avoidance response to offshore wind turbines in order to assess the risk of collisions.

2. MATERIAL AND METHODS

This study was conducted at the Nysted offshore wind farm (160 MW) situated in the western part of the Baltic Sea offshore from southern Denmark. The 72 turbines (each 2.3 MW; blade length: 41 m; hub height: 69 m; red lights (or red flashing lights on edge turbines) mounted on the nacelle top) are placed in eight north–south oriented rows with a distance of 850 m between rows. The distance between each turbine in the rows is 480 m. The flight trajectories of migrating waterbirds were mapped by the use of a surveillance radar (Furuno FR2125, peak power 25 kW, variable pulse length/volume 0.3–1.2 μs, pulse repeat frequency 9410± 30 MHz, vertical beam width 20°, monitor resolution 1280×1024 pixels where each pixel represents a square of 23×23 m) mounted at an 8 m high observation tower situated 5.6 km northeast of the wind farm. Radar range was set to 11 km. There was a shading effect from individual turbines on the echoes of the flying bird flocks, resulting in short parts of the trajectories being undetectable by the radar. These parts where reconstructed by drawing a straight line between the points of disappearance and reappearance. This procedure will most probably neither under- nor overestimate the avoidance behaviour, since the vast majority of the disappearing parts of trajectories were situated between the rows of turbines, and not at the rows themselves, where the measurement of distance between the bird flock and the nearest turbine was performed. The decreasing ability to follow bird flocks by radar with increasing distance was not corrected for, since (i) the data for this analysis represent a subsample of the flocks that was large enough for radar detection and (ii) the species under study tend to migrate in relatively large flocks that are easily detected by this radar at the distance of interest. Furthermore, data collection was conducted only in calm winds (less than 10 m s^{-1}) and no-precipitation situations. Thus, the amount of sea and rain clutter on the radar monitor was minimized and the detectability of birds was optimized.

The species involved in the present analysis comprise mainly common eider (*Somateria mollissima*) and geese, of which approximately 200 000–300 000 and approximately 10 000, respectively, pass the study area each autumn (Kahlert *et al.* 2000). Species identification was conducted visually on a subsample of the flocks, and all flocks were identified by species using radar (flight speed or echo signature). Digitized migration trajectories were transformed to a GIS (geographic information system) platform in the local datum of the UTM (universal transverse mercator) 32 projection for spatial analyses. Spatial movements of migrating flocks were mapped relative to the nearby wind turbines, and hence, were extremely precise with regard to mutual distance between bird flocks and turbines. The same radar, study area and study objects have been the focus of another study by Desholm (2003), where the accuracy of the radar measurements was sufficient to detect a small but significant difference between geese and common eiders in their ability to migrate along straight lines.

In order to compare situations with good and poor visibility only, the data collected during twilight were excluded from the analysis. Night was defined as the period from 2 h after sunset to 2 h before sunrise, and day as the period from sunrise to sunset. During daylight the birds were most probably responding to the turbines themselves, and at night to the red warning lights. For the proportion analysis, only flocks passing both transect A (11 km long; oriented parallel to the eastern row of turbines and 5.3 km from these) due south of the radar platform and either transect B, C or D (see below) were included (transects A–D are depicted in figure 3 in the Electronic Appendix). Flocks were defined as entering the wind farm if they crossed transect B, situated along the eastern row of turbines. Flocks were defined as not entering the wind farm if they crossed either transect C, between the north-eastern corner of the wind farm and the radar platform, or transect D, between the southeastern corner of the wind farm and the southern end of transect A. The avoidance response has previously been shown to be consistent irrespective of various crosswind conditions (Kahlert *et al.* 2004).

3. RESULTS

By tracking the spatial migration pattern of waterbirds by radar (figure 1) we found that the diurnal percentage of flocks entering the wind farm area decreased significantly (by a factor 4.5) from pre-construction to initial operation. At night, 13.8% of flocks entered the area of the initially operating turbines, but only 6.5% of those flew closer than 50 m to turbines. During the day, over the same period, these figures were 4.5 and 12.3%, respectively. This means, *ceteris paribus*, that only 0.9% of the night migrants and 0.6% of the day migrants flew close enough to the turbines to be at risk of colliding with the turbines.

The proportion of flocks ($P_{\text{day \& night}}$) entering the wind farm (Kahlert *et al.* 2004) decreased significantly from 40.4% ($n=1406$) during pre-construction (2000–2002) to 8.9% ($n=779$) during initial operation (2003; $\chi^2=239.9$, $p<0.001$). P_{night} was significantly higher compared with P_{day} (13.8%; $n=289$ and 4.5%; $n=378$, respectively; $\chi^2=17.1$, $p<0.001$).

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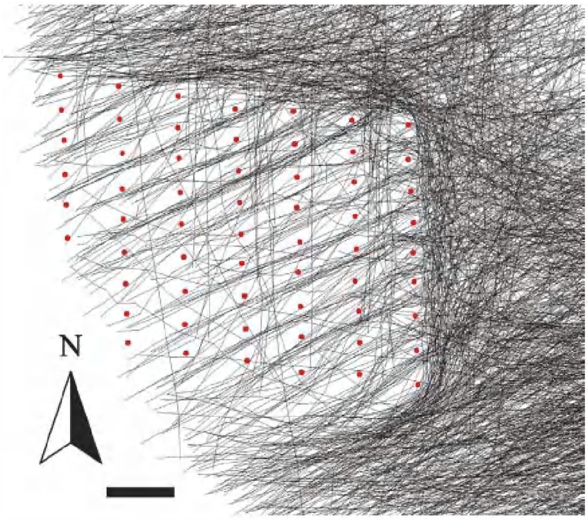

Figure 1. The westerly oriented flight trajectories during the initial operation of the wind turbines. Black lines indicate migrating waterbird flocks, red dots the wind turbines. Scale bar, 1000 m.

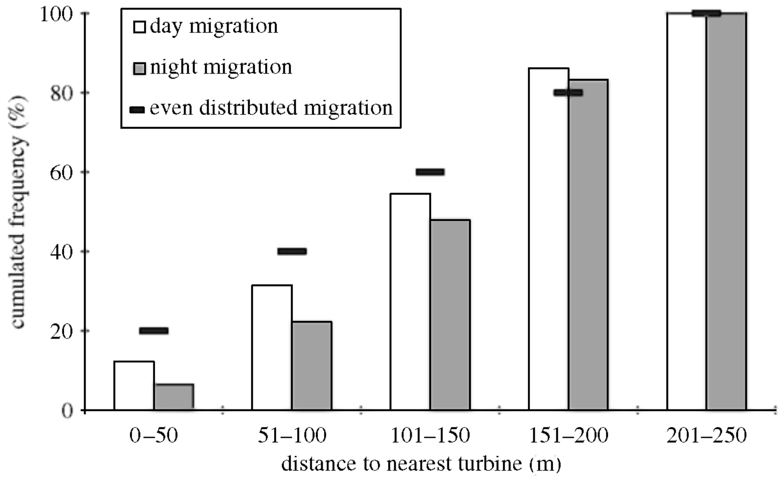

Figure 2. The cumulated frequency distribution $F_N(x)$ of the distances between bird flocks and the nearest turbine when passing the north–south oriented rows of turbines.

The cumulated frequency distribution, $F_N(x)$, of the distances between bird flocks and the nearest turbine when passing the north–south oriented rows of turbines was significantly different from an evenly distributed migration pattern both during day- and night-time (figure 2; Kolmogorov–Smirnov one-sample test; $D=0.0846$, $n=260$, $p<0.05$ and $D=0.1775$, $n=400$, $p<0.01$ for day and night, respectively). Finally, birds migrated significantly closer to individual turbines during the daytime than at night (Kolmogorov–Smirnow two-sample two-tailed test, $D=0.1273$, $n_{\text{day}}=260$, $n_{\text{night}}=400$, d.f.$=2$, $p<0.05$; figure 1). Mean flock sizes (95% confidence intervals) on log-transformed data of common eider and geese for autumn 2003 were 14.6 (13.3–16.2) and 7.7 (5.8–10.4), respectively. As the species-specific distributions of flock sizes differed markedly from normal distributions, log-transformation of data was undertaken when calculating the mean flock size and the 95% confidence intervals. This approach is generally less sensitive to extreme observations of very large flocks, which may occur at a very low frequency, compared to calculation of simple averages.

4. DISCUSSION

To date, 14 marine wind farms (in total 213 turbines) are in operation around the world (five in Denmark, three in Sweden, two in the Dutch IJsselmeer and two in the UK). However, few have provided adequate case studies upon which to base the current advice relating to the impacts of offshore wind farms on birds. The present radar study documents a substantial avoidance response by migrating waterbirds to a large offshore wind farm. A larger proportion of the birds fly within the wind farm at night- compared with day-time, but counteract this higher risk of colliding with the turbines in the dark by remaining at a greater distance from the individual turbines. Overall, less than 1% of the ducks and geese fly close enough to the turbines to be at any risk of collision. To date, the avian avoidance factor has never been implemented in models for estimating the number of bird-turbine collisions. Our findings stress the importance of applying the avoidance factor when dealing with wind farm-related mortality.

These estimates of potential collision risk are over-inflated since those bird flocks migrating within the horizontal reach of the turbine blades may actually fly below or above, or fly unharmed through the turbine's sweep area (Tucker 1996). Quantification of these altitude options will be addressed in subsequent research. Caution should be taken, though, since this study covers one year of initial operation only and has focused on waterbirds (mainly geese and common eiders). During the initial operation, frequent visits of maintenance vessels may have influenced the avian avoidance response to the sweeping turbines in an uncertain way. Before solid conclusions can be reached, complementary studies at other sites are needed to confirm these findings, to include possible habituation behaviour over the years to come, and to cover other focal species such as divers (*Gavia* sp.) and common scoter (*Melanitta nigra*).

These findings also stress that the agenda for future environmental impact assessments should change. Rather than focus only on possible local catastrophe, efforts should also be made to assess the cumulative impacts of small-scale local effects on the different geographically defined avian populations. Such an approach necessitates collaboration among scientists, reflecting that the preservation of migrating birds is, by its nature, an international effort.

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VI

The effect of avoidance rates on bird mortality predictions made by wind turbine collision risk models

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Short communication

The effect of avoidance rates on bird mortality predictions made by wind turbine collision risk models

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The model of Band *et al.* (2005) used data describing the structure and operation of the turbines: number of blades; maximum chord width and pitch angle of blades; rotor diameter; and rotation speed; and of bird size and flight: body length; wingspan; flight speed; flapping; or gliding flight, to derive a probability of collision. This approach was found to be generally sound mathematically (Chamberlain *et al.* 2005). Sensitivity analysis suggested that key parameters in determining collision risk were bird speed, rotor diameter and rotation speed, although variation in collision risk was still small within the likely range of these variables. Mortality is estimated by multiplying the collision probability by the number of birds passing through the area at risk height, determined from survey data. Crucially, however, the model assumes that an individual bird takes no avoiding action when encountering a turbine, so an adjustment must also be made for avoidance behaviour.

In this paper, we examine critically the estimation and use of avoidance rates in conjunction with the collision risk model (CRM). The sensitivity of predicted mortality to errors in estimated avoidance rates is assessed in three studies that have used the CRM. It should be noted that we consider only direct mortality caused by wind turbine collisions, but we accept that there may be other indirect effects on bird populations such as disturbance, displacement and loss of habitat (Langston & Pullan 2003, Percival 2005, Fox *et al.* 2006) that are outside the scope of this paper.

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CASE STUDIES

In the following case studies, we term the probability of a bird being hit as it passes through the rotors as 'collision risk'; the probability of a bird taking avoiding action when encountering a turbine as 'avoidance rate'; and its converse (1-avoidance rate), i.e. not taking avoidance action (Band *et al.* 2005) as 'non-avoidance rate'. The number of birds struck per unit time (as a product of collision risk; the number flying at risk height; and avoidance rates) is termed 'mortality rate' (assuming that each bird hit dies). Key parameters used in the first two case studies below are given in Table 1.

Case Study 1. Bewick Swans at Little Cheyne Court, southern England

An estimated 109 Bewick's Swans *Cygnus columbianus* flew at risk height through the Little Cheyne Court site over 180 days (Percival 2004). The study used an avoidance rate of 0.9962 (based on Painter *et al.* 1999, mainly for gulls which have different flight characteristics), giving a final predicted mortality rate of 0.145 (collision risk) × 109 (number of birds at risk) × 0.0038 (non-avoidance rate) = 0.06 birds over 180 days. A doubling of the non-avoidance rate from 0.0038 to 0.0076 doubles the mortality rate. A 10% decrease in avoidance rate increases the non-avoidance rate and therefore the mortality rate over 27 times to 1.64 birds (i.e. 0.145 × 109 × (1–0.8962)) over the same period.

Case Study 2. Golden Eagles at Ben Aketil and Edinbane, Skye, western Scotland

Estimated collision risks for Golden Eagle *Aquila chrysaetos* at potential wind farm sites at Ben Aketil and Edinbane were 0.112 and 0.133, respectively, with an avoidance rate of 0.995 drawn from work on Golden Eagles in the USA (Madders 2004). Again, if we assume an example of a 10% decrease in avoidance rate (i.e. fewer birds take avoidance action), then there are substantial effects on predicted mortality rate. At Ben Aketil, annual mortality would increase from 0.12 to 2.51 individuals per year. At Edinbane,

Table 1. Key parameters used in determining mortality rates at potential wind farm sites. Collision risk is derived from the collision risk model (CRM).

Case Study	1. Percival (2004)	2. Madders (2004)	
Species	Bewick's Swan	Golden Eagle (Ben Aketil)	Golden Eagle (Edinbane)
Time span	180 days	1 year	1 year
Collision risk	0.145	0.112	0.133
Avoidance rate	0.9962	0.995	0.995
Mortality rate	0.06	0.12	0.55

respective figures would be 0.55 and 11.55. Clearly, if avoidance rates really were so low, then there would be serious impacts on local Golden Eagle populations. However, the sensitivity of estimated collisions to avoidance rates is such that a reduction from this value of only 0.005 (i.e. doubling the non-avoidance rate from 0.005 to 0.010) would double the mortality rate. A further issue in interpretation here is that mortality rates were based on the number of passes by birds, rather than the number of individual birds, representing repeated sampling of the same individual. There is therefore an implicit assumption that any bird killed would be immediately replaced. An assessment of the validity of this assumption is outside the scope of this paper.

Case Study 3. Seabirds at Kentish Flats, southern England

Using survey data and an avoidance rate of 0.9998 taken from Winkelman (1992), Gill *et al.* (2002) estimated mortality rates derived from the CRM for four groups of seabirds (terns, divers, Gannets *Morus bassana* and Black-headed Gull *Larus ridibundus*) at Kentish Flats, UK. The estimated avoidance rate was used for all of the above groups by Gill *et al.* (2002), even though it was derived for passerines only (Winkelman 1992). It seems inappropriate to use the avoidance rate for passerines when all species considered at Kentish Flats were considerably larger and have very different flight characteristics from passerines. Furthermore, despite the authors' statement that the avoidance rate used is 'the worst case scenario', it is in fact one of the lowest rates presented in the source reference (see Table 12 in Winkelman 1992). For example, the maximum estimated nocturnal mortality for gulls is 0.18%, giving an avoidance rate of 0.9982. Application of this rate to the data resulted in over an eight-fold increase in mortality rates. This Kentish Flats study would have been a good candidate for presenting a range of avoidance rates, rather than a single (and arguably inappropriate) rate.

DISCUSSION

The original CRM was developed assuming birds showed no avoidance behaviour when encountering a wind turbine. Avoidance behaviour was incorporated by multiplying predicted collision risk by non-avoidance rate. Estimates of avoidance are typically very high (> 0.95 in most case studies). Hence, they heavily and linearly influence predicted collision rates. Small variations in avoidance rates result in relatively large changes in predicted collisions, so errors in avoidance rate estimation can have large impacts on estimated mortality rates.

Bird surveys at wind farm sites are typically carried out in good weather conditions and in daylight. Avoidance behaviour, however, is likely to vary according to conditions: it is reasonable to expect that avoidance rates would be much reduced at times of poor visibility, in poor weather (themselves depending in part on season) and at night (e.g. Winkelman 1992, Still *et al.* 1996). Furthermore, in conditions of poor visibility, birds tend to be drawn towards, and circle in the vicinity of, continuous lights, which may represent an attraction and therefore substantially affect avoidance rates (e.g. Gauthreaux & Belser 1999, Manville 2000). Birds may also be drawn to the vicinity of turbine structures for other reasons. Offshore, gulls and Cormorants *Phalacrocorax carbo* use them as perches, as do birds of prey on land, and where the presence of turbines increase feeding opportunities, birds may be further drawn into their vicinity elevating collision risk (Fox *et al.* 2006).

Avoidance rates have been calculated by dividing the estimated actual mortality rate by the number of birds 'at risk' (e.g. flying through the area at turbine height). Since both sources are subject to considerable observer, stochastic and systematic error, avoidance rates suffer from compounded error, both in accuracy and precision. Potential improvements to bird survey methods, particularly at night and in poor visibility could include remote sensing survey technologies (see below). Calculation of post-construction mortality rates has typically relied on corpse searches (Langston & Pullan 2003), using tideline searches for off-shore and coastal wind farms (e.g. Winkelman 1992, Still *et al.* 1996, Painter *et al.* 1999). There are potential biases in estimating mortality in this way due to searching efficiency, corpse removal by scavengers, injured birds leaving the area before death, 'obliteration' of birds struck by turbines (especially smaller species) and, for coastal locations, corpses being washed out to sea. Adjustments to mortality rates have been made to try and compensate for these factors by some authors (e.g. Winkelman 1992, Painter *et al.* 1999). Nevertheless, there is likely to be much local variation: scavenger communities are likely to differ locally; search efficiency depends on bird size and the vegetation in the surrounding area (Winkelman 1992); and at coastal sites, local tide, currents and weather conditions will affect recovery rates (Painter *et al.* 1999). Furthermore, postmortem examination has been used to assess mortality caused by turbine collision and compared to background mortality (where major physical injury has been taken as evidence of collision). However, birds may be driven to the ground by vortices associated with turbines rather than as a result of a collision (Winkelman 1992). Given these factors, it is probably unwise to use mortality rates (and therefore avoidance rates) derived from studies in locations that differ greatly from the potential site under consideration (in terms of habitat and topography for example), or indeed from different species (see Case Study 3 above). Rather, avoidance rates should be derived from the same species and from localities as similar as possible to the location under consideration.

Given the above caveats, avoidance behaviour of birds should ideally be studied *in situ* rather than be inferred

Table 2. Effects of 10% variation in input parameters on predicted mortality rates of Bewick's Swans at Little Cheyne Court (Percival 2004).

Input variable	Baseline′	Baseline ± 10%	Collision risk	Revised collisions	% increase
Max. chord (m)	5.00	5.50	0.153	0.063	5.62
Pitch angle (°)	30.00	33.00	0.150	0.062	3.55
Bird length (m)	1.21	1.33	0.151	0.063	4.24
Wingspan (m)	1.96	2.16	0.147	0.061	1.48
Bird speed (m/s)	20.00	18.00	0.158	0.065	9.07
Rotor diameter (m)	92.00	82.80	0.150	0.062	3.55
Rotation speed (/s)	3.00	2.70	0.158	0.065	9.07
Bird count	109.00	120.00	0.145	0.066	10.20
Avoidance rate	0.9962	0.897	0.145	1.628	2613.19

Variables were changed by 10% (increased or decreased) so that mortality rates increased. The original collision risk was 0.145 and the original number of predicted collisions was 0.06 (Table 1).

from two variables (mortality rates and bird counts at different heights) both of which can be subject to (sometimes considerable) error (Chamberlain *et al.* 2005). This error, even when small, can have relatively large effects on predicted mortality. This is illustrated by the example in Table 2 using data from Case Study 1. Table 2 lists all variables used in the calculation of mortality rates, including those used in the CRM, bird survey data and avoidance rates. By varying each parameter in turn by 10% (in the direction that leads to an increase in the predicted mortality rate), the effect that error in each parameter can have on the predicted mortality rate becomes obvious. Clearly, the effect of variation in avoidance rate is far higher than any other variable in the CRM. Even when all other parameters were changed simultaneously by 10%, the predicted mortality was estimated only at 0.091 per 180 days (a 52% increase from the original 0.06), compared to 1.63 per 180 days for a change in avoidance rate (a 2613% increase).

Small changes in avoidance rates can lead to large percentage changes in mortality rates. However, actual mortality rate increases in terms of numbers of birds killed may still be small. In a species such as Golden Eagle with a low reproductive rate (Whitfield *et al.* 2004), such an increase is likely to have much greater impacts on populations than it would in a passerine species. This raises a more general issue; species that exhibit low natural mortality rates with low reproductive potential (K-selected) are likely to suffer rapid declines in absolute numbers when subject to additive mortality (Fox *et al.* 2006). These species are typically rarer (and hence of disproportional nature conservation value) than short-lived species with high reproductive potential (r-selected). Where r-selected species are abundant and widespread, the effect in proportional terms (though not necessarily to local populations) is likely to be less. Whilst outside the scope of this paper, further research into the wider population impacts of increased mortality due to wind turbine collisions, especially on K-selected species such as Golden Eagle, is to be recommended.

Spatially explicit patterns of avoidance shown by birds can be generated under a range of meteorological, light, diurnal and seasonal conditions using relatively crude surveillance azimuth radar (e.g. conventional marine radar, Kahlert *et al.* 2004). This has been successful in measuring the level of avoidance at large spatial scales shown by migrating waterbirds (mainly ducks) to an extant offshore wind farm in Denmark (Desholm & Kahlert 2005). Furthermore, statically mounted thermal infra red imagery can be used to view rotating turbines in a way that could potentially directly record actual collision rates and mortal wounding events associated with air vortices, as well as flight avoidance of the rotor swept area by birds (Desholm 2003). This provides real time collision rates offshore (where collections of corpses is not practical) and onshore (to verify estimates from corpse collections), potentially generating data at the species or species group level (Desholm 2003). Archived imagery from such devices can also show the specific avoidance behaviour of individuals of particular species in close proximity to turbines that can further inform the development of meaningful parameterization of avoidance behaviour (Desholm *et al.* 2006). Use of such remote technologies is essential if we are to be able to provide useful precision on estimates of a parameter that makes such a huge difference to predicted collision risk.

CONCLUSIONS

Whilst the ultimate collision probabilities generated from the CRM approach are theoretically robust, their modification by the probability of avoidance shown by different species of bird is specifically ignored by the present formulation and ill-served with available real data at the present time (Band *et al.* 2005). We suggest that the value of the current model in estimating actual mortality rates is questionable until such time as species-specific and state-specific (i.e. different bird activities and behaviours under a range of conditions, for example breeding birds, recently fledged or moulting birds) avoidance probabilities can be better established. The CRM may be useful for comparative purposes, but this is dependent on sound evidence that potential sites being compared can be assumed to have equal avoidance rates. Avoidance rate studies should be carried out as a matter of urgency. Currently, inferring avoidance rates from survey sample data on bird occurrence and estimated mortality (themselves subject to error) is inadequate. Even small errors can have large effects on predicted mortality rates, such that no matter how robust the estimates of collision risk in the absence of avoiding action, the final predicted mortality is meaningless. We cannot therefore recommend the use of CRM without further research into avoidance rates. Indeed, Band *et al.* (2005), who developed the CRM, concur with this, in stating 'For the CRM to predict accurately measures of collision mortality, it is essential that more information is collected on avoidance'. Potential methodologies to obtain data on species and state specific avoidance rates include the use of surveillance azimuth radar and thermal infra red imagery (Desholm *et al.* 2006).

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VII

A stochastic model analysis of avian collision risk at wind farms

DESHOLM, M. & KAHLERT, J.

Manuscript

A STOCHASTIC MODEL ANALYSIS OF AVIAN COLLISION RISK AT WIND FARMS

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Key words: collision, avian migrants, wind turbines, avoidance behaviour, applied ecology

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Abstract

Recent concern about the adverse effects of collision mortality on avian migrants at wind farms has highlighted the need to understand temporal and spatial patterns of bird-wind turbine interactions. Here, we evaluate the utility of stochastic collision models incorporating data on avoidance behaviour collected during an offshore Danish case-study using surveillance radar and thermal imaging equipment. Out of 235,136 migrating sea ducks only 47 individuals were predicted to collide with turbine rotor-blades, an overall mean collision risk of c. 0.02%. Birds were shown to demonstrate active avoidance behaviour at multiple levels. They avoided the wind farm as a whole, individual turbines when flying within the wind farm, the vertical risk zone, the rotor blades at the last instance during approach and finally birds minimised the number of turbine rows traversed, contributing to an overall avoidance rate of 94.6%. The fact that most birds avoided flying within the wind farm at all had the highest impact on the modelled number of collisions. Even though most studies suggest that situations with poor visibility will constitute the high risk collision periods, this is not necessarily the case for all species and at least not for the Common Eiders migrating in the Baltic Sea, since we show that they tend to migrate above turbine height at night and otherwise terminate their daytime migration in poor visibility. We propose that stochastic model analyses of avian collision risk should be implemented as a standard risk prediction procedure during environmental impact assessments prior to construction and as a management tool for estimating the collision rate in post-construction studies. Thereby, the presented collision model can help tackling the often site and species specific collision issue that we have just started to understand. Finally, the model approach should also be applied at land-based wind farms where we still know so little about the factors governing the collision pattern and were the offshore remote technologies can easily be adopted.

INTRODUCTION

Migrating birds collide with human made obstacles such as tall buildings, communication towers, bridges, light houses, oil rigs, wind turbines and power lines (Avery et al. 1976, Winkelman 1992, Nilsson & Green 2002, Jones & Francis 2003, Langston & Pullan 2003, Petersen et al. In press). At offshore wind farms, the practical challenge of estimating the magnitude of this anthropogenic mortality factor is significant, since currents and the harsh environment at sea makes the standard procedure of collecting casualties from the ground impractical (Desholm et al. 2005, Fox et al. 2006, Hüppop et al. 2006, Pettersson 2005).

In addition to extensive development of wind power on land, several European countries already have offshore wind farms in operation (Denmark, UK, and Sweden). The industry is currently making a substantial investment in developing the exploitation of the marine areas, with at least 13,000 offshore wind turbines currently proposed in European waters (ICES 2003, Fox et al. 2006). In North America, wind power production is exclusively land-based, but plans exist for offshore wind farms in the US (in Nantucket Sound, Gulf of Mexico and the Great Lakes; Koning 2004). If future patterns follow those in Europe, the necessity for applying novel approaches to study interactions between birds and wind turbines at sea, as alternatives to standard carcass collection protocols, will soon be apparent in the New World also.

Environmental impact assessments (EIA; equivalent to the North American EIS) for offshore wind farms require some pre-construction assessment of the rate of collisions that occur amongst different bird species under different environmental conditions. To date, relatively few offshore wind farms have been built and fewer still have robust post-construction measurement of collision rates. Modelling of collision rates, based on observed movements of birds at a proposed site in time and space require collation of fine scale data on avian trajectories. Such data are extremely time consuming or near impossible to collate through direct human observation and increasingly, we rely upon remote techniques to gather data on bird behaviour in a way which can provide a robust objective basis for modelling (for a review of remote technologies see Desholm et al. 2005). Such studies require the use of radar (Eastwood 1967, Bruderer 1997a, Bruderer 1997b) to accurately plotting flight trajectories prior to and post-construction and thermal imaging systems (Winkelman 1992, Desholm 2003a) to estimate the flight altitude in the wind turbine risk zone (i.e. the rotor-blade sweep area), to assess species composition and finally for validating the modelling results through direct collision detection. Both radar and thermal imaging systems can operate in situations with low visibility (at night and during fog) which are the conditions under which most bird-wind turbine collisions are expected to occur (Garthe & Hüppop 2004, Desholm et al. 2005).

The present paper describes a stochastic model developed in order to estimate the number of bird fatalities at wind farms, and shows how the use of remote technologies (Desholm et al. 2005) can provide important model input data on the behavioural ecology of migrating birds that can help us understand the factors and processes that govern the severity of this wind farm related mortality.

The model is constructed and run using the Stella modelling software (ISEE Systems 2004) which is easy to operate without any programming experience, and hence, could represent a contribution to the development of a tool-kit for managers, consultants and scientists working on the bird-turbine collision issue. In addition, the model provided insight into the processes, which determine the collision rate by sensitivity analysis. Furthermore, instead of only measuring the site specific number of casualties per turbine per year directly, it focuses on species specific behaviours applicable to future pre-construction EIA-studies for predicting the local effects of proposed wind farms on the avian migrants at other sites.

The aims of this study were three-fold: 1) to compile information to construct a stochastic predictive collision model for avian migrants that includes avoidance behaviour, 2) to validate this model by measuring the number of collisions directly using a thermal imaging system, and 3) to assess the importance of the avoidance factor in collision predictions. Finally, we consider the implications of our results for future EIA-studies for proposed wind farms.

METHODS

Model framework

The collision prediction model was constructed as a stochastic model for avian migrants, and it incorporated an assessment of the variability present in the different input variables. In figure 1 the conceptual diagram of the model is presented which shows the state variables and the external variables (model input data) and how these components are interrelated by the mathematical formulations of the processes. The model estimates the autumn number of collisions between birds and rotor-blades (see Ecological Archives for the model code).

The model consist of 10 state variables (n_i) each representing either a risk window (e.g. study area, wind farm, sweep area of the different north-south rows of turbines) or the avoiding/colliding segments of the population. Only one of the state variables was provided as model input data, the number of birds entering the study area (n_1). The remaining model input data were represented by five different external variables (r_1, r_2, r_3, r_4, and c) all representing transition rates between state variables. The first three transition rates (r_1, r_2, r_3) describe the proportion of birds going from one risk window to the next, the r_4 describe the proportion of birds trying to pass the sweep area of the first turbine row without performing any last-second evasive behaviour, and c is the probability of passing the sweeping rotor-blades by chance (Fig. 1; Tucker 1996, Band et al. In press).

The first part of the model covers the front row of turbines only, and hence, the second and last part of the model deals with the probability of passing the secondary and subsequent rows (Fig. 1). This approach implies that only birds passing the area swept by the rotor-blades at the first row of turbines, and which showed no evasive response towards the rotating turbine-blades, will have the possibility of passing the area swept by the rotor-blades of the consecutive rows of turbines. This is because birds avoiding the turbines in the first row will, in all probability, exhibit the same perception of risk when passing the turbines at the next row of turbines, and hence, most probably perform an evasive response again.

During every iteration (each representing one autumn season) of the model, a wind direction was sampled, since it influenced both the orientation of the rotor-blades (consequently also r_2) and the probability of passing safely the sweeping area (c is known to differ in opposing and following winds). The migration event was simulated from n_1 through $n_{collision}$ in accordance to the stochastic collision model (Fig. 1). At each iteration those transition probabilities for which probability distributions can be collected in the field post-construction were re-sampled.

The end product of the stochastic collision model will be the predicted number of birds colliding with the turbine rotor-blades and follows:

$$n_{collision} = (n_5 \times (1-c)) + \sum(n_{6\text{-}8} \times (1-e_6)) \quad (1)$$

The case-study

The study was conducted from autumn 2000 to spring 2006 at the Nysted offshore wind farm situated in the Baltic Sea in the southern part of Denmark (Fig. 2; 54°32'N, 11°46'E). The area is known to be passed by c. 250,000 migrating Common Eiders *Somateria mollissima* and tens of thousands of geese each autumn (passing westward during September and October) and spring (passing eastwards from mid March to mid April; Desholm 2003b). The 72 turbines (2.3MW, blade length: 42m, hub height: 69m, red lights or red flashing lights (edge turbines) mounted on the nacelle top) are placed in eight north-south orientated rows spaced 850 m apart. The distance between each turbine in the rows is 480 m. Wind direction was measured every ten minutes from a meteorological mast (25m a.s.l.) situated within the wind farm area or from a weather station at Gedser Odde. Both radar and thermal imaging techniques were applied to parameterize the predictive collision model for Common Eiders and to validate the model framework. Only daytime migration was modelled since common eiders were shown by the TADS to fly above turbine height at night (Petersen et al. In press.). Only five out of the 193 flocks, for which flight altitude could be estimated, were migrating at night, and hence, a proper day vs. night comparison of flight altitudes could not be carried out. All data were consequently pooled in to a single data set. In order to explain the very low number of birds during the night-time from TADS-recordings below 110 m (the altitude interval covered by the TADS in horizontal viewing mode), a comparison was made between the number of waterbird flocks recorded by radar and the number recorded by TADS during a period (17-19 October 2005) of high migration intensity when simultaneous monitoring was conducted with both TADS and radar. During day-time, the TADS recorded 96% of the flocks recorded by the radar (N=50) and at night the TADS recorded 0% of the flocks recorded by the radar (N=26). Only flocks passing within the field of view (24°) and range (900m) of the TADS were used in this analysis. Consequently, it is concluded that the common eiders are flying above turbine height (>110m) during the night and that the night-time collision risk therefore is close to zero. As a consequence of this we only ran the collision prediction model for the daytime situation.

Using radar.—The radar study was carried out two days per week during the period 1 September – 31 October. Data from 2000 to 2002 refer to the pre-construction period and data from 2003 to 2005 the post-construction period. The flight trajectories of migrating waterbirds were mapped by the use of a surveillance radar (Furuno FR2125, peak power 25 kW, variable pulse length/volume 0.3-1.2μs, pulse repeat frequency 9410 ±30 MHz, vertical beam width 20°, monitor resolution 1280 × 1024 pixels, each pixel represents a square of 23m x 23m) mounted on an 8m high observation tower situated 5.6km to the northeast of the wind farm (Fig. 2). Species identification was conducted visually on a sub-sample of the flocks but all flocks were identified as waterbirds by radar signature (based on high flight speeds and stout echoes). Digitized migration trajectories were transformed to a GIS-platform in the local datum of the UTM 32 projection for spatial analyses. Spatial movements of migrating flocks were mapped relative to the nearby wind turbines, and hence, were extremely precise with regard to mutual distance between bird flocks and turbines.

Using Thermal Animal Detection System (TADS).—The TADS-study was carried out 24 hours per day from 15 April to 15 March (2004 and 2006) and from 1 September to 31 October (2004 and 2005) and all data refer to the post-construction period. Although the model analysis is dealing with the autumn migration season only we have, due to the relative low amount of TADS-data, also included spring data, and hence, we assume that the Common Eiders are behaving equally during the two different migration seasons. The TADS is an infrared based detection system (camera model Thermovision IRMV 320V from FLIR, 24° lens, pan/tilt head, remote controlled via Internet) that can monitor the behaviour of animals under all light conditions, including total darkness (thermal detection) and in an automated way so thermal video sequences are stored only if relatively warm bodies (e.g. animals) enter the field of view (Desholm 2003a, Desholm et al. 2005, Desholm et al. 2006). One TADS covers c. 32% of the area swept by the rotor-blades of a single turbine at the Nysted offshore wind farm. The TADS was mounted (c. 7.5m a.s.l.) on the H8-turbine during autumn and on the A2-turbine during spring (Fig. 2) representing the sectors with highest migration volume of waterbirds during the respective migration seasons, and were chosen to potentially register as many passing birds as possible during both day and night. In order to identify birds appearing on the imagery to species level, a combination of body shape, the movements of the flying bird and the wing beat frequency has to be taken in to account. Three different viewing modes were used during data collection: 1) the horizontal view for estimating the flight altitude of the waterbirds passing in between the turbines (manual recordings), 2) the 45° view for monitoring the airspace just next to the turbine, and 3) the vertical view for monitoring the bird-turbine collisions as a mean of validating the model predictions (automatic recordings). Manual recordings must be processed by a human observer post-recording. The speed of the process can be enhanced by increasing the frame rate during the viewing process. Automatic recordings must be filtered by a human observer post-recording to remove thermal video sequences triggered by warm non-bird objects (e.g. drifting clouds, rain and aircraft). The monitoring efficiency amounted to 56.4% when TADS was operated in the vertical viewing mode (Petersen et al. In press).

Model input variables

Migration volume (n_1).— An estimate of the total seasonal migration volume was adopted from Petersen et al. (In press), and was estimated on the basis of sampled data from the entire before and after study period (1999-2005). Furthermore, the variation in the phenology (occurrence during the migration season broken into 10 days-periods) and the diurnal pattern (variation in migration between one-hour intervals during daytime) were considered. Hence, for each hour in each 10-day-period, a daily mean migration intensity was calculated (number of birds/hour) and multiplied by the number of daylight hours in order to obtain the mean total number of migrating Common Eiders in a 10-day period, where the change in diurnal migration pattern represented the variation. Mean migration volume estimates for each 10-day period were summed over the autumn season to calculate the autumn migration volume. The autumn daytime migration volume (n_1) was estimated to 235,136 (95% confidence limits: 164,895; 305,360) Common Eiders passing the study area at Nysted offshore wind farm (see Petersen et al. In press). Obviously the estimated number of collisions will be directly correlated with n_1, and hence, no variation is built in to this input parameter. Any variation in n_1 will not influence the proportion of the birds passing the study area that actually collide with the turbines.

Proportion entering the wind farm (r_1).—The overall proportion of flocks crossing the eastern row of turbines was estimated using the radar data and follows the procedure of Desholm & Kahlert (2005). The pre-construction data represent the non-avoidance situation and the post-construction data the situation were the avoidance behaviour is taken in to account. Here, data were grouped by date and if less than 10 radar tracks were observed on a given day they were grouped with the following days until at least 10 tracks were present in each group. This resulted in 20 and 47 periods for which an average value for r_1 and its standard deviation could be calculated for the pre-construction and post-construction period, respectively (Table 1). Frequency distributions were produced and, since both were judged to be normal distributed, their mean and standard deviation were used to re-sample r_1 at each model iteration.

Proportion within horizontal reach of rotor-blades (r_2).—For this input variable, radar data defining the shortest distance to nearest turbine for flocks passing through the wind farm area were obtained from all waterfowl tracks (mainly Common Eider) passing the eastern row (Fig. 1) during post-construction representing the avoidance scenario and for hypothetical flocks showing spatial evenly distributed migration representing the non-avoidance scenario. The proportion (r_2) of the migrating flocks that pass within the horizontal risk distance (HRD; equal to the projected length of the rotor-blades on the north-south axis) of the turbines can be calculated for all possible wind directions. At each model iteration a wind direction was re-sampled from a normal distribution (mean direction: 168.9°, SD: 118.67°) describing the frequency distribution of wind directions associated with all the 10,672 post-construction waterfowl radar tracks where wind data were available. This wind direction was then used to estimate the HRD from the turbine:

$$HRD = L - \left(L \times \cos \left(D_{wind} \times \frac{\pi}{180} \right) \right) \tag{2}$$

where L is the length of the rotor-blades (42m) and D_{wind} is the direction from which the wind is blowing. In figure 3, the cumulated frequency distribution of the distance to nearest turbine (measured on a continuous scale) for flocks passing through the eastern turbine row and within horizontal rotor-blade reach is shown. Each re-sampled HRD was then inserted in the equations, describing the distance between birds and turbines, presented in figure 3 to calculate r_2.

Proportion within vertical reach of rotor-blades (r_3).— In order to estimate the proportion (r_3) of birds flying within the vertical reach of rotor-blades an altitude frequency distribution must be generated. Flight altitudes were estimated by the use of horizontal TADS video sequences showing flocks of birds passing in between the turbines. Flight altitudes were estimated from the distance and vertical angle to each bird flock by trigonometry (Fig. 4). The distance (A) to the recorded flocks of birds was estimated by:

$$V_v = \arctan \frac{a}{b} \tag{3}$$

where C represents half the distance the flock flew when passing the field of view and V_h equals half the horizontal angle of the applied camera lens which was a 24° lens. C was calculated for each flock by multiplying the time it took to pass half of the field of view with the mean ground speed (mean air speed corrected for a given wind assistance). Mean air speed for Common Eiders, which was used in the calculation of flight altitudes, was estimated to 17.34m/sec (SD = 2.4; n = 352) for all flocks detected by radar in the study area during 1999-2004 and visually identified to species.

From the visually obtained line of sight the vertical angle (V_v) to each bird can be estimated by:

$$A = \frac{C}{\tan V_h} \tag{4}$$

where a denotes the projected height of the bird at the neighbour turbine and b denotes the distance between the two turbines. Knowing the distance and angle to the bird, the flight altitude (T) of the recorded flocks of common eiders was estimated by:

$$T = (\sin(V_v) \times A) + H \tag{5}$$

where V_v is derived from equation 4 and A from equation 3 and H denotes the mounting height of the TADS (7.5m).

Measuring flight altitude by means of TADS is constrained by the relative small vertical opening angle of the camera lens (18°), which results in a limited field of view. This will exclude bird flocks flying high and close to the TADS from being detected. Consequently, the number of flocks flying at the same height as the sweeping rotor-blades will be underestimated inside the wind farm if a correction is not made for this effect. A correction factor (equals one plus the proportion of the altitude interval not covered by the TADS) was multiplied with the number of registrations in each 10 m altitude interval to correct for the decreasing TADS-coverage with increasing altitudes inside the wind farm. The view direction was set towards the south in autumn and towards north in spring in order to obtain data from both inside and outside the wind farm (Fig. 2).

The flight altitude was estimated on the basis of 44 flocks recorded inside the wind farm and 149 flocks outside during 152 hours of horizontal TADS-recordings conducted during the post-construction study period. The relatively low volume of data meant that no reliable variance estimate could be produced for the mean proportion of flocks flying within the vertical reach of the rotor-blades, and hence, the mean value was used for all model iterations.

A frequency distribution of flight altitudes was produced for flocks observed flying inside (corrected for coverage; avoidance scenario) and outside the wind farm (non-avoidance scenario; Fig. 5) and the corresponding r_3-values were calculated (Table 1). However, since no observations was made above 60 m inside the wind farm, a comparison between flight altitudes inside and outside the wind farm was based on the data from the 0-60 m interval only. The common eiders were flying lower inside the wind farm compared to outside (Kolmogorov-Smirnov two-sample two-tailed test, D=0.2316, $n_{in(corrected)}=51$, $n_{out}=149$, d.f.=2, $p<0.05$). The percentage of flocks flying below the rotor-blades (<30m) were 84.2% and 55.7% for flocks flying inside and outside the wind farm, respectively.

Proportion trying to cross of the area swept by the rotor-blades without showing avoidance behaviour (r_4).—During the TADS-operation period of 123.6 days, no waterbirds, which were the focal species in this study, were detected as approaching the rotor-blades at short distance when the vertical viewing mode was used. Therefore, it was not possible to estimate an r_4-value based on the data collected for this study. However, Winkelman (1992) reported that 92% of the birds approached the rotor without any hesitation during day time. This proportion was adopted as the r_4-value for the avoidance scenario and 1.00 was used for the non-avoidance scenario.

Probability of passing safely the rotor-blades by chance (c).— Finally, an avoidance-by-chance factor (c) must be incorporated to account for those birds crossing the area swept by the rotor-blades safely without performing any last-second evasive actions. Procedures for calculation of c can be found in Tucker (1996) and Band et al. (In press) and can be directly adopted for any collision prediction model. For this model, c was adopted from Tucker (1996) where different mean probabilities are presented for head (0.665) and tail (0.809) wind situations. The re-sampled wind directions from an earlier stage in the model were used to determine whether the head or tail wind value of c should be used for the given model iteration.

Mean number of rows passed (n_m).— The average number of north-south orientated turbine rows passed by the migrating flocks of common eider when crossing the wind farm area was estimated from the autumn radar data both pre-construction (non-avoidance scenario) and post-construction (avoidance scenario). Only tracks entering the wind farm area through the eastern gate were used. Each track was followed through the wind farm area and the number of north-south orientated turbine rows passed was counted. If a track terminated inside the wind farm area its last node was prolonged until it left the wind farm area by the projected route. The mean number of rows passed by the Common Eiders was then adopted in the collision prediction model. On average, each flock passed 5.9 (SD = 2.5, N = 296) and 4.3 (SD = 2.7, N = 555) rows of turbines during pre- and post-construction, respectively, which represent a significant avoidance response (Z = 8.59, $P<0.001$). For the present model a rounded mean of 6 and 4 rows were adopted (Table 1).

Sensitivity analyses

To help focus resources on the most important of the model input variables, a sensitivity analysis was carried out. This was done by modelling a set of scenarios (1-7) with varying assumptions about avoidance behaviour excluding either the impact from the avoidance behaviour at all spatial scales or one at a time and then observe the corresponding response on the most important state variable, the $n_{collision}$. Hence, it will be possible to distinguish between high-leverage avoidance variables, which have a significant impact on the system behaviour, and low-leverage avoidance variables, which have minimal impact on the system.

RESULTS

Running the model

Using the model framework and input values described above in this stochastic predictive collision model (Fig. 1) for the Nysted offshore wind farm resulted in an average (±SD) number of 47.1 (±46.2) migrating Common Eiders colliding with the 72 wind turbines during one autumn season (Table 1). The vast majority of the modelled autumn seasons had less than 100 casualties but as can been seen in figure 6 the variation between seasons are substantial ranging from 0 to 321 casualties. The estimated 95% confidence intervals (CI) was ± 0.9, and consequently, this means that we are 95% confident that the mean lies between 46.2 and 48.1 Common Eiders colliding with the turbines at the Nysted offshore wind farm. Hence, the general risk of collision for Common Eiders passing the study area is estimated to lie between 0.020% and 0.021% $(((n_{collision} \pm CI)/n_1)*100\%)$. Subtracting the modelled $n_{collision}$-value of scenario 1 (47.1; Table 2) from the value of scenario 7 (871.7; Table 2) and dividing it with the value of scenario 7 gives us an estimate for the overall avoidance factor of 0.946%. This means that 94.6% of the birds that would collide in the hypothetical situation without any avoidance behaviour do actively avoid a collision in the real world.

Model validation

In total, 1,086 hours of effective TADS collision monitoring (vertical viewing mode) were conducted during the study period and no Common Eiders or any other animal were detected. During the 1,350 hours of monitoring of the airspace just next to the turbine (45° viewing mode) the TADS detected eleven birds/flocks of birds, two bats, one moth, and two birds/bats passing the field of view. Of these 16 automatically triggered sequences only one passerine/bat was recorded as colliding with the rotating turbine blades as it was observed (45° viewing mode) falling down from the sky without beating its wings.

Since a single TADS covers c. 30% of the area swept by the blades of one 2.3MW turbine and it has a monitoring efficiency of only c. 50% it is likely to detect 15% of the collisions only if they are distributed evenly over the sweep area. Consequently, if less than 6.7 Common Eiders (calculated as all birds colliding divided by the 15% of the casualties detected by the TADS) are colliding per turbine per autumn then our single TADS will most likely fail to detect any of these casualties.

Using the modelled average of 47.1 Common Eiders colliding with the 72 turbines at the Nysted offshore wind farm during one autumn season results in 0.7 collisions per turbine per autumn. Thus, the results of both the stochastic collision model and the TADS monitoring scheme confirmed that the average number of collision per turbine per autumn lies within the magnitude of less than 10 casualties.

Sensitivity analysis

The way this model framework handles birds making multi-row crossings has significant implications for the contribution each individual row makes to the overall number of estimated casualties. The first row encountered by the migrating Common Eiders accounts for the vast majority of the collisions (88.1%), whereas the following three rows contributed more or less equally with c. 4% each (row 2: 3.8%; row 3: 4.4%; row 4: 3.7%).

It makes no sense to perform a sensitivity analysis on each of the external variables, since they are all represented by transition probabilities, and hence, the output values (e.g. $n_{collisions}$) will be directly proportional to the values of the input variables. This means that a change in any transition rate of, for example, 10% will result in an approximately 10% change in the estimated number of bird-turbine collisions.

The most extreme difference between any two scenarios was the 1749.1% increase in collision numbers (from 47.1 to 871.7 casualties) between scenario 1 including all the avoidance factors to scenario 7 with no avoidance factors included (Table 2). Individually, scenario 2 (no avoidance reaction towards the wind farm as a whole) had the highest impact on the modelled number of casualties resulting in a 270.5% increase. The other high-leverage avoidance variable was the vertical avoidance of rotor-blades (scenario 4) resulting in a 179.6% increase in $n_{collisions}$. The horizontal avoidance of individual turbines (scenario 3) can be characterized as a medium-leverage avoidance variable and among the low-leverage avoidance variables we find the last second avoidance towards the sweeping rotor-blades (scenario 5) and the avoidance of passing turbine rows (scenario 6; Table 2).

DISCUSSION

The model framework

The spatial and temporal pattern of bird-wind turbine fatalities will always be the result of a substantial number of interactions and processes between the physical structures, the weather and the behaviour and decisions made by the flying birds. Historically, the vast majority of studies on avian collision rate has been based on carcass collection protocols, where the area beneath the human constructions (e.g. wind turbines, towers or light houses) is searched regularly and a study specific search efficiency and scavenger removal rate are accounted for (Barrios & Rodriguez 2004). However, as more and more offshore wind farms are proposed the need for novel approaches, applicable to the often harsh and remote conditions encountered at sea, is increasing worldwide. The remote technologies and modelling framework presented in this study provide the management tools for not only estimating the number of fatalities but also for delineating the processes governing the observed collision patterns. Gaining knowledge of these processes is fundamental for predicting environmental effects pre-construction, not only for the offshore wind farms but also at the many land-based installations throughout Europe and North America. The results of the present study support this view. Furthermore, knowledge about the species specific reaction patterns of birds flying in the vicinity of wind turbines is an essential prerequisite for proposing mitigating measures aiming at reducing any adverse impact on the populations involved.

External input variables

The model input variables were obtained partly from the data collected during the present study and partly from the literature. Five out of seven parameters have been derived from this study (n_1, r_1, r_2, r_3, and n_m) and two parameters (c and r_4) originate from other sources (Winkelman 1992, Tucker 1996). The degree to which risk perception and thereby avoidance behaviour to man-made structures differs between bird species is at present almost completely unknown. However, simple visual observations indicated that significant differences do exist even between rather related species. For example, at the fixed link between the island of Öland and mainland Sweden, Common Eiders tend to avoid migrating under the bridge which is in sharp contrast to Long-tailed Ducks *Clangula hyemalis* (Jan Pettersson pers. comm.). The fact that two species of large diving ducks can behave so differently when passing the same bridge, implies that care must be taken when applying behavioural avoidance data directly from one focal species when predicting impacts on another species. This also puts the present study into perspective, as one of the first of its kind to be followed by several other studies with the common future aim of enabling a robust generalisation across species for use in future predictive EIAs and EISs.

In the discussion that follows, we consider in sequence some of the variables of the model framework and assess their importance for the estimation of the bird-wind turbine collision risk and their potential role in the future environmental management of both land-based and offshore wind farms.

The approach of making input values dependent on the wind is obvious, since wind exerts such an influence on avian migration pattern (intensity, heading, ground speed and altitude; Alerstam 1990, Erni et al. 2002, Desholm 2003b, Liechti 2006, Nilsson et al. 2006) as well as on the orientation and rotation speed of wind turbines, all factors that are likely to influence the wind farm related mortality. Additionally, many bird species select specific favourable wind conditions before departure or enroute, for migration and thus, may passively influence their collision risk.

Estimation of migration volume may seem trivial but migration count schemes are never complete and therefore the estimation technique needs to account for all the birds not recorded (e.g. night migrants and birds passing when the observer is off duty). Even though c. 20% of the Baltic Common Eiders migrate at night time (Alerstam et al. 1974, Desholm 2005b) the present TADS study indicated that they do so at altitudes higher than the upper reach of the turbines of the Nysted offshore wind farm. These findings are supported by the study by Blew et al. (2006) who conducted a boat-based vertical radar study on avian migrants in the Nysted wind farm. They found that birds (all species grouped together) flying in the wind farm area tended to fly less frequently in the lower 100 m altitude segment at night compared to during day-time. This was evident, even though their vertically operated ship radar underestimated, to an unknown degree, the migration volume at 0-100m above the water surface, the altitude segment mainly used by the day-time migrating Common Eiders. Collisions between birds and man-made obstacles are believed most often to occur during periods with low visibility (e.g. at night-time; Garthe & Hüppop 2004, Desholm et al. 2006), but the tendency shown by waterbirds (including Common Eiders) to increase flight altitude above 110m during night-time migration significantly lowers the potential collision risk in this instance. This means that the night time collision risk is, all else being equal, relatively low and the reason it is excluded from the present model analysis.

Of all the avoidance factors, the strategy of performing evasive manoeuvres toward the wind farm as a whole seems to be the most important risk minimizing behaviour among migrating Common Eiders. Without the three year base-line, it would have been very difficult to quantify and prove statistically that this behaviour was actually a real avoidance response and not just the normal migration pattern given the present topography. Collecting data by radar seems to be the only operational way of dealing with the r_1-variable since this deflection of flight trajectories is evident at distances of at least 3 kilometres from the wind farm (Petersen et al. In press).

The behaviour of avoiding the HRD of the individual turbines turned out to represent a medium-leverage avoidance variable resulting in a 52% increase in modelled number of casualties if left out of the analysis. In the study by Desholm and Kahlert (2005), Common Eiders were shown to increase their distance to individual turbines when crossing the wind farm area at night compared to day-time. Now that we have shown that these birds migrate above turbine height at night it could be speculated how these two co-occurring behaviours interact. We propose that birds migrating above the wind turbines experience a much better view of all the rows of turbines (or the red lights in top of each turbine), and hence, are capable of navigating with a higher precision down the corridors which they apparently still perceive as a potential low risk route of some kind, even when flying above risk altitude.

The comparative analysis of the flight altitudes between day-time migrating Common Eiders outside and inside the wind farm revealed, when first corrected for coverage, that they tend to adjust their altitude below the lower reach (<30m) of the rotor-blades when flying inside the wind farm. So not only do the Common Eiders avoid flying inside the wind farm and close to individual turbines to a high degree, they are also actively decreasing the collision risk, when flying inside the wind farm, by partially avoiding the vertical risk zone. We would like to stress here that the often used approach of applying vertical operated surveillance radars for quantifying the altitude distribution of avian migrants (Koning 2004, Desholm et al. 2005, Desholm et al. 2006, Blew et al. 2006) may often be of limited value in bird-turbine collision studies. This because of the unknown underestimation of flight activity in the lower 50-100m a.s.l. which constitutes the most important zone when dealing with collision risk. As far as we know, the only technical alternative for collecting altitude data during darkness is the use of thermal imaging (i.e. the TADS). As mentioned above, the lack of bird flocks passing the field of view of the horizontally operated TADS is likely to be caused by the waterbirds flying above rotor-blade height when flying inside the wind farm area at this time of the day.

The r_4-variable was assessed to be a low-leverage avoidance variable and since we were unable to collect enough data on the last second evasive behaviour by Common Eiders we were forced to use historical data (Winkelman 1992). Again, data collection on this behaviour is constrained by the very low number of flocks trying to cross the area swept by the rotor-blades and therefore compiling data on this variable is a very resource demanding process (i.e. long monitoring time or high number of turbines to be monitored) if robust estimates are ever to be produced.

To our knowledge, the risk minimising behaviour of reducing the number of turbine rows to be crossed has never been documented before. Despite its low-leverage avoidance score, we recommend that future bird-wind farm studies take n_m in to account, especially at proposed wind farms involving a high number of turbines or with a design that induces a high number of potential row-crossings.

We would like to emphasise the importance of including the c-value in predictive collision models since it accounts for a substantial reduction (e.g. in the present model between 66.5% and 80.9% of those birds passing the area swept by the rotor-blades) in the estimated number of collisions. However, the relatively complicated algorithms used for estimating the c-value (Tucker 1996) may be rather difficult to comprehend for non-mathematicians, and thus, the present framework incorporated this external variable as being either a head- or tail-wind mean probability. One could argue that the Tucker-model (Tucker 1996) should be implemented in its original and full version but we decided here not to do so and thereby hope that it will be easier to use the present model framework for managers and consultants which will be dealing the many future EIA/EIS on wind farms.

Importance of multi-level avoidance rates

When this study was initiated in 1999 we only knew that c. 250.000 Common Eiders were passing our study area at Gedser Odde (Fig.2) each autumn (Kahlert et al. 2000). From the outset ecologists and the public was rather concerned whether these heavy sea ducks, known to have some of the highest wing-loads among birds, were able to manoeuvre their way around these man-made structures at sea. This fear has been proven not to be the case since they showed a high tendency to perform avoidance behaviour at multiple levels (Table 1). Birds avoided the wind farm as a whole, individual turbines when flying inside the wind farm, the horizontal risk zone, the rotor blades during the last second of approach and finally birds reduced the number of turbine rows to be crossed by taking the shortest routes out of the wind farm, all adding up to an overall avoidance rate of 94.6%. This avoidance rate is slightly lower than those of c. 99.5% published for Bewick's Swan (Percival 2004) and Golden Eagle (Madders 2004) but still high.

Because of the high volume and migration density of a relatively long-lived seaduck population through the Nysted area, this study is intentionally biased. It has turned out that the study has been dealing with a species that to a high degree is avoiding offshore wind turbines at this particular site. However, other species may be attracted to these fixed installations in the sea either due to a high abundance of food items (staging sea birds), because turbines may represent perfect perching facilities (gulls and cormorants) or because the night lighting of the turbines may attract night-migrating photo tactic bird species (e.g. passerines during foggy conditions). Applying the present model framework to such species would necessitate some adjustments, although the overall approach (i.e. the model, the remote technologies and the analyses described in this paper) would be more or less the same.

Collision estimation

The first crude version of the model was one with a deterministic framework using only mean values for the different input parameters and it resulted in an estimated 68 Common Eiders (range: 3-484) colliding each autumn at the Nysted offshore wind farm (Desholm 2005b). The estimated average number of collisions of 47.1 Common Eiders using the improved stochastic model equals 0.7 individuals per turbine per autumn, which lie within the range of published estimates at other wind farms (Winkelman 1985, SEO/BirdLife 1995, Osborn et al. 2000, Lucas et al. 2004, Pettersson 2005). Caution should be taken though when comparing such site-specific estimates, since for obvious reasons local conditions, such as migration volume, species composition, wind farm design, weather conditions and topography, most likely will play a significant role in determining the number of local collisions. Therefore it is important to compile and publish species specific behavioural data on avoidance, which can then be applied in future pre-construction predictive collision studies at other locations experiencing different local conditions.

Desholm & Kahlert (2005) concluded preliminarily that less than 1% of ducks and geese migrated close enough to the turbines to be at any risk of collision. Applying this more sophisticated modelling approach, we can now, with a high statistical certainty, predict that less than 50 Common Eiders, on average, will collide with turbines at the Nysted offshore wind farm during each autumn, which amounts to less than 0.022% of all Common Eiders passing the study area.

The model framework presented here have deliberately not embraced night-time periods and periods with very low visibility that are usually thought of as high-collision situations (Jones & Francis 2003, Garther & Hüppop 2004, Desholm et al. 2006). This is because these situations are judged to be of minimal importance in the present study, because: 1) the focal species tend to fly above turbine height at night (see above) and 2) situations when visibility is below 1km hardly ever occur at the study area during migration periods (Petersen et al. In press and references herein), and 3) we have anecdotal evidence that Common Eiders land on the water and cease migration when unfavourable weather conditions suddenly appear (Petersen et al. In press). This also explains why we have chosen to deal with rotor-blades collisions only, since collisions with the foundations and turbine towers are, due to lack of the motion-flare effect, judged to be a solely low-visibility issue and therefore not relevant in the present study.

From the outset of this study, we planned to use the TADS as a validation tool for the modelled number of collisions. However, since no Common Eiders were actually observed to collide with the turbine during the TADS monitoring such a validation proved to be possible on a magnitude-scale only. However, the TADS collision monitoring scheme is of added value since thermal imaging hardware can be used to collect behavioural avoidance data to support estimation of the important external input variable for the stochastic collision model.

MANAGEMENT IMPLICATIONS

This study provide one method to estimate the number of bird-wind farm collisions through stochastic modelling by incorporating the remotely measured species- and site specific avoidance rates. An overall collision risk of 0.02% was estimated for Common Eiders in the case-study at the Nysted offshore wind farm giving rise to an average number of 47 wind farm related casualties among 235,136 autumn migrating individuals. To put these local collision figures into perspective a comparison with other anthropogenic mortality factors seems appropriate and here the Danish annual hunting bag of c. 70,000 Common Eiders is one option. It would take 745 wind farms (if 2x47 Common Eiders are used as a crude annual collision number assuming that spring and autumn mortality rates are equal) with the same impact to equal the Danish hunting bag, and hence, it can be concluded that the mortality impact from the Nysted offshore wind farm is relatively low also on a national level. Moreover, this approach also offers a direct way of compensating for any political unacceptable cumulative mortality level, by regulating the hunting practice, if proper mitigating measures cannot be found or applied.

Care must be taken when applying these avoidance data to other species, since the number of studies on this issue is still too limited to draw any cross-species generalisations. Hopefully in the near future, when more studies have been performed, it will be possible to apply general knowledge in predicting the impacts of proposed wind farms, without the necessity for conducting resource demanding post-construction studies. We propose that stochastic modelling frameworks should be implemented as a standard management procedure, even at land-based wind farms where the offshore remote technologies can easily be adopted.

This new framework can also be used to assess other anthropogenic impacts (i.e. bird strikes with aircrafts and other man-made obstacles) on birds or for instance on bats. Here our TADS-registrations of bats implies that bat-wind farm collisions may not be a solely land-based issue, at least not for migrating species.

Finally, the present findings show that, even though most studies suggest that situations with low visibility will constitute the high risk collision periods (Garthe & Hüppop 2003, Fox et al. 2006), this is not necessarily the case for all species and at least not for the Common Eider.

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Figure legends

Figure 1
Schematic presentation of the collision model where the boxes to the left represent the four scale-specific conflict windows and the two large boxes to the right the non-colliding and colliding segments of the migrants. The eight values of n_i denote the number of birds/flocks which enter each box and can be calculated in accordance with the equations presented in the boxes. The migration volume in the study area is represented by n_1. Risk of collision is denoted r_i and is defined as the proportion of birds/flocks exposing themselves to a collision by crossing a potential collision window (e.g. wind farm or area swept by the rotor-blades). The evasive transition rates are denoted as e_i and c is a factor describing the by-chance-probability of not colliding with the rotor-blades when crossing the area swept by the rotor-blades.

Figure 2
Map showing the Nysted offshore wind farm in south-eastern Denmark. Arrows indicate the schematic migration pattern of Common Eider during autumn. The turbines mentioned in the text are indicated by their letter-digit codes. The radar range is shown and the black bar equals five kilometres.

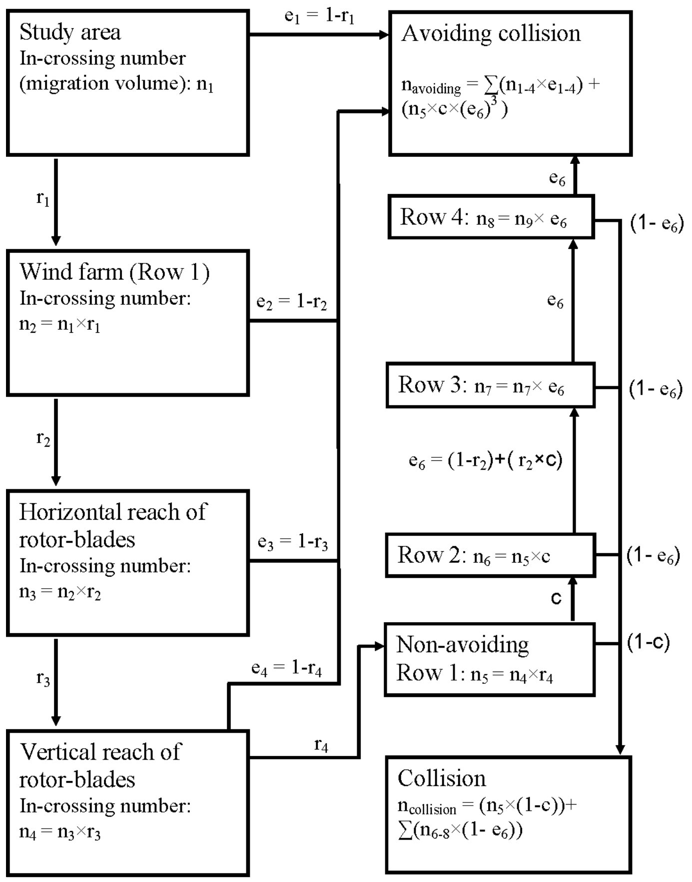
Figure 3
Regression lines, their equations and coefficients of determination representing the cumulative frequency distribution of the distance (continuous variable range: 0-45m) to nearest turbine for flocks of waterbirds entering the wind farm through the eastern row of turbines. The solid line represent the non-avoidance scenario (even migration distribution) and the dotted line the avoidance scenario (post-construction radar data; n = 558 flocks).

Figure 4
Schematic presentation of the trigonometry features used for estimating the flight altitude (T) of the migrating waterbirds. A denotes the distance (m) between the TADS and the bird flock (depicted as a single bird), V (equals V_v in the text) the vertical angle of the flock, b the distance between the two turbines (480m), a the projected height on the neighbour turbine of the flock, and H the mounting height of the TADS.

Figure 5
Frequency distribution of the flight altitude of flocks of migrating waterbirds (mainly Common Eiders) passing the view of the TADS during autumn 2004, autumn 2005 and spring 2006. "In" means flocks flying inside the wind farm and "Out" flocks flying just outside the wind farm. Numbers inside the wind farm were corrected for the unequal coverage of the different altitude levels (see text).

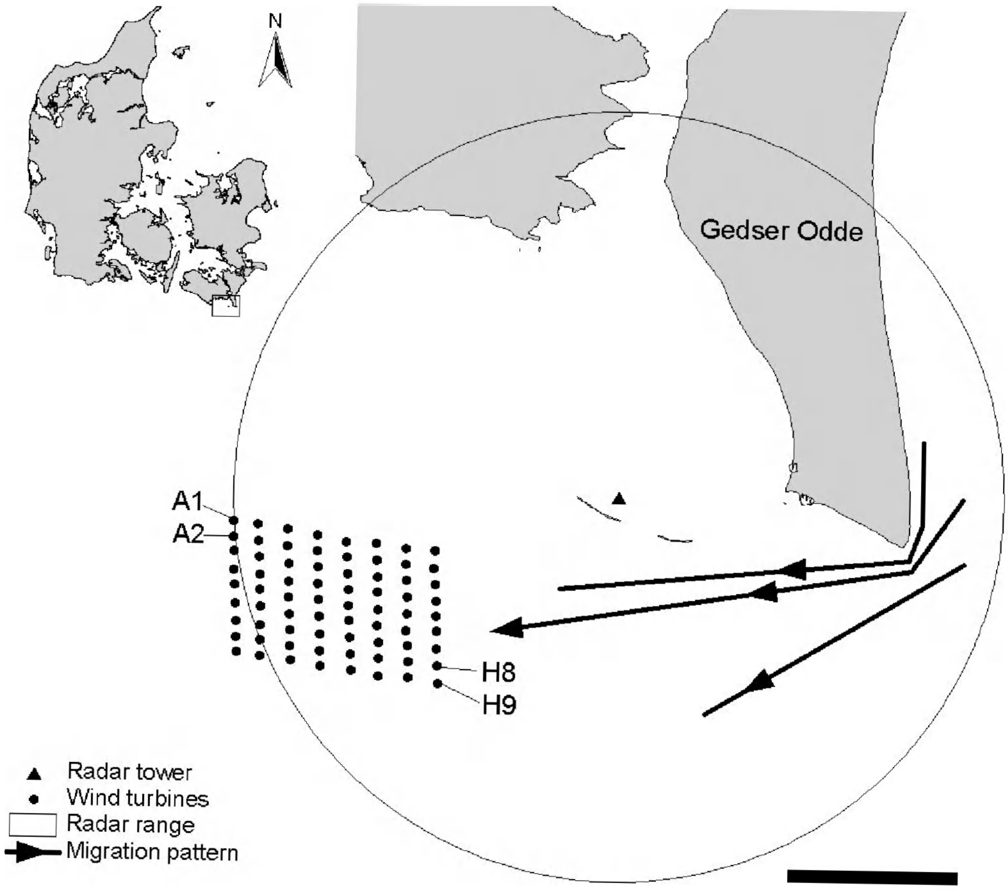
Figure 6
Frequency distribution showing the number of estimated collisions per autumn season for the Nysted offshore wind farm. A total of 10,000 iterations of the stochastic collision model were applied.

Figure 1



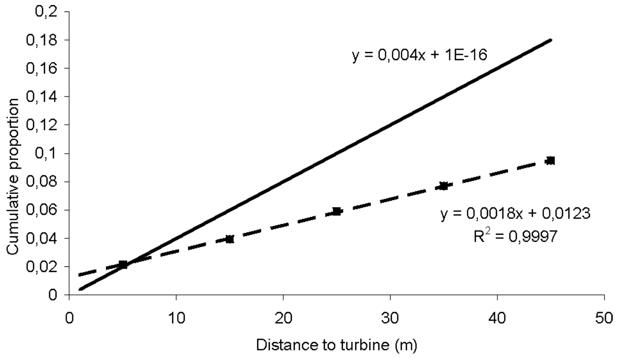
Study area
In-crossing number
(migration volume): n1
e1 = 1-r1
Avoiding collision
navoiding = ∑(n1-4×e1-4) +
(n5×c×(e6)^3)
r1
e6
Row 4: n8 = n9× e6
(1- e6)
Wind farm (Row 1)
In-crossing number:
n2 = n1×r1
e2 = 1-r2
e6
Row 3: n7 = n7× e6
(1- e6)
r2
e6 = (1-r2)+(r2×c)
Horizontal reach of
rotor-blades
In-crossing number:
n3 = n2×r2
e3 = 1-r3
Row 2: n6 = n5×c
(1- e6)
c
Non-avoiding
Row 1: n5 = n4×r4
(1-c)
r3
e4 = 1-r4
r4
Vertical reach of
rotor-blades
In-crossing number:
n4 = n3×r3
Collision
ncollision = (n5×(1-c))+
∑(n6-8×(1- e6))

Figure 2



N
Gedser Odde
A1
A2
H8
H9
Radar tower
Wind turbines
Radar range
Migration pattern

Figure 3



0,2
0,18
0,16
0,14
0,12
0,1
0,08
0,06
0,04
0,02
0
Cumulative proportion
y = 0,004x + 1E-16
y = 0,0018x + 0,0123
R2 = 0,9997
0
10
20
30
40
50
Distance to turbine (m)

Figure 4

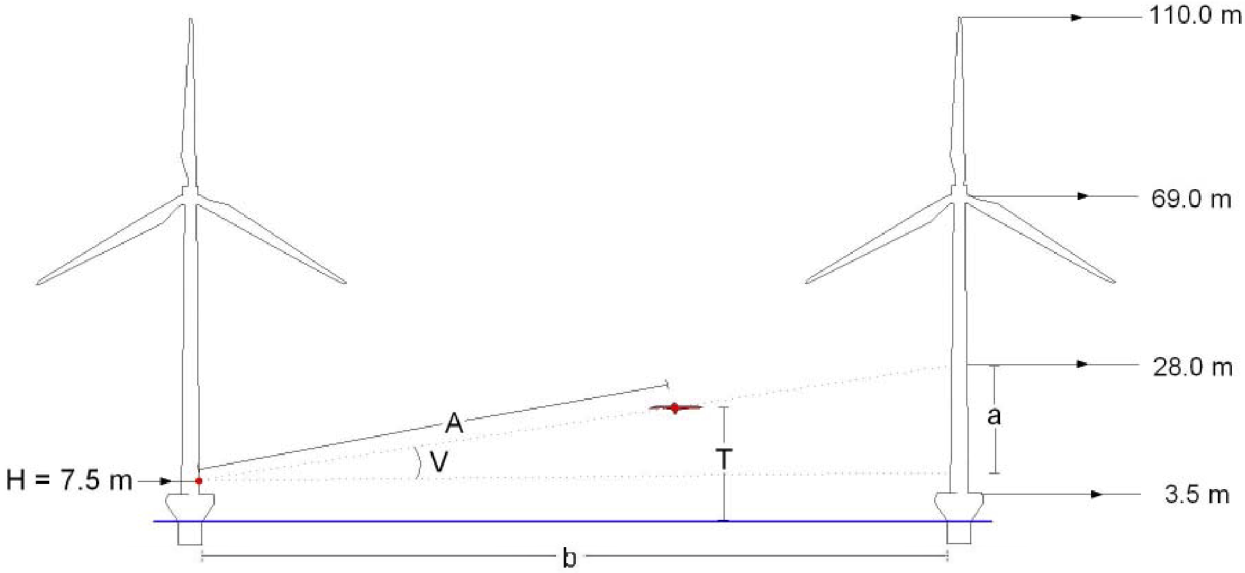
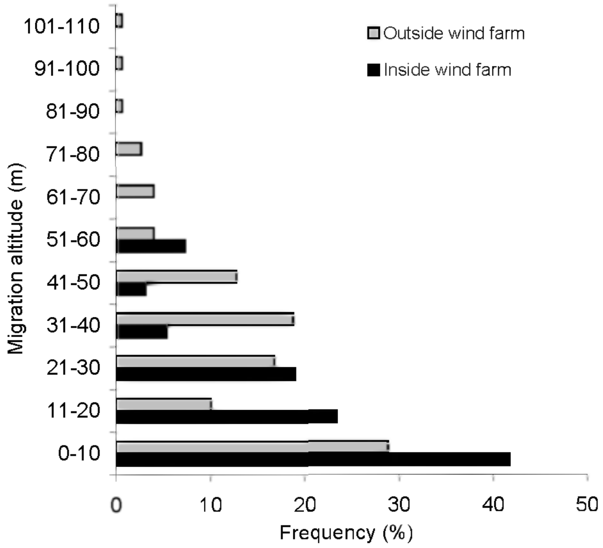
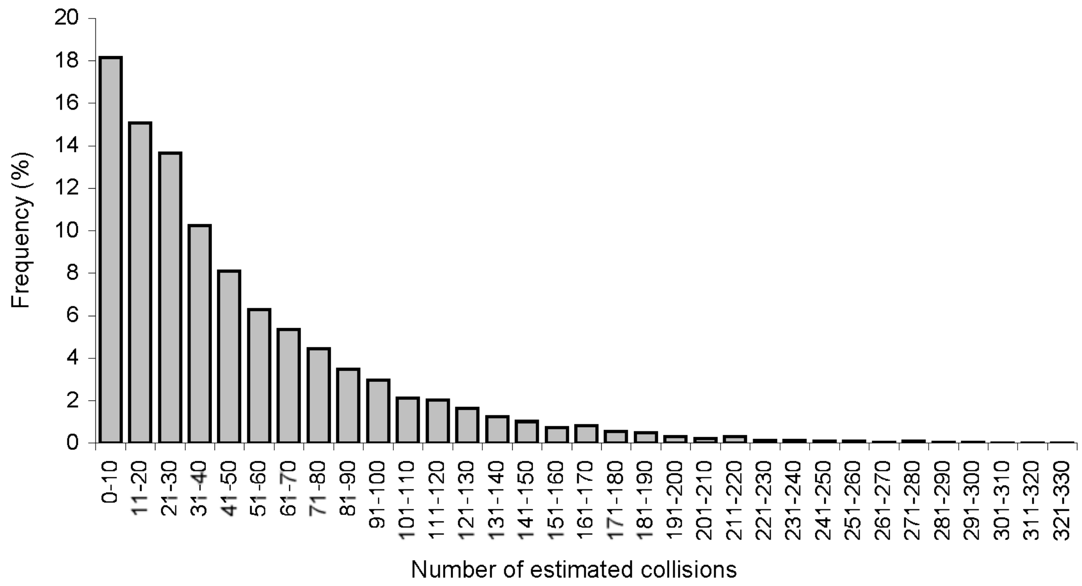


Figure 5



101-110
91-100
81-90
71-80
61-70
51-60
41-50
31-40
21-30
11-20
0-10
Migration altitude (m)
Outside wind farm
Inside wind farm
0
10
20
30
40
50
Frequency (%)

Figure 6



20
18
16
14
12
10
8
6
4
2
0
Frequency (%)
0-10
11-20
21-30
31-40
41-50
51-60
61-70
71-80
81-90
91-100
101-110
111-120
121-130
131-140
141-150
151-160
161-170
171-180
181-190
191-200
201-210
211-220
221-230
231-240
241-250
251-260
261-270
271-280
281-290
291-300
301-310
311-320
321-330
Number of estimated collisions

Table 1
Input and output average values (±SD) for the stochastic predictive collision model run with 1000 iterations. For explanation of abbreviations see text and conceptual diagram (Fig. 1). HRD denotes the horizontal risk distance and equals the projected length of the rotor-blades on the north-south axis (see text). The avoidance values are estimated as the percent change from the non-avoidance to the avoidance scenario. Numbers in superscript refer to the origin of data: 1) Petersen et al. In press, 2) Tucker 1996, 3) present study, 4) Winkelman 1992.

	Parameters	Details	Avoidance scenario	Non-avoidance scenario	Avoidance (%)
Model input	n_1	Fixed value[1]	235,136	235,136	-
	C	Head wind / tail wind[2]	0.665/0.809	0.665/0.809	-
	r_1	Normal distribution[3]	0.1155 (0.0793)	0.4380 (0.1296)	73.6
	r_2	HRD variable due to wind[3]	(HRD*0.0018)+0.0123	(HRD*0.004)+1*10^{-16}	47.7
	r_3	Fixed value[3]	0.1581	0.4430	64.3
	r_4	Fixed value[4]	0.92	1.00	8.0
	n_m	Fixed value[3]	4	6	33.3
Model output	$n_{collision}$	Stochastic modelling	47.1 (46.2)	871.7 (850.7)	94.6
	Collision risk (%)	$((n_{collision}±CI)/n_1)$*100%	0.020 – 0.021	0.36 – 0.38	-

Table 2
Summary data of the sensitivity analysis of the five different avoidance behaviour factors. Seven scenarios have been modelled using the non-avoidance values for the external input variables presented in table 1. N denotes the number of model iterations.

Scenario	Excluded avoidance factors	Number of collisions (SD)	95% CL	Increase (%)	N
1	None	47.1 (46.2)	0.9	0.0	10,000
2	r_1	174.7 (128.7)	2.5	270.5	10,000
3	r_2	71.5 (89.3)	1.8	51.7	10,000
4	r_3	131.8 (132.7)	2.6	179.6	10,000
5	r_4	50.9 (50.6)	1.0	8.0	10,000
6	n_m	51.0 (50.3)	1.0	8,2	10,000
7	All five	871.7 (850.7)	16.7	1749.1	10,000

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Code for the stochastic collision model developed using the Stella software by Mark Desholm, E-mail: mde@dmu.dk

```
Avoiding_collision(t) = Avoiding_collision(t - dt) + (e2 + e3 + e4 + e1 + Flow_c4) * dt
INIT Avoiding_collision = 0
e2 = (1-Proportion_within_horizontal_reach)*Wind_farm
e3 = (1-r3)*Horizontal_reach_of_blades
e4 = (1-r4)*Vertical_reach_of_blades
e1 = (1-r1)*Study_area
Flow_c4 = Passed_row_3_by_chance-Multicross_collision_row_4
Collision(t) = Collision(t - dt) + (one_minus_c + Multicross_collision_row_2 + Multicross_collision_row_3 + Multicross_
collision_row_4) * dt
INIT Collision = 0
one_minus_c = (1-c)*Non_avoiding
Multicross_collision_row_2 = (Passed_row_1_by_chance*(((Threshold_distance*2)/480)*(1-c)))
Multicross_collision_row_3 = (Passed_row_2_by_chance*(((Threshold_distance*2)/480)*(1-c)))
Multicross_collision_row_4 = (Passed_row_3_by_chance*(((Threshold_distance*2)/480)*(1-c)))
Horizontal_reach_of_blades(t) = Horizontal_reach_of_blades(t - dt) + (flow_r2 - flow_r3 - e3) * dt
INIT Horizontal_reach_of_blades = 0
flow_r2 = Proportion_within_horizontal_reach*Wind_farm
flow_r3 = r3*Horizontal_reach_of_blades
e3 = (1-r3)*Horizontal_reach_of_blades
Non_avoiding(t) = Non_avoiding(t - dt) + (flow_r4 - one_minus_c - flow_c) * dt
INIT Non_avoiding = 0
flow_r4 = r4*Vertical_reach_of_blades
one_minus_c = (1-c)*Non_avoiding
flow_c = Non_avoiding*c
Passed_row_1_by_chance(t) = Passed_row_1_by_chance(t - dt) + (flow_c - Multicross_collision_row_2 - flow_c2) * dt
INIT Passed_row_1_by_chance = 0
flow_c = Non_avoiding*c
Multicross_collision_row_2 = (Passed_row_1_by_chance*(((Threshold_distance*2)/480)*(1-c)))
flow_c2 = Passed_row_1_by_chance-Multicross_collision_row_2
Passed_row_2_by_chance(t) = Passed_row_2_by_chance(t - dt) + (flow_c2 - flow_c3 - Multicross_collision_row_3) * dt
INIT Passed_row_2_by_chance = 0
flow_c2 = Passed_row_1_by_chance-Multicross_collision_row_2
flow_c3 = Passed_row_2_by_chance-Multicross_collision_row_3
Multicross_collision_row_3 = (Passed_row_2_by_chance*(((Threshold_distance*2)/480)*(1-c)))
Passed_row_3_by_chance(t) = Passed_row_3_by_chance(t - dt) + (flow_c3 - Multicross_collision_row_4 - Flow_c4) * dt
INIT Passed_row_3_by_chance = 0
flow_c3 = Passed_row_2_by_chance-Multicross_collision_row_3
Multicross_collision_row_4 = (Passed_row_3_by_chance*(((Threshold_distance*2)/480)*(1-c)))
Flow_c4 = Passed_row_3_by_chance-Multicross_collision_row_4
Study_area(t) = Study_area(t - dt) + (- flow_r1 - e1) * dt
INIT Study_area = 235136
flow_r1 = Study_area*r1
e1 = (1-r1)*Study_area
Vertical_reach_of_blades(t) = Vertical_reach_of_blades(t - dt) + (flow_r3 - e4 - flow_r4) * dt
INIT Vertical_reach_of_blades = 0
flow_r3 = r3*Horizontal_reach_of_blades
e4 = (1-r4)*Vertical_reach_of_blades
flow_r4 = r4*Vertical_reach_of_blades
Wind_farm(t) = Wind_farm(t - dt) + (flow_r1 - flow_r2 - e2) * dt
INIT Wind_farm = 0
flow_r1 = Study_area*r1
flow_r2 = Proportion_within_horizontal_reach*Wind_farm
e2 = (1-Proportion_within_horizontal_reach)*Wind_farm
c = if(180>Wind_direction_autumn_post_construction>0)then(0.809)else(0.665)
Proportion_within_horizontal_reach = (Threshold_distance*0.0018)+0.0123
r1 = NORMAL(0.1155,0.0793)
r3 = 0.1581
r4 = 0.92
Threshold_distance = 42-(ABS(COS(Wind_direction_autumn_post_construction*(pi/180)))*42)
Wind_direction_autumn_post_construction = NORMAL(168.92,118.68)
```

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DMU	Danmarks Miljøundersøgelser

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This thesis is the result of a PhD study on bird-wind farm collisions and consists of a synopsis, five published papers, one submitted manuscript and another ready for submission. The papers describe the findings from pre- and post-construction visual, radar and thermal imaging studies (1999-2006) of migrating birds at the Nysted offshore wind farm in the Baltic Sea, Denmark. This thesis poses and answers the following questions: a) what hazard factors do offshore wind farming pose to wild birds, b) how should one choose the key focal species to study, c) how can remote sensing techniques be applied to the study of bird wind farm interactions, and d) specifically, how do waterbirds react when approaching an offshore wind farm? The main aim of the study was the development of a predictive bird-wind farm collision model that incorporates the avoidance rate of birds at multiple scales. Out of 235,136 migrating sea ducks only 47 individuals were predicted to collide with the wind turbine rotor-blades, equivalent to an overall mean collision risk of c. 0.02%. This thesis shows the added value of modelling in supplementing sound empirical studies in accessing the effects of major human development pressures on migratory bird populations.

Wind farm related mortality among avian migrants

National Environmental Research Institute
Ministry of the Environment

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