Unforeseen Responses of a Breeding Seabird to the Construction of an Offshore Wind Farm

Andrew J.P. Harwood, Martin R. Perrow, Richard J. Berridge, Mark L. Tomlinson and Eleanor R. Skeate

Abstract Sheringham Shoal Offshore Wind Farm (OWF), comprised of 88 3.6 MW turbines, was built within foraging range of Sandwich Tern *Thalasseus sandvicensis* breeding at a European designated site. Boat-based surveys (n = 43) were used to investigate changes in tern abundance within the site and within 0–2 and 2–4 km buffer areas before and throughout the construction of the OWF, over a study period between 2009 and 2012. Visual tracking of individual birds (n = 840) was also undertaken to document any changes in behaviour. This study is amongst the few to detail the response of a breeding seabird to the construction of an OWF. Navigational buoys in the 0–2 km buffer were used extensively by resting and socialising birds, especially early in the breeding season. Visual tracking illustrated avoidance of areas of construction activity and birds surprisingly kept their distance from installed monopiles. Avoidance was strengthened during turbine assembly, with around 30% fewer birds entering the wind farm, relative to the pre-construction baseline. Flight lines of birds that entered the site were generally along the centre of rows between turbines. A focus on transit flight meant that feeding activity was lower in the site than the buffer areas. As the site remained permeable to terns flying to and from foraging grounds further offshore, the overall abundance within the site was not significantly reduced. Although a number of the responses observed were unforeseen by Environmental Impact Assessment, the overall conclusion of only minor adverse effects was upheld. Analysis of further data from the operational site is now planned.

Keywords Sandwich Tern · Offshore wind farm · Visual tracking · Boat-based survey · Avoidance behaviour

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Introduction

Offshore wind energy is a rapidly developing industry, particularly in countries bordering the North Sea in north-western Europe, but increasingly across the globe including China and the USA (Breton and Moe 2009; Da et al. 2011). The associated risks of offshore wind farm (OWF) development for seabirds are well documented (e.g. Garthe and Hüppop 2004; Furness et al. 2013; Gove et al. 2013) and the following effects are typically assessed during Environmental Impact Assessment (EIA): mortality through collision with rotating blades, disturbance due to construction and maintenance activities, displacement leading to direct habitat loss, and barriers to movement resulting in changes in energy expenditure during commuting and foraging flights (see DECC 2011 in relation to National Policy in the UK). In the case of breeding birds, changes in energy budget may impact upon dependent chicks and thus breeding productivity, although this has not been quantified as yet (Masden et al. 2010).

Recent evidence also suggests the potential for indirect effects of construction upon seabirds, in particular the effect of piling noise on sensitive fish species such as clupeids, with consequent effects on prey availability (Perrow et al. 2011a). However, in the long-term, indirect effects could benefit seabirds through improved prey resources associated with reef and sanctuary effects (Linley et al. 2007). Such benefits may be countered by increased collision risk. For example, Thelander and Smallwood (2007) reported increased mortality of Red-Tailed Hawk *Buteo jamaicensis* at onshore turbines due to increased prey (rodents) around the turbine bases.

Despite the large number of offshore wind farms currently in operation or under construction, there are few detailed published studies on the real impacts upon birds (Desholm and Kahlert 2005; Petersen et al. 2006, 2014; Masden et al. 2009, 2010; Plonczkier and Simms 2012; Lindeboom et al. 2011; Skov et al. 2012; Leopold et al. 2013; BSH and BMU 2014; Vanermen et al. 2012, 2015a). This is partly because of the significant technical challenges and costs associated with monitoring and quantifying the response of birds to OWFs.

To determine changes in the distribution and abundance that indicate displacement, surveys of large areas around or away from the development are required to allow investigation of natural variation or gradient effects. However, appropriate spatial and temporal resolution must be maintained to provide sufficient data and statistical power to detect changes associated with the development (Vanermen et al. 2015b). Digital aerial surveys are increasingly being used (Buckland et al. 2012) to efficiently cover large study areas, although intensive boat-based surveys may allow rapid changes in the distribution and abundance of birds, for example due to tidal cycles, to be more effectively sampled (Embling et al. 2012). Sophisticated modelling techniques have also been developed to discriminate the effects of development from natural background variation (see Petersen et al. 2011, 2014).

Visual survey techniques using standard visual aids (e.g. binoculars) and laser rangefinders (Pettersson 2005; Skov et al. 2012), have been used to monitor the response of birds to structures. Technical equipment, including a variety of radar, video and thermal imaging systems (Desholm et al. 2006; Krijgsveld et al. 2011; Plonczkier and Simms 2012; Skov et al. 2012; BSH and BMU 2014) have also been employed to attempt to quantify avoidance and collision risk from the movements of individuals and/or flocks of both seabirds and migrating land birds. However, the observation of actual collisions remains an extremely rare event and risk is typically assessed through modelling of passage rates (Skov et al. 2012; Brabant et al. 2015).

Monitoring the behavioural response of birds is more readily achieved and, for some breeding species in particular, individual-based tracking with radio and GPS devices, to determine general patterns of use, has recently been employed for wind farms (Perrow et al. 2006, 2015; Wade et al. 2014; Thaxter et al. 2015). However, remote monitoring tools may not be suitable for all species and the sample sizes and behavioural detail (e.g. foraging activity and subtle responsive changes in flight height and direction) that can be achieved may be limiting.

Defining a behavioural reaction to the construction and operation of a wind farm is also complicated by the fact that it may illicit a gross response in sensitive species, with avoidance beginning several kilometers from the potential risk (Desholm and Kahlert 2005; Plonczkier and Simms 2012). Even where a species is less sensitive, the response can vary according to environmental conditions (Skov et al. 2012) or be subject to considerable inter-annual, seasonal and individual variation (Thaxter et al. 2015). Establishing a baseline prior to construction is likely to be essential to help separate cause and effect of behavioural responses, but this is rarely accommodated in studies. Furthermore, most studies to date have been conducted on non-breeding birds during passage. For seabirds, the energetic constraints imposed by provisioning chicks seem likely to modify the risks that adult birds may take. Thus, observations derived from birds during dispersal should only be applied to breeding birds with extreme caution, if at all.

Here, we present findings from monitoring work specifically targeting Sandwich Tern at the Sheringham Shoal OWF. This study contains a number of important elements that further the understanding of interactions between birds and wind farms: (1) a breeding seabird is monitored when the population is most sensitive to impacts, (2) the initial response to wind farm construction is investigated—such studies are generally inhibited by restricted access to survey vessels (e.g. Lindeboom et al. 2011; Leopold et al. 2013; Vanermen et al. 2015a, b), (3) gross changes in the use of the study area during construction are explored using a gradient analysis applied to boat-based survey data, (4) complementary visual tracking data is used to evaluate individual responses to the development, and (5) the study provides an opportunity to test the EIA predictions.

Methods

Study Site

The 317 MW Sheringham Shoal OWF consists of 88 3.6 MW Siemens wind turbine generators (rotor diameter of 107 m) and two substations. It was the first of the OWFs within the Crown Estate's Greater Wash (UK) Round Two development area to be consented (Fig. 1). Construction began in February 2010 with the installation of eight navigation buoys to delimit the site for marine vessels. To protect against scour, large quantities of rock were installed at 75 turbine locations and the two substations in March 2010. Monopile installation began on 24 June, and by the end of November 2010 22 monopiles and the two substations had been

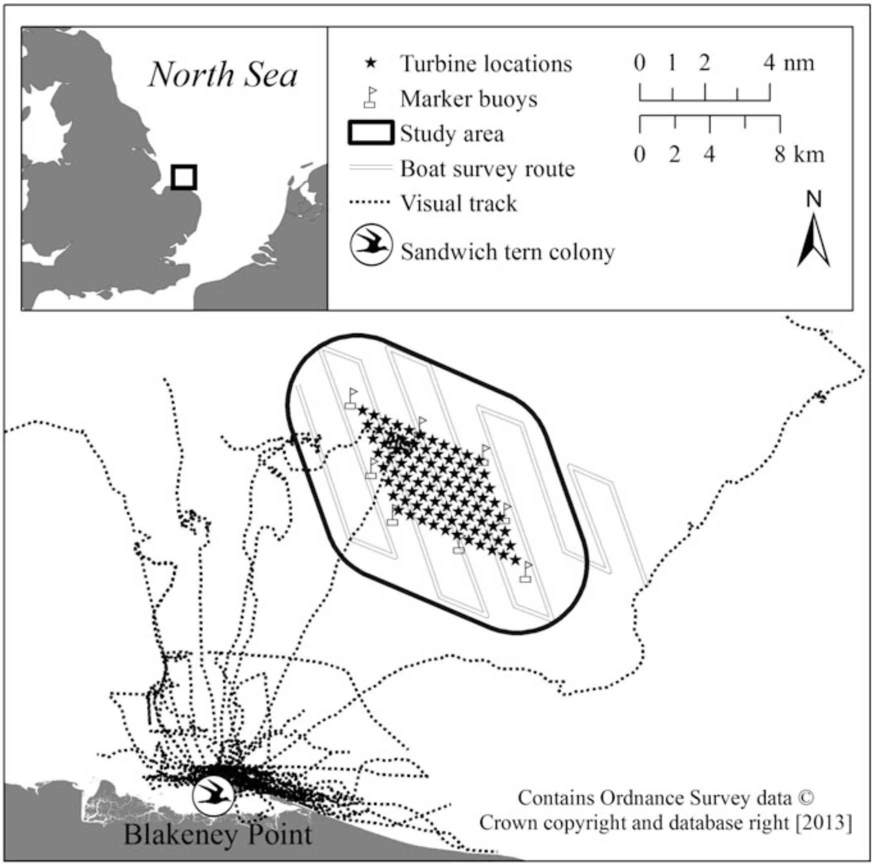

Fig. 1 Location of Sheringham Shoal Offshore Wind Farm, study area and boat-based transect route relative to visual tracking from the Blakeney Point colony conducted prior to the development of the site in 2007 and 2008 (Perrow et al. 2010)

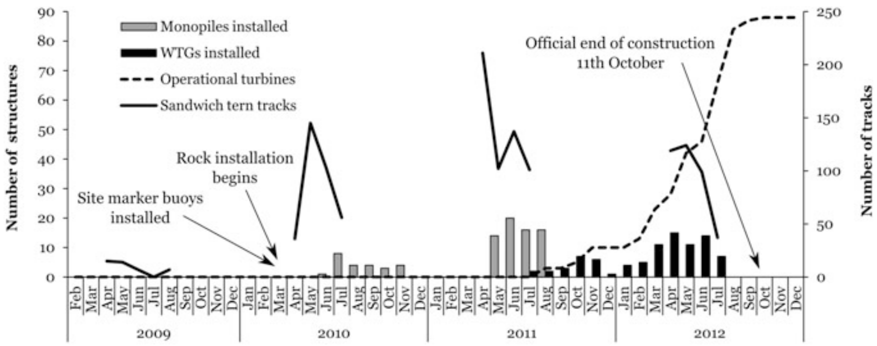

Fig. 2 Sheringham Shoal OWF construction progress relative to the number of visual tracks achieved in the study area during the Sandwich Tern breeding season from April to July inclusive in each year

installed (Fig. 2). Pile driving of individual monopiles was brief, taking between 30 and 40 min. Construction works were more frequent and sustained during 2011, including regular pile driving and cable laying during the installation of the final 66 monopiles between May and August. Assembly of the tower, nacelle and blades for each turbine started in July 2011, with the first power produced in August 2011. Turbine assembly was completed by the end of July 2012, by which time 46 turbines were connected and able to deliver power. The OWF was officially opened on 27 September 2012.

The OWF is located between 18 and 24 km from Blakeney Point, which, in combination with Scolt Head, contains the largest concentration of breeding Sandwich Terns in the UK and is designated as a qualifying feature of the internationally important North Norfolk Coast Special Protection Area (SPA). The SPA can support over 4000 pairs and is designated as containing 24.7% of the UK population (Mitchell et al. 2004). Both colonies lie within the mean maximum foraging range of the birds from the OWF (49 km—Thaxter et al. 2012). However, Blakeney Point is closer to the OWF and previous tracking work (Fig. 1) has suggested this is likely to supply the majority of birds encountered (Perrow et al. 2010).

Although both colonies may be active in the same year, the typical pattern is for the highly colonial Sandwich Tern to favour one or the other. Previous data suggests a periodicity of four or more years between colony switches (NNNS 2007), although Blakeney Point was the dominant colony throughout the duration of this study, with 2500–3753 pairs (Table 1). Boat-based surveys of Sheringham Shoal, as part of the EIA in 2004–2006, confirmed the presence of Sandwich Terns throughout the breeding season (April to July inclusive), with maximum densities of 0.3 and 0.72 ind. km^{-2} in the site and study area respectively (SCIRA Offshore Energy Ltd 2006). It was assumed that most, if not all, of these birds originated from Blakeney Point.

The relatively low density of Sandwich Terns recorded during site characterisation resulted in low numbers of annual predicted collisions (12 at 99% avoidance).

Table 1 Estimated number of pairs, fledged chicks and chicks fledged per pair of Sandwich Terns nesting at Blakeney Point over the study period of 2009–2012 inclusive

Parameter	2009	2010	2011	2012
Number of pairs	3100	2500	3562	3753
Chicks fledged	1300	900	1700–2000	2200
Chicks pr^{-1} $year^{-1}$	0.43	0.36	0.48–0.56	0.59

Thus, the effect was deemed to be '*minor adverse*' in EIA terms; that is, undesirable but of limited concern (SCIRA Offshore Energy Ltd 2006). A similar effect was predicted in relation to temporary disturbance during construction, through increased boat traffic. The potential for minor adverse barrier effects to occur was thought likely to be offset by the orientation and layout of the turbines, which incorporated the preferred northeast-southwest flight lines of Sandwich Terns. No disruption of flight lines leading to increased energy expenditure of the birds was anticipated. Indirect effects upon the available prey base and effects of increased noise and vibration, as well as cable laying activities, were all predicted to be of negligible significance (SCIRA Offshore Energy Ltd 2006).

Use of the Wind Farm Area

In order to determine any changes in the abundance and distribution of birds according to the construction and operation of the wind farm, a gradient design (Strickland et al. 2007) was employed. This incorporated the wind farm site and two sequential buffer areas at 0–2 and 2–4 km from the site. These areas were surveyed by boat-based line transects (300 m either side of the vessel) for birds 'on the water' (perching on surface floating objects) and using radial snapshots (180° scan centred on the bow of the vessel out to 300 m) for birds in flight (Fig. 1). Two experienced ornithologists (one on each side of the vessel) carried out observations at all times whilst a third recorded data. Survey intensity varied slightly between months, with two surveys completed in April each year and three in the following months. However, the monitoring schedule set with the statutory authorities only incorporated two surveys in May 2010. A total of $n = 43$ surveys were therefore available for analysis.

Density estimates were calculated for each of the three areas by combining separate densities of Sandwich Tern 'on the water' and in flight, derived by dividing the numbers of observed birds by the respective areas sampled. Distance sampling corrections were not employed as there were insufficient observations of birds on the water to generate a viable detection function. It was assumed that all birds in flight were detected to a distance of 300 m, according to standard practice (Camphuysen et al. 2004). Population estimates for each of the areas were estimated by scaling the densities to each respective area for later analyses.

Variations in the abundance of birds over the breeding season and between areas were investigated using Generalised Additive Models (GAMs). GAMs were chosen as they allow for data which is non-normally distributed and could potentially better describe complex seasonal trends in the abundance of Sandwich Terns in the area (Hastie and Tibshirani 1990). Thus, the model framework included 'year day' (i.e. day 1–365 or 366 in a leap year) as a continuous variable (using a smooth function with degrees of freedom limited to 4 or less), 'site' (i.e. wind farm, 0–2 km buffer and 0–4 km buffer) and 'year' (2009–2012 inclusive) as factors. Year was used as a factor, rather than discreet development periods, as it provided a balanced dataset, which also accounted for inter-annual variability in abundance. An interaction between 'site' and 'year' was tested first to determine whether there were significant variations between combinations of sites and years. 'Monitoring year' and 'site' were investigated independently if the interaction was not significant. To account for the variability in the size of each of the areas, for which populations were derived from survey densities, an offset (log area) was also included in the model.

A negative binomial distribution (including log-link function) was used as it outperformed others trialled, due to its ability to deal with over dispersion in the data (Zuur et al. 2009). The optimal model was chosen as the one with the lowest Akaike information criterion (AIC) value and in which all remaining explanatory variables presented significant effects. The deviance explained by the model was used to evaluate the fit with Pearsons correlation (r) and Spearman rank correlation (ρ) coefficients as measures of model accuracy. A non-parametric Runs test was used to determine whether there was significant autocorrelation within the model residuals. All analyses were carried out using R 3.1.2 software (R Core Team 2014), stats (R Core Team 2014), mgcv (Wood 2011) and lawstat (Noguchi et al. 2009) packages.

Visual Tracking in the Wind Farm Study Area

Visual tracking of Sandwich Terns applied the methods established by Perrow et al. (2011b), and later adopted by Robertson et al. (2014) and Wilson et al. (2014). Birds were followed at a distance, so that they are not influenced by the vessel (generally upward of 50 m), whilst continually recording positions and behaviour. The resultant tracks aim to closely represent the path taken by the birds, albeit undertaken a few seconds later.

The movements of Sandwich Terns were tracked within a study area, defined by a 4 km buffer around the site (Fig. 1), throughout the breeding seasons in 2009 to 2012 inclusive. In 2009, tracking effort was limited (four days) during trialling of the method. Tracking was undertaken from a high-powered rigid-hulled inflatable boat (RIB) in a range of weather conditions (with at least reasonable visibility) up to sea state four (Fig. 3). Birds apparently heading toward the wind farm site were generally detected and tracked from a distance of greater than 2 km from the site, a

Fig. 3 Example of RIB (10 m) typically used for visual tracking (*left*) and representation of the view of a tracked bird (*right*)

distance at which Sandwich Terns are unlikely to exhibit any avoidance behaviour in relation to structures or activity (Everaert and Stienen 2007). One ornithologist continuously observed the bird whilst a second took notes. Tracking ended when the bird left the study area, was lost from view (due to speed or weather) or landed on an object.

Tracks were plotted and analysed in ArcGIS v.10.1 (ESRI 2011: ArcGIS Desktop, Release 10, Redlands, CA, USA) and using Geospatial Modelling Environment (GME) software (Beyer 2012). Data were processed to remove tracks not entering the study area, that were short (arbitrarily selected as <1 km) and where birds did not fly toward the wind farm or the track was not long enough to reach it. Processed tracks were plotted by month against structures (monopile foundations or wind turbines) installed prior to, or during the month in 2011 and 2012. Tracks were also assigned to three discreet periods associated with particular site activity for further analysis: pre-construction (20th April 2009–23rd June 2010), initial construction (monopile installation between 24th June 2010 and 2nd July 2011) and final construction (turbine installation between 3rd July 2011 and 10th July 2012).

Cumulative proximity distributions (see Petersen et al. 2006) were calculated based on the numbers of birds flying within binned distances (50 m intervals truncated at 2 km—the main zone of interest) of the nearest structure present on the day of tracking. Pre-construction tracks were used as an indicative baseline, where distributions were calculated as if all structures had been present. As both monopiles and turbines were present in the final construction phase, the cumulative proximity distributions were calculated for each structure type separately to investigate any differences in response. All samples were non-normally distributed or did not show homogeneity of variance (Shapiro-Wilk and Fligner-Killeen tests respectively). Thus, non-parametric Kruskal-Wallis tests were carried out to determine if the phase had a significant effect on the distribution of the data. Multiple Kolmogorov-Smirnov tests were used to determine if there were significant differences between the cumulative distributions for each phase.

Results

Use of the Wind Farm Area

Boat-based surveys suggested that the area supported relatively low densities of Sandwich Terns of <1 ind. km^{-2}, with a few exceptions, during the breeding season (Fig. 4). The abundance of birds and seasonal trends in the 2–4 km buffer area were consistent throughout. In this outer buffer, densities peaked in May before falling in subsequent months. In the 0–2 km buffer this trend was seen in 2009, but in the subsequent years densities peaked in April. Although not as clear, the use of the wind farm site was also generally greatest in April. Abundance in the 0–2 km buffer increased from 2010 (when construction began) onwards, largely due to increased densities in April and May. Densities in the wind farm site also increased in 2011 when the use of the 0–2 km buffer peaked. The observed trends in the 0–2 km buffer and wind farm site suggest some attraction to these areas. Estimates of birds perched on floating objects, especially navigation buoys or turbine structures, appeared to contribute greatly to these observed trends (Fig. 4).

The gradient analysis resulted in 'year day' (edf = 1.001, $p < 0.001$) and 'site' (df = 2, $p = 0.003$) being included in the most parsimonious model. Although the interaction between 'site' and 'year' was significant in the full model (also including 'year day'), there was no improvement based on AIC values (ΔAIC = 8.07). The selected model had a deviance explained of 27.8% and predictions appeared to fit the data well (Pearsons correlation coefficient of 0.58 and Spearman rank correlation of 0.64). The Runs test found no autocorrelation in the model residuals (Runs statistic = −0.97, $p = 0.331$). The modelled relationship between abundance and 'year day' was approximately linear, decreasing from a peak at the start of April to a minimum at the end of July, with larger confidence intervals at the start and end of the breeding season. This is consistent with the trends seen in the mean density data illustrated in Fig. 4, although there was a lag in the peak abundance in the 2–4 km buffer. Birds were significantly more abundant in both the 0–2 km ($p < 0.001$) and the 2–4 km ($p = 0.043$) buffers relative to the wind farm site.

The flight directions of birds using the study area varied between years, but north-eastern (overall mean of 20.56%) and south-western (overall mean of 18.61%) trajectories were generally preferred (Table 2). In the wind farm site, there was a clear switch in preference from a northerly flight trajectory in 2009 and 2010 to north-easterly in 2011 (main piling period). In 2012 (installation of turbines), almost 50% of birds observed were heading in this direction (Table 2). Within the 0–2 km buffer no such trend was observed, although far fewer birds (almost half) were seen heading on a north-easterly trajectory in 2012 when the turbines were being installed. This reduction was balanced by more birds heading back toward the colony on a south-westerly course in 2012. In contrast, there was no apparent drop-off in the proportions of birds heading north-easterly in the 2–4 km buffer in 2012 (Table 2).

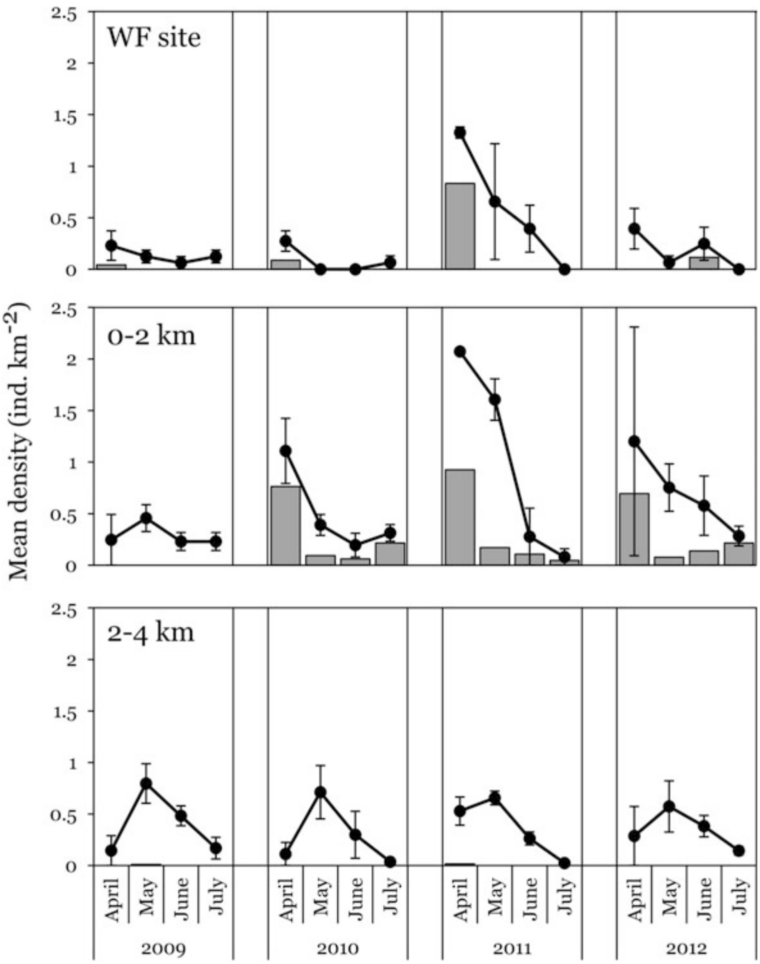

Fig. 4 Mean monthly overall Sandwich Tern density estimates (*solid lines* with associated standard errors) and densities of birds perched on objects (*grey bars*) derived from boat-based surveys of the wind farm site (WF), 0–2 km buffer and 2–4 km buffer during the breeding seasons in 2009–2012 inclusive

Visual Tracking Across the Wind Farm

A total of 154 days of tracking were achieved across the three study phases, comprised of 28 days during the pre-construction phase, 59 days during initial construction and 67 days during the final construction phase. A total of 1256 tracks

Table 2 Percentages of birds observed heading in different flight directions during boat-based surveys within the Sandwich Tern breeding season in 2009–2012 inclusive

Area	Year	Flight direction (%)								
		N	NE	E	SE	S	SW	W	NW	No direction
WF site	2009	***23.19***	10.14	5.80	0.00	13.04	20.29	13.04	1.45	13.04
	2010	***27.27***	4.55	13.64	6.82	6.82	11.36	9.09	4.55	15.91
	2011	4.55	***26.52***	12.88	10.61	9.09	18.18	2.27	0.76	15.15
	2012	10.91	***47.27***	1.82	1.82	9.09	16.36	1.82	3.64	7.27
0–2 km buffer	2009	12.30	***17.21***	12.30	11.48	10.66	16.39	9.84	3.28	6.56
	2010	13.38	***24.84***	13.38	8.92	7.64	10.19	6.37	0.00	15.29
	2011	5.84	19.84	4.28	5.84	11.28	20.23	7.78	3.11	***21.79***
	2012	12.98	12.50	9.13	4.33	12.98	***29.81***	8.65	3.37	6.25
0–4 km buffer	2009	14.98	12.15	10.93	4.86	13.36	***27.53***	9.72	2.02	4.45
	2010	8.00	***26.67***	16.67	2.67	14.67	9.33	6.67	2.00	13.33
	2011	5.41	***24.84***	10.51	10.83	10.83	21.34	5.10	5.10	6.05
	2012	10.09	20.18	6.42	14.98	8.56	***22.32***	4.89	3.06	9.48
Overall mean (±se)		12.41 (2.00)	***20.56*** (3.18)	9.81 (1.27)	6.93 (1.30)	10.67 (0.72)	18.61 (1.85)	7.10 (0.94)	2.69 (0.43)	11.21 (1.54)

The predominant flight directions in each year are highlighted in bold italics were recorded in this time. Post processing removed 33% of these, leaving 840 tracks (covering a total distance of almost 9700 km) for further analysis. The mean track distance and durations were 11 km (1–39.6 km) and 17.6 min (1.2–82.5 min) respectively. The average estimated flight speed was 40.2 km h^{-1}, although on occasion birds outpaced the RIB at full speed (>70 km h^{-1}). Tracks were also cut short as a result of poor weather, exclusions around operational vessels or by birds landing on buoys. Otherwise, 65% tracks were completed by a bird leaving the study area.

All tracks from each monitoring phase are shown in Fig. 5, illustrating the dominant north-east to south-west flyway, with passages across a broad front through the study area. During pre-construction, some of the tracks clearly reflect transits to and from site marker buoys (installed in March 2010), particularly to the south-west, west and south of the wind farm. The main flyway appeared to split during the initial construction phase, with many tracks heading east-northeast/west-southwest or north/south. When turbine installation began in

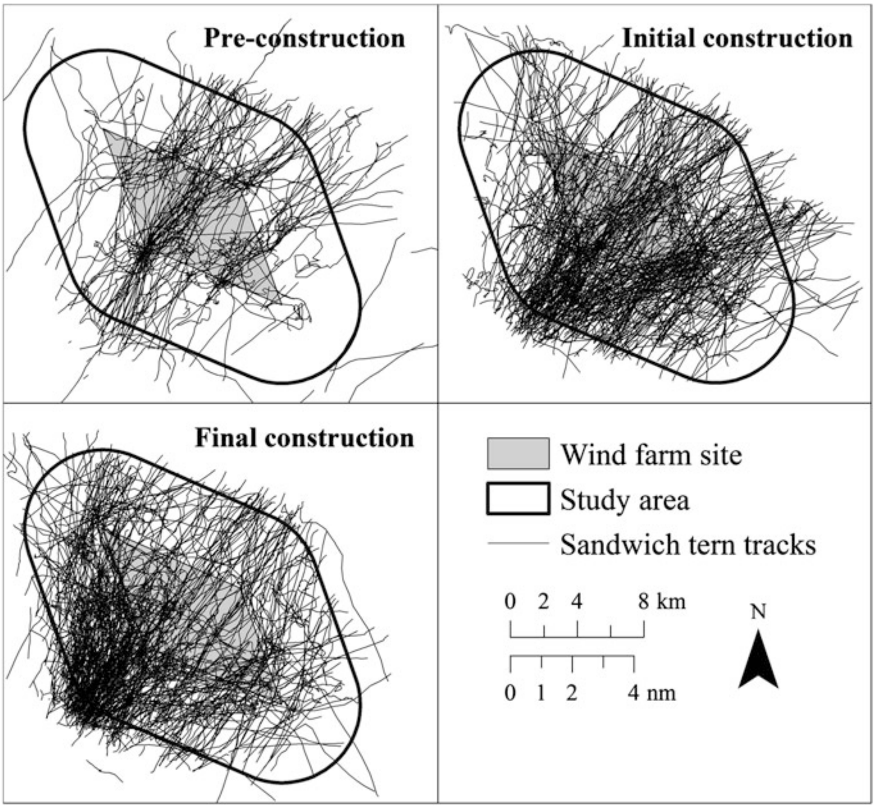

Fig. 5 All Sandwich Tern tracks recorded during the pre-construction, (n = 277), initial construction (n = 530) and final construction (n = 449) phases

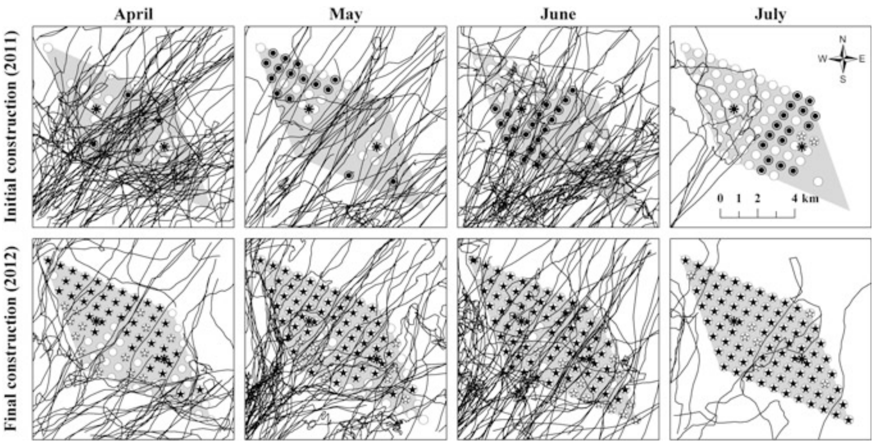

Fig. 6 Filtered tracks in each month during initial construction in 2011 (*n* = 340) and final construction in 2012 (*n* = 256), relative to monopiles installed (*solid black circles*) or already present (*solid white circles*) and turbines installed (*white stars*) or already present (*solid black stars*) in respective months. *Asterisks* denote sub-stations

the final construction phase, the tracks showed much clearer diversions around the periphery of the wind farm site. However, birds still used the wind farm throughout construction and well-defined passage routes through the site started to emerge.

Further segregation of tracks into individual months in 2011 and 2012, when the bulk of the construction was carried out, demonstrated that Sandwich Terns were avoiding areas where structures were being installed in 2011, and areas where turbines were being installed or were already present in 2012 (Fig. 6). For example, in April 2011 the areas around the substations, where much of the work was taking place, were used much less than other part of the site. In May, June and July the main areas where piling was taking place were also avoided. In 2012, fewer birds penetrated the site and those that did avoided areas where construction was taking place or turbines were already present (Fig. 6). When individuals did enter the site, the tracks tended to be linear and followed corridors aligned south-west to north-east within the array. Many individuals that seemingly diverted around the site were observed cutting the corners of the array, where the chance of encountering a structure is lowest. Indeed, the overall proportions of tracks which entered the site changed dramatically from 95.0% during pre-construction, to 82.5% when the monopiles were being installed and to only 65.1% during the installation of turbines. The proportions of observed foraging attempts within the wind farm also suggested a coincident decline in the use of the area from 48% during the pre-construction phase, to 30% during initial construction and only 19% in the final construction phase (Table 3). Conversely, the area around the wind farm became proportionally more important in relation to foraging; particularly in the 0–2 km buffer (Table 3).

Table 3 The percentages of foraging attempts (n = 3342) by all tracked birds in the wind farm site and two buffers during the three monitoring phases

Year	% of foraging attempts in each area		
	WF site	0–2 km buffer	2–4 km buffer
Pre-construction	47.9	38.8	13.3
Initial construction	30.1	39.0	30.9
Final construction	19.0	46.5	34.5
Overall mean	32.3	41.4	26.2

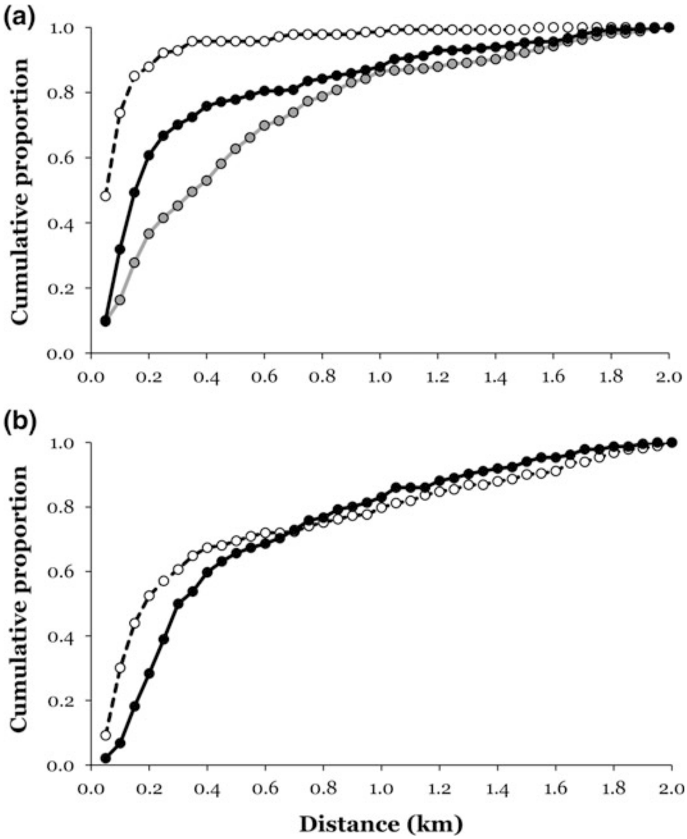

Fig. 7 Comparison between cumulative proximity distributions (truncated to 2 km) for: **a** the pre-construction phase assuming all structures were present (*open circles*, n = 141), initial construction phase (*grey circles*, n = 349) and final construction phase (*black circles*, n = 298), and **b** the final construction phase in relation to monopiles (*open circles*, n = 282) and turbines (*black circles*, n = 236) present at the time of tracking

Figure 7a illustrates the cumulative proximity distributions for tracked birds during the three phases. A high proportion of the birds (48%) flew within 50 m of a future turbine during pre-construction, whilst considerably fewer came as close to a structure during the initial and final construction phases (both at 10%). Furthermore, 88% of the tracks during the pre-construction phase would have passed within 250 m of a future turbine, compared to 42 and 67% during the initial and final construction phases respectively. The Kruskal-Wallis test indicated a significant effect ($x^2 = 158.64$, $p < 0.001$) of the study phase on the proximity of tracks to structures. Subsequent Kolmogorov-Smirnov tests between different combinations of phases suggested highly significant differences ($p < 0.001$) in the distributions of the data in each case. However, these results should be treated with caution as relatively few monopiles were present within the site for much of the breeding season during the initial construction phase, and therefore the chance of birds coming close to them would have been proportionally lower. In the final construction phase, birds were more sensitive to the presence of turbines than to the monopiles present at the same time (D = 0.243, $p < 0.001$), with almost no birds coming within 50 m of a turbine (Fig. 7b).

Discussion

The general preference for north-eastern and south-western flight trajectories through the study area, shown by both boat-based surveys and visual tracking, mirrored the pattern for the two breeding seasons (2004 and 2005) monitored for the Environmental Statement (SCIRA Offshore Energy Ltd 2006). These trajectories are consistent with outbound and inbound flights from the expected origin of birds from Blakeney Point. The general decline in use of the study area over the breeding season is consistent with the abandonment of more distant foraging areas with increasing pressure to provision chicks (Ojowski et al. 2001). This further reinforces the previous assumption that breeding birds comprise the majority, if not all, of the birds observed in the study area. Moreover, there is no evidence for the alternative view of a sizeable pool of non-breeding birds in the region, which would be manifested as nightly roosts of birds that could not be attributed to colonies. Such a phenomenon has not been recorded in the extensive local literature (e.g. Taylor and Marchant 2011).

A low proportion of feeding activity was recorded during boat-based surveys with just 120 (4.6%) of the 2602 Sandwich Terns recorded noted as fishing, closely matching the 3.5% of 624 records in 2004–2005 (SCIRA Offshore Energy Ltd 2006). This tends to support the theory that Sandwich Terns are principally transiting through the Sheringham Shoal OWF study area to foraging grounds around Inner Cromer Knoll and Cromer Knoll, as well as Haddock Bank, a large linear sandbank.

These features are largely within mean maximum foraging range from the colony at between 40 and 50 km from Blakeney Point and are potentially attractive to shoaling clupeids (Atlantic herring *Clupea harengus* and European sprat *Sprattus sprattus*) and sandeels (*Hyperoplus lanceolatus* and *Ammodytes* spp.) that dominate the diet of Sandwich Terns (Stienen et al. 2000).

The modelling did not identify a significant change in the birds' use of the different components of the study area between years, despite the obvious difference in mean (±1SE) breeding season population size in the study area. The population size ranged from 53 ± 15.1 in 2010 to 114 ± 30.7 in 2011. The abundance of birds in the study area broadly reflected changes in size of the Blakeney Point colony, which supported the lowest number of pairs in 2010. However, the magnitude of any inter-annual variability was insufficient to detect a statistically significant change in the abundance of birds. Thus, a strong link to construction events in different years could not be established. However, the modelling did confirm that both the 0–2 km buffer and 2–4 km buffer areas supported higher populations of birds than the wind farm. The accumulation of Sandwich Terns around buoys, present only in the 0–2 km buffer, was thought to be responsible for the higher densities in this area, especially early in the season (Fig. 4). Up to 18 individuals were noted on a single buoy, with birds recorded on at least one buoy during 56% of surveys. The numbers of birds on buoys was sufficient to contribute an approximately equivalent density of 'birds on the water' to that of 'birds in flight'. In fact, as only three of the eight (37.5%) buoys fell within the transect route, the true numbers of Sandwich Terns using buoys at any one time seems likely to have been considerably underestimated. The buoys were attractive as a platform on which to rest (Fig. 8), although a variety of social interactions, including courtship feeding and mating, were also recorded. Buoys thus operated as a social hub from which foraging flights were initiated or interrupted, as also revealed during tracking. This was particularly evident in April and May, early in the breeding season when pair bonds were being reinforced. It is plausible that the lack of significant difference in population size between the 0–2 and 2–4 km buffer partly reflected an attraction of Sandwich Terns to buoys from a wider area, with birds having to cross the 2–4 km buffer to ultimately reach the buoys. Alternatively, the maintenance of the population size in the 2–4 km buffer may be linked to the fact that at least the southern part of it was the closest point to the source of birds from the colony.

Lindeboom et al. (2011) observed a similar attraction to OWF infrastructure at Egmond aan Zee. Here, large numbers of Great Cormorant *Phalacrocorax carbo* utilised the actual turbine bases to rest and dry their wings between foraging trips mainly within the wind farm. When foraging, Great Cormorant dive from the surface and pursue fish underwater and, if flight heights in the wind farm are below the sweep of the rotor blades, they could use habitat within wind farms with little risk. In fact, use of turbine bases at Egmond aan Zee allowed Great Cormorant to

Fig. 8 Sandwich Terns using one of the Sheringham Shoal OWF site marker buoys

move further offshore than they could otherwise. At the Blighbank OWF, Lesser Black-backed Gull *Larus fuscus* and Herring Gull *Larus argentatus* were generally attracted to the site and were seen roosting on structures. Lesser Black-backed Gulls were also seen feeding on pelagic prey within the array and around the turbine bases (Vanermen et al. 2015a). Unlike gulls and cormorants, terns have not been seen using the handrails around turbine bases, but were recorded resting on the transition pieces of the monopiles before turbine assembly in 2011. It may be speculated that individuals that were already familiar with buoys were responsible for this rare behaviour.

Otherwise, there was evidence of Sandwich Terns avoiding areas under construction and keeping their distance from standing structures in a similar fashion to Common Eider *Somateria mollissima* in the study of Larsen and Guillemette (2007). Seaduck and waterfowl in general appear to be wary of novel objects, although they can quickly habituate where there is a reason to do so. At Horns Rev, Common Scoter *Melanitta nigra* overcame what appeared to be a particularly strong fear of the wind farm after their bivalve mollusc prey colonised turbine bases (Petersen and Fox 2007). It was not anticipated that the fast-flying and agile Sandwich Tern would show wariness of structures that actually posed no risk. However, during the initial construction phase a small proportion of flights (8% relative to the pre-construction baseline conditions) that were initially heading for the site deviated away from it.

One obvious alternative explanation for the avoidance of areas of construction activity by Sandwich Terns is that construction activity affected the distribution of important prey, particularly hearing-specialist clupeids that are especially sensitive to pile driving noise (Thomsen et al. 2006). Sandeels, the other prey species of choice for Sandwich Terns, are thought to be relatively insensitive as they have no swim bladder. However, piling of individual turbines at Sheringham Shoal OWF was of very short duration (30–40 min), with the time between events generally being at least one day. This potentially provided ample time for fish to quickly recolonise and maintain abundance. In fact, there was some evidence that Sandwich Terns were occasionally attracted to, rather than repelled by, construction activity due to prey abundance, with a few records of Sandwich Terns aggregating immediately after piling events. For example, during tracking on July 3rd 2011 more than 200 terns and several hundred gulls were observed feeding on fish, mostly clupeids, that may have been affected by piling noise.

Furthermore, apart from these isolated events, tracking revealed a general decline in feeding activity in the site relative to the buffers during both the initial and final construction phases. With no obvious source of noise in the final construction phase there would appear to be no reason why the prey would be affected. However, prey distribution may be influenced by the increased use of the site by larger predators such as Harbour Seal *Phoca vitulina* that is now known to forage at Sheringham Shoal OWF (Russell et al. 2014), as well as large predatory fish such as Atlantic Cod *Gadus morhua* that also favour OWFs (Reubens et al. 2013). But perhaps a more tenable explanation is simply that Sandwich Terns were less inclined to forage within the site as they focussed on maximising the distance from each turbine and thus tended to pass through the centre of the rows within the array.

During the final construction phase, when testing of turbines presented some collision risk, 30% fewer of the tracked birds, relative to the pre-construction baseline, entered the wind farm site and instead appeared to deviate around it. This closely aligns with the macro-avoidance rate of 28% reported by Krijgsveld et al. (2011) from radar studies of the operational Egmond aan Zee. Petersen et al. (2006) had previously demonstrated that Sandwich Terns were significantly more likely to enter the Horns Rev OWF where one or both of the turbines either side of the point of entry were not in operation. Taken together, these results imply that Sandwich Terns have a good perception of danger and modify their actions accordingly. However, as some other authors (e.g. Leopold et al. 2013) have not detected a clear response, this may vary on a case-by-case basis. At this stage, there is no particular evidence that the response of breeding Sandwich Terns using the Sheringham Shoal OWF was radically different to that of migrating birds at Egmond aan Zee and Horns Rev, despite the potential difference in energetic costs for birds in different stages of their reproductive cycle.

According to Masden et al. (2010), in their comparison of a range of common seabirds, terns would have the lowest additional energy cost associated with increased foraging distance as a result of any deviation around wind farms. Put simply, the Sandwich Terns from the Blakeney Point colony may be able to undertake noticeable modifications to flight patterns, or accommodate the loss of some foraging habitat, without incurring a significant energetic cost.

Conclusions

This study is one of the very few to shed light on the response of a breeding seabird to the construction of an OWF. Although no statistically significant changes in the use of the study area over time were detected, the boat-based survey results suggested an increased use of the 0–2 km buffer area consistent with the installation of navigation buoys prior to construction. Unforeseen by the EIA, these buoys became the focus of courtship and social activity early in the breeding season. The visual tracking revealed Sandwich Terns avoided areas where piling was taking place and, also unforeseen by the EIA, were initially wary of the installed monopiles, with birds maintaining distance from them despite relatively little associated risk. As construction advanced and turbines were installed, an increasing number of tracked birds appeared to deviate around the wind farm rather than entering it. This is consistent with the predictions of the EIA that minor adverse barrier effects could occur. Indeed, the general conclusion of the EIA of only a minor adverse effect during the construction phase was upheld.

Although a relatively high proportion of tracked birds appeared to be displaced from the OWF in the presence of fully assembled turbines, boat-based survey densities did not decline significantly. In part, this may be because even when all turbines were constructed, the spacing of turbines at 650–720 m meant the site was still highly permeable to transiting birds that tended to select the centre of rows between turbines. In turn, such flight behaviour was favoured by the general layout of the wind farm array providing corridors with a northeast-southwest alignment. Reductions in foraging observations within the wind farm were also noted as construction advanced, likely reflecting the reduced time spent in the site and the more direct flights of individuals through the array.

Analysis of further data from the operational site, when there is a greater risk of collision, is ongoing. Considering the response of Sandwich Terns observed to date, further modification of behaviour is anticipated. At this stage, it is also important to note that the general use of the site and number of birds at potential risk in the operational site would be likely to decline considerably if Sandwich Terns resume periodic switching of breeding between Blakeney Point and the more distant colony at Scolt Head.

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