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Radar monitoring of migrating pink-footed geese: behavioural responses to offshore wind farm development

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Summary

1. In the context of growing demand for offshore wind energy production in recent years, much effort has been made to determine the collision risk that offshore wind turbines pose to birds. Currently, only limited species-specific data on migrating birds' avoidance rates and associated mortality at offshore wind farms exist.

2. During a 4-year study, bird detection radar was used to monitor behavioural responses and flight changes of migrating pink-footed geese in relation to two offshore wind farms during and after construction.

3. Radar recorded a total of 979 goose flocks migrating through the whole study area, of which 571 were visually confirmed as 39 957 pink-footed geese *Anser brachyrhynchus*. Overall, we calculated that 97·25% of all flocks recorded by radar, in 2009 and 2010 combined, migrated without any risk of additional mortality associated with the constructed wind farms.

4. We identified a growing tendency of geese to avoid the wind farms and calculated that, for 2009 and 2010 combined, avoidance was exhibited by 94·46% of the original 292 flocks predicted to enter the wind farms.

5. *Synthesis and applications*. Migratory geese responded to offshore wind farms by adopting strong horizontal and vertical avoidance behaviour. For the first time, wind farm avoidance rates have been recorded for pink-footed geese, and these rates will allow more robust impact assessments to be undertaken for both this species and waterfowl in general. Remote sensing techniques should be used to undertake long-term impact assessments at offshore wind farms to provide an evidence-base for assessing the mortality risk for migratory birds.

Key-words: *Anser brachyrhynchus*, bird collision risk, bird detection radar, wind farm avoidance

Introduction

Owing to concerns over climate change and fossil fuel depletion, the case to develop wind power as a renewable energy source has become much stronger in recent years. The UK is the world leader in generating electricity from offshore wind, currently with 16 operational offshore wind farms, and a further six under construction and 30 being approved, submitted or planned (BWEA 2012). Currently, there is *c.* 3 GW of global offshore capacity, with an expectation of 16 GW capacity being completed by 2014 (BTM Consult ApS 2010). However, although providing a step in reducing carbon emissions and associated effects of climate change, the increasing extent of marine renewable energy installations may result in adverse effects on wildlife at sea, including migrating birds (BirdLife International 2003; Drewitt & Langston 2006; Wilson *et al.* 2010).

In recent years, much effort has been made to determine the collision risk that offshore wind turbines pose to birds (Drewitt & Langston 2006). However, the complexity of the task calls for the existing methods of assessing mortality risk to be improved. In cases where only scarce bird count data are available, predictive simulations have been undertaken to quantify potentially harmful population-

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level impacts (Perez Lapena *et al*. 2010). However, to better understand the spatio-temporal interrelationships of specific species with offshore constructions, information on species avoidance responses is an essential prerequisite (Fox *et al*. 2006).

Radar has been used in ornithological research since its development in World War 2 (Lack & Varley 1945; Eastwood 1967) and is recognized as a powerful tool in monitoring bird behaviour (Gauthreaux & Belser 2003). Radar provides a suitable platform for monitoring avian activity in conditions and environments where conventional monitoring is compromised, for example adverse weather conditions, night-time and other periods of reduced visibility (Kunz *et al*. 2007). Depending on the mode of operation, radars used in ornithological studies can be primarily grouped as Doppler radars, tracking radars and surveillance radars. Each type of radar is suitable for a particular purpose, primarily due to differences in radar characteristics, namely range of detection, wavelength and Doppler capability. Examples of established avian radar systems include NEXRAD, a system of long-range, high-powered WSR-88D Doppler weather radars used to map the distribution and abundance patterns of bird migration over large scale in the United States (Gauthreaux & Belser 2005). Adapted military tracking radars have also been used to measure density and altitudinal distribution of birds over shorter ranges and scales, to track single targets in three dimensions and to measure wing-beat patterns allowing species identification (Bruderer 2007). By providing spatio-temporal information on bird movements at the local scale, surveillance radars lie in between large-scale weather (Doppler) radars and short-range, task-specific tracking radars. They can be used to study the migration corridors and also to investigate site- and species-specific response behaviour in relation to the surrounding environment (Gudmundsson 1993). Unlike Doppler and tracking radars, surveillance radars are generally more versatile, affordable and widely available, therefore more appropriate to use in case-specific environmental assessments as well as in providing information for use in biological conservation. Alongside other techniques, including infrared cameras, video surveillance equipment, microphones and ceilometers, surveillance radar systems are increasingly valuable in collecting reliable and quantitative offshore bird data (Desholm *et al*. 2006). It has been suggested that they are the most appropriate radars to study bird behaviour in relation to a single wind farm (Desholm & Kahlert 2005); however, owing to limitations in radar technology, human assistance is still requisite to ensure completeness of any environmental radar study (obtaining count data and species identification remains the domain of ornithologists).

Despite studies confirming the efficacy of surveillance radars, knowledge of wind farm avoidance by birds remains limited and estimating mortality rates using models remains questionable until species-specific and site-specific avoidance probabilities are better established (Chamberlain *et al*. 2006; Smales 2006). Modern bird detecting surveillance radar presents an excellent opportunity to enhance our knowledge of migrating birds and their avoidance responses in relation to offshore wind farms.

Avoidance ability varies between species (Garthe & Huppop 2004; Whitfield 2009) but environmental factors, such as weather conditions, visibility or local topography, can also influence birds' vulnerability to collisions with wind turbines. Birds of open habitats, such as geese, show relatively high avoidance distances from vertical structures, for example the distance up to which disturbance from wind turbines could be noticed can be as far as 850 m (Pedersen & Poulsen 1991; Hötker, Thomsen & Jeromin 2006). However, because of limited flight manoeuvrability, often nocturnal flight activity and, depending on species, biogeographical population size, this group of birds still remains vulnerable to collisions with turbines.

The proliferation in renewable energy installations around the UK coasts has the potential to impact on the internationally important numbers of geese wintering in the UK (Patterson 2006), namely bean goose *Anser fabalis* Latham, pink-footed goose *Anser brachyrhynchus* Baillon, white-fronted goose *Anser albifrons* Scopoli, greylag goose *Anser anser* Linnaeus, brent goose *Branta bernicla* Linnaeus and barnacle goose *Branta leucopsis* Bechstein. A number of built, planned and proposed wind farms are situated within the flight corridors used by these migratory species resulting in the need to assess any effects to population integrity associated with turbine collision and/or barrier effects.

Of two discrete populations of pink-footed goose, the larger Greenland–Iceland population migrates to the UK and smaller Svalbard population winters primarily in the Low Countries (the Netherlands, Belgium and Luxembourg). It is currently estimated that 360 000 pink-footed geese from Greenland and Iceland winter in the UK (Mitchell 2010; Musgrove *et al*. 2011) with sites in Scotland, north-east England and eastern England (primarily Norfolk) supporting nationally and internationally important numbers of these birds (Mitchell & Hearn 2004; Holt *et al*. 2011). As the numbers of geese progressively change between different locations throughout the autumn arrival period, the Norfolk population often exceeds 80 000 by mid-December (Mitchell 2010).

During the autumn migration, geese may encounter several offshore wind farms within their flight path, with the recently constructed and operational Lynn and Inner Dowsing (LID) Wind Farms, 5–8 km off the English east coast, being the final ones encountered before birds reach their Norfolk wintering grounds. The existence of a well-established migration corridor and an abundance of migrating geese near LID Wind Farms create an ideal situation for remote sensing techniques to be used to monitor wind farm avoidance behaviour.

The aim of this paper is to report on flight behaviour and associated avoidance action exhibited by migrating pink-footed geese in relation to an offshore wind farm during and after construction. In order to assess the impact of the wind farms on geese flight trajectory, we assumed a null hypothesis that the flight trajectory of migrating geese would be unaffected by the presence of the constructed wind farms.

Materials and methods

STUDY DESIGN

A 4-year radar study was conducted at a single location in north Skegness (TF 57172 64601), Lincolnshire, England (Simms *et al.* 2008, 2009, 2010, 2011). The radar unit was positioned 50 m from the shoreline with an unobstructed view of the LID Wind Farms, which comprised 54 turbines arranged in two adjacent arrays 5–8 km offshore. The study began in 2007 during the wind farm construction phase, when only turbine foundations at *c.* 30 m above sea level had been or were being erected. At this stage, the wind farm did not pose any danger or obstruction to migrating geese, and although there was a jack-up barge and several boats operating within the study area, the level of disturbance to migrating geese was low. The study continued in 2008–2010 with the wind farm completed and fully operational. The monitoring period ranged from 38 to 46 days in September–November each year to coincide with the peak autumnal migration period (Mitchell & Hearn 2004). The radar was operational 24 h a day, and two ornithologists undertook observations during peak migrational daylight hours (10·00–17·00) to complement and validate radar recordings.

RADAR EQUIPMENT AND DATA COLLECTION

A mobile, self-contained radar unit, equipped with Japan Radio Company, S-band surveillance scanner delivering 30 kW of output power, was used to collect and record data continuously during the monitoring periods. For the majority of the study, the radar operated at a 6 nautical mile (Nm) range, sending short pulse signal at 3088 MHz, making the detection of large birds, like geese, possible within a radius of 11 km. Advances in radar methodology enabled the effective detection range to be extended to 8 Nm (14·8 km) at the end of the radar deployment in 2010, allowing birds to be tracked and followed farther offshore than in previous years. Radar data were filtered to remove any non-bird targets, like boats, aeroplanes and weather events, using bird tracking software 'MERLIN' (Detect Inc., Panama City, FL, USA). In this study, where key bird targets were flocks of migratory waterfowl, a strong filtering system was implemented to allow long-distance tracking of relatively large targets. Although this aggressive screening filter would not record smaller targets, for example individuals and small flocks of passerines, it does allow a high level of detection and continuous tracking of larger targets (notably wildfowl flocks). All bird tracks were recorded automatically into an Access database, and video of the live radar display was stored for further analysis.

Migrating geese flocks produce a unique, pixelized signature that transcribes well into a repeatable, easily identifiable target on the radar display. This distinctive pattern and radar track trail allow radar operators to recognize flocks of migrating geese 3–4 km before the birds were within visual range of the shore-based observers. Two observers gathered additional information on species, numbers, flock formation, height and avoidance behaviour. Continuous radiocommunication and predetermined field reference points were used to ensure correct flock identification and data transcription.

Weather conditions were recorded at 15-min intervals using a VANTAGE PRO2 weather station (Davis Instruments, Hayward, CA, USA). Wind strength and direction, temperature, barometric pressure and rainfall were recorded. In addition to the automated recording, cloud cover in oktas, sea state (Beaufort Scale) and visibility (km) were recorded by observers every 2 h during the observation period.

DATA ANALYSIS

The standard MERLIN tracking algorithm (Kelly 2010) was run with settings optimized (e.g. target size and speed) for the detection of goose flocks. Radar scan returns (every 2·5 s) classified by MERLIN programme as bird targets were automatically colour-coded live on the radar display. The recent locations [all returns within the last 12 scans (30 s)] of any moving bird target were displayed alongside its current position, plotting a dotted track on the screen. The track pattern depends on a bird's size, flock formation, speed and flight style, permitting various radar signatures to be associated with different bird groups. The radar display video was reviewed to check for the presence of the distinctive goose flock track patterns in all recorded data sets (including night-time). The recordings were analysed using active video playback, and any potential tracks were paused and examined frame by frame to enable positive identification of goose tracks. This process also allowed the interpolation of tracks that were occasionally lost to 'MERLIN' software but were still visible on the radar screen. Geese tracks were then transcribed to GIS platform, using ARCVIEW. (ESRI 2011: ArcGIS Desktop, Release 10, Redlands, CA, USA)

To analyse the avoidance behaviour of geese in relation to wind turbines, the number of goose flocks crossing four sectors – (i) Inner Dowsing Wind Farm only; (ii) Lynn Wind Farm only; (iii) both wind farms; and (iv) neither wind farm – was counted in each year. In order to test our null hypothesis that the trajectory of goose tracks would be unaffected by the presence of the constructed wind farms, we identified the initial directional heading of each track to see whether tracks with headings intersecting with the wind farm arrays deviated from their expected course.

The mean heading of each flightline was calculated based on the heading of the first kilometre of each recorded radar track; this heading was then used to extrapolate the flightline through the study area. Chi-square tests were used to identify the differences between extrapolated and actual flightline numbers through the four sectors. A chi-square 4 × 4 contingency table was used to analyse the trends in goose avoidance behaviour in relation to the operational wind farm in 2008–2010.

During the 2009 and 2010 surveys, vertical flight activity was also assessed by recording flight heights for tracks flying within the LID Wind Farm footprint. Birds were deemed to be at risk of collision if their flight heights overlapped with the turbine rotor swept zone (35–125 m) and were within the wind farm footprint (defined as the minimum convex polygon encompassing all turbines in each array). Although turbines only occupy a proportion of the wind farm footprint, because of the variations in numbers and corresponding width of goose skeins size [flocks in this study have been recorded up to 900 m in width (I.C. Simms, personal observation)], any flocks passing through the footprint are therefore considered to be at risk of collision.

Results

During construction phase in 2007 and whilst the wind farms were operational in 2008–2010, the radar recorded a total of 979 goose flocks migrating through the study area (204, 186, 304 and 285 flocks in respective years) (Fig. 1). Of the 979 radar-detected flocks, 571 were visually identified comprising 39 957 pink-footed geese. The 4-year radar monitoring period totalled 172 days (Table 1). The marked increase in the number of geese recorded in 2009 and 2010 was attributable to variations in the timing of the study periods and in year goose arrival dates. Recorded weather data for all years fell within the typical range of Met Office historical data (October averages for East England 1971–2000) (Met Office 2011). The prevailing wind direction was south-westerly, average cloud cover was six oktas, and average sea state was moderate. In periods of reduced visibility during daylight hours, a single track (flock) was recorded in 2009 and 13 tracks (flocks) in 2010.

Similar weather conditions of moderate north-westerly winds, low cloud cover and good visibility resulted in three distinct migration pulses recorded by the radar between September and November each year (Fig. 2). The first peak in late September and early October appears comparatively weaker than the others principally due to variations in study commencement dates; the first migration pulses were only recorded in 2008 and 2009. The largest numbers were recorded in the second peak in mid-October. The third peak in activity was spread over 2 weeks from 28 October onwards, and it accounted for 35% of total number of goose flocks.

Diel migration activity was concentrated during the daylight hours in the early afternoon (12·00–14·00) with only 15% of flocks recorded during the hours of darkness (19·00–07·00), Fig. 3.

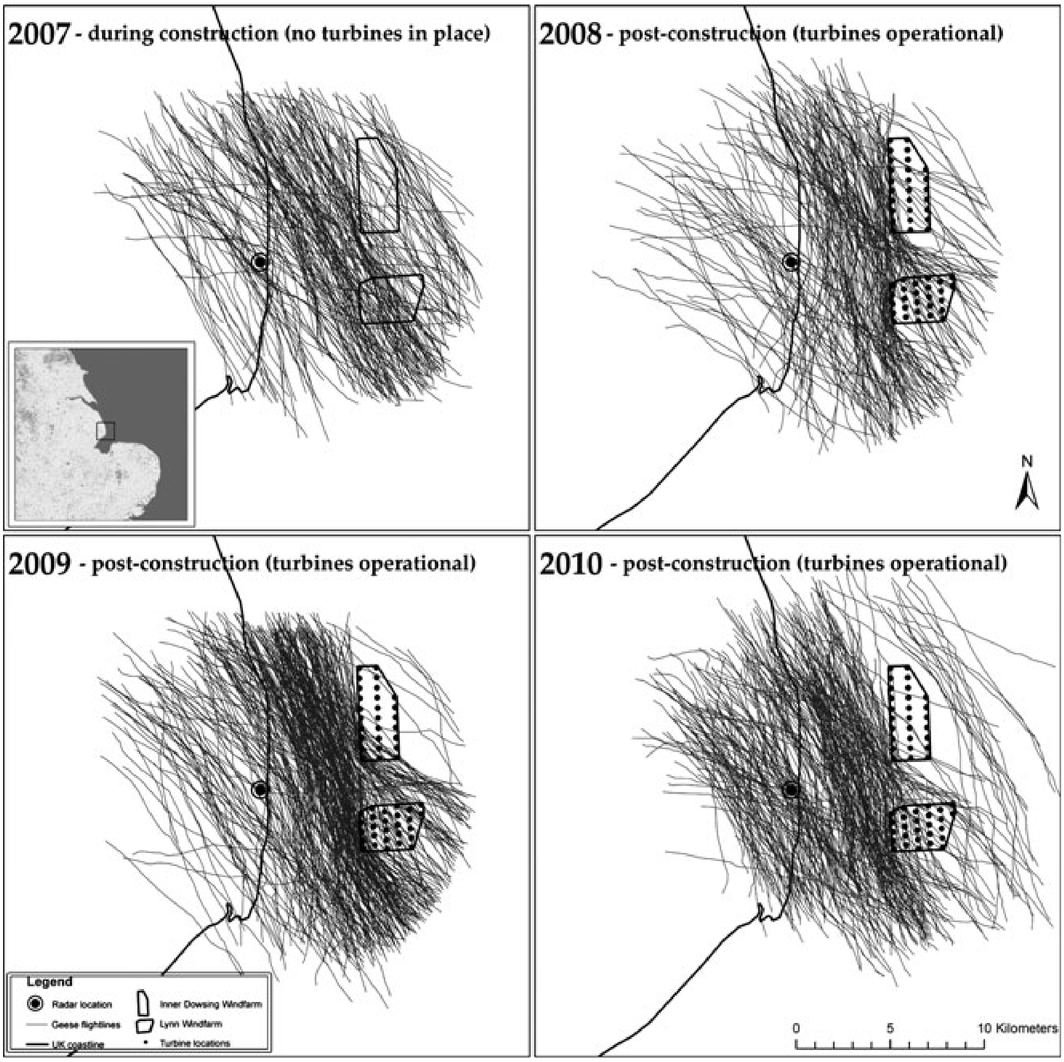

Fig. 1. Goose flock movement trails recorded by radar during 2007–2010.

Table 1. Survey effort in 2007–2010 and number of geese identified on the basis of the characteristic radar signature for geese. Total number of goose tracks recorded by the radar comprises the number of goose flocks visually confirmed by ornithologists and unobserved geese

Survey year	2007	2008	2009	2010
Deployment period	7 Oct–14 Nov	29 Sep–9 Nov	21 Sep–5 Nov	28 Sep–12 Nov
Operational days	38	42	46	46
Radar goose tracks	204	186	304	285
Observed goose flocks	115	71	235	243
Individuals	7357	7102	14 495	14 295

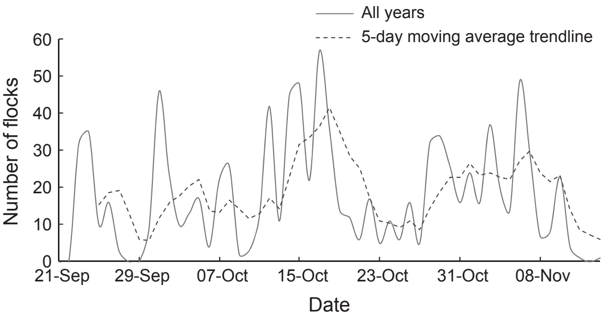

Fig. 2. Phenology of autumnal pink-footed geese migration recorded by radar at Skegness during 2007–2010.

The geese migrated along a corridor oriented north-west to south-east in a broad front both over the land and sea, covering mostly the space between the coastline and the wind farms (Fig. 1). Radar detected goose flocks up to 13·5 km away; on average, the birds were first detected at 7920 m (±59 m). Detection distance was primarily dictated by flight altitude and flock size. For the first three study years, 60% of flocks were first detected over the sea; however, this trend was reversed in 2010 when higher proportion of flocks was first detected over the land (55%).

WIND FARM AVOIDANCE

In 2007, almost half of all migrating goose flocks were recorded within the wind farm footprint (48%). Directional analysis of flight pathways showed no significant variation ($\chi^2 = 2{\cdot}77$, d.f. = 3, $P < 0{\cdot}427$) from the initial heading (108 flights predicted and 98 recorded), that is, that the geese did not exhibit any significant avoidance action in relation to the wind farm foundations or wind farm construction boat traffic. Thus, flightlines were extrapolated from their initial heading to predict the number of flocks that may fly through the wind farm arrays. This defined the null hypothesis of expected distribution of tracks within and outside the wind farm arrays for future years.

In subsequent years (2008–2010), of those flocks with initial flight bearings intersecting with the wind farm area, 216 (56·7%) exhibited avoidance and flew outside the arrays (Fig. 1). A simulation based on predictive heading

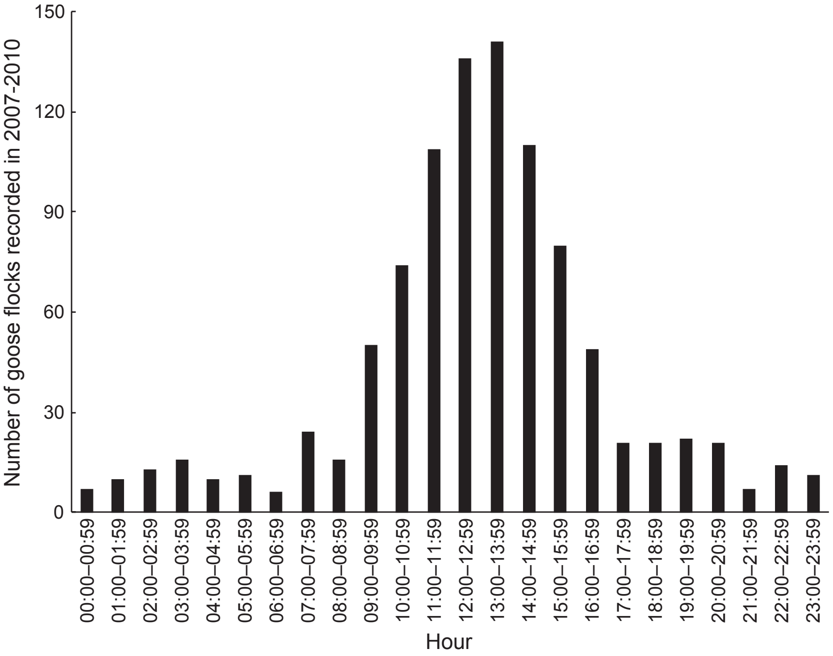

Fig. 3. Diel variation in hourly movements of pink-footed geese during 2007–2010, showing peak migration activity in early hours of afternoon.

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showed significant differences between the number of flocks in 2008–2010 expected within and outside the arrays ($\chi^2 = 19$; 22·2 and 46·8 respectively, d.f. = 3, $P < 0{\cdot}001$, for all three tests). It was predicted that 89, 164 and 128 flocks should have flown through the wind farm footprint; however, only 49, 114 and 53 flocks were actually recorded intersecting LID Wind Farms. Therefore, the reduction in number of flocks entering the combined wind farm footprint in 2008–2010 amounted to 40, 50 and 75 in respective years.

There were significant differences in the numbers of geese detected in the four different study sectors that showed a growing tendency to avoid the wind farm ($\chi^2 = 62{\cdot}02$, d.f. = 9, $P < 0{\cdot}001$). Overall, the proportion of goose flocks recorded outside the wind farm arrays increased from 52% ($n = 204$) in 2007 to 81·4% ($n = 285$) in 2010. Furthermore, the proportion of geese flying through the Lynn Wind Farm more than halved over the study period, reducing from 31·4% to 14%.

In 2009 and 2010, vertical avoidance was recorded in 84 of 93 flocks with observed height data flying within the LID Wind Farm footprint. Therefore, 90·32% of flights predicted to transverse the wind farm areas that showed no horizontal avoidance exhibited flight height activity outside the rotor swept zone risk area.

For 2009 and 2010, of the 292 flocks predicted to fly through the arrays, only 167 actually did so. Of observed flocks with height information ($n = 93$), only 9·68% ($n = 9$) flew through rotor swept zone height whilst within the wind farm array footprint. We therefore estimate, based on the relative proportions for 2009 and 2010 combined, that of the original 292 flocks predicted to enter the wind farm arrays, only 5·54% (16·17 flocks) would be at risk of turbine collision. With a mean flock size of 60·2 birds, the number of individuals at risk of collision for this 2-year period is estimated at 973.

Height information was not available for flocks recorded by the radar outside observation hours; 70% ($n = 52$) of flocks recorded in the periods of darkness (19·00–07·00) showed horizontal avoidance action.

Discussion

For the first time for this species, wind farm avoidance rates have been established, using a combination of bird detection radar and visual observations. Our calculated avoidance rate of 94·46% is lower than the current theoretical avoidance rate of 99% adopted by the UK statutory bodies (SNH 2010); however, it should be noted that our avoidance rates refer to wind farm and not individual turbine avoidance.

Within this study, we demonstrated that geese respond to an offshore wind farm by adopting avoidance behaviours, principally not only by amending their flight course but also by gaining altitude to avoid collision with turbines. With the offshore wind industry rapidly growing, it is important that statutory bodies, along with developers, have a solid understanding of the potential impact that wind farms could have on wildlife in the marine environment (Allison, Jedrey & Perkins 2008). To fully anticipate the consequences of offshore installations, one needs to adopt a species-specific approach in assessing the impact on bird populations (Masden *et al.* 2010). Where the evidence-base is poor, more long-term impact assessments are required (Stewart, Pullin & Coles 2007). Our current study therefore fills an important gap in documenting the avoidance behaviour of birds in relation to offshore wind farms.

Within this study, directional analysis of 2007 (preoperational) flight pathways showed no significant variation from their initial heading; however, the predictive heading-based simulation showed significant differences between the number of flocks expected and actually recorded within and outside the arrays in 2008–2010.

In addition to horizontal avoidance recorded by the radar, in 2009 and 2010, vertical avoidance was recorded by visual observations in 90·32% of flocks with observed height data flying within the LID Wind Farm footprint. When combining all avoidance for this period, 16·17 flocks were estimated to pass through the wind farms within the rotor swept zone, that is, at risk of colliding with the turbine blades. In terms of all recorded flocks for this period, either predicted to pass through or outside the wind farms, only 2·75% were within risk of turbine collision. No correlation was found between the time of day or weather conditions and birds' presence in the collision danger zone owing to the small sample of birds recorded within the wind farm at rotor swept height.

Collating the 24-h radar data, weather information and visual observations allowed us to further describe the phenology of this extended multipeak migrational event. Three distinct peaks were recorded in late September, mid-October and early November. Most flights were recorded in days with north-westerly tailwinds and good visibility in the early afternoon (12·00–14·00) with only 15% of flocks recorded during the hours of darkness (19·00–07·00). Reduced visibility and strong headwinds can play a major part in increasing collision risk (Huppop *et al.* 2006); therefore, it is important to consider the effects of these conditions whilst assessing any possible impacts of LID on the migrating geese. Within this study, only 14 diurnal flights were recorded in poor visibility. The geese tended to fly at lower altitudes during periods of reduced visibility (at 100–150 m) than during advantageous weather conditions (250–300 m). However, peak goose movements were observed in the early hours of afternoon during favourable weather conditions: tailwind, low cloud cover and fine visibility; therefore, any increased risk of collisions in poor weather and visibility can be regarded as negligible for this population.

This study showed an overall increase in levels of avoidance towards the wind farms which bore elements of non-habituation. We saw that the percentage of birds avoiding the wind farms increased with time, which was especially noticeable within the Lynn Wind Farm, where over flying flocks halved during the study period, reducing from 31·4% to 14% of all recorded radar flocks. Although further work investigating and quantifying the behavioural aspects of wind farm avoidance highlighted in this paper is still ongoing (I.C. Simms & P. Plonczkier, unpublished data), it can be stated that this increased avoidance is in contrast with previous studies, for example with pink-footed geese habituating to onshore wind farms on their wintering grounds (Madsen & Boertmann 2008). A possible mechanism for this contrast in behavioural adaptation could relate to the increased levels of wind farm exposure experience within the populations and associated perceived risk. Learned behaviour may influence a population to avoid turbines on migration where they may pose a threat of collision but to habituate to their presence when foraging on wintering grounds.

The radar system equipped with bird recognition software proved an appropriate tool in monitoring and recording the geese behaviour in relation to an offshore wind farm, especially when combined with complementary visual observations. Such a method can be successfully applied to track waterfowl movements elsewhere, providing the basic criteria for radar detection are met (line of sight, radar coverage, topography). A radar system of similar specification was used at the Danish Nysted offshore wind farm to investigate the avoidance responses of waterfowl during autumn passage and proved to be an effective tool in the collection of valuable information on wind farm avoidance (Desholm & Kahlert 2005). Our results, in which 97·25% of all flocks recorded by radar in 2009 and 2010 migrated without any risk of additional mortality associated with the constructed wind farms, are of a similar nature to the Danish findings (<1% of birds were at risk of collision with turbines). The lower rates of avoidance recorded in our study probably relate to a combination of varying factors, namely differences in species physiology, flight strategies and flock behaviour. Several other studies have also shown that some species of seaduck alter their flight routes to avoid flying through wind farms (Percival 2003); however, applying avoidance rates from different species should always be undertaken with great caution. One should also take into account that in other geographical regions there might be temporal differences for peak bird movements, even for the same species, which may alter the risk of collision.

Our study suggests, at least for the present turbine arrays, that there is likely to be little impact on the geese migrating through the study area. The avoidance rates recorded will enable statutory bodies, nature conservationists and renewable developers to make informed decisions on the overall effects of wind farm developments on migratory waterfowl. However, the cumulative effects of further developments especially in the vicinity of our study area are yet to be quantified, and we recommend that further studies are undertaken for similar species in other offshore areas along their key migration routes.

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