



## Research

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## Conservation biology

# Patterns of migrating soaring migrants indicate attraction to marine wind farms

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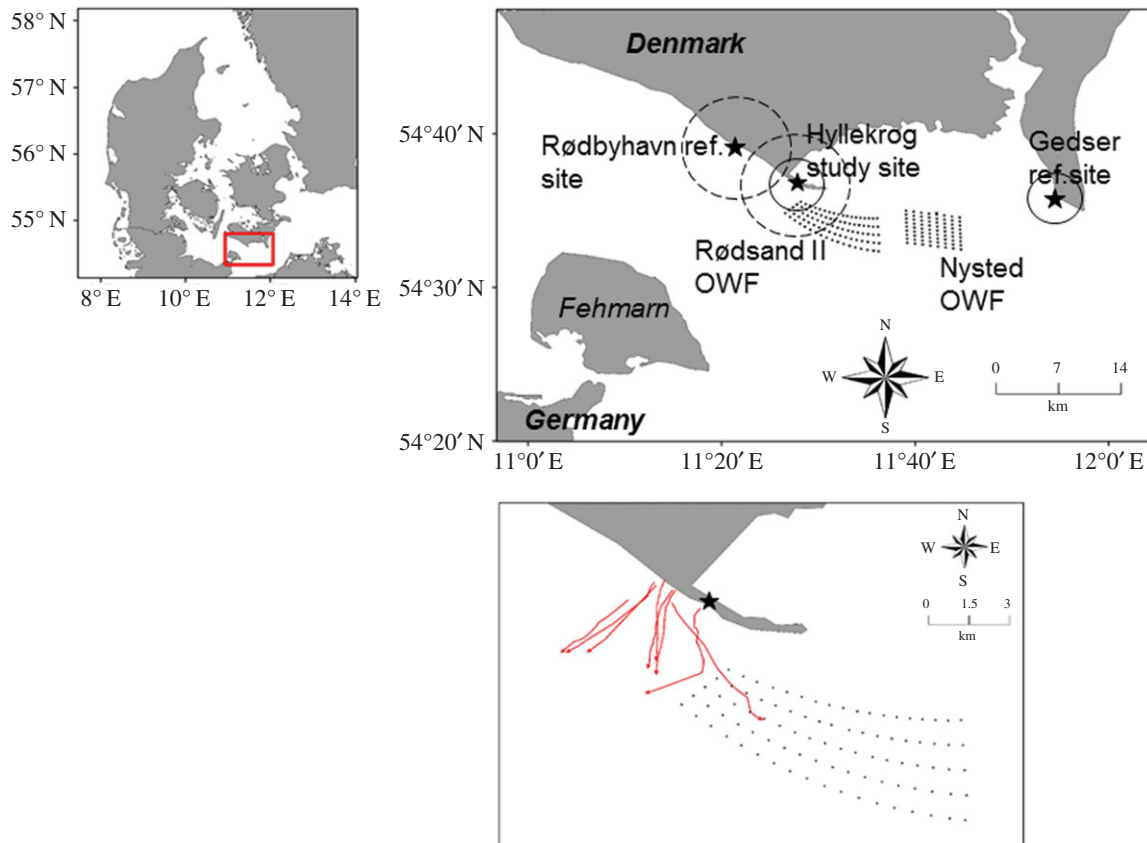
Monitoring of bird migration at marine wind farms has a short history, and unsurprisingly most studies have focused on the potential for collisions. Risk for population impacts may exist to soaring migrants such as raptors with *K*-strategic life-history characteristics. Soaring migrants display strong dependence on thermals and updrafts and an affinity to land areas and islands during their migration, a behaviour that creates corridors where raptors move across narrow straits and sounds and are attracted to islands. Several migration corridors for soaring birds overlap with the development regions for marine wind farms in NW Europe. However, no empirical data have yet been available on avoidance or attraction rates and behavioural reactions of soaring migrants to marine wind farms. Based on a post-construction monitoring study, we show that all raptor species displayed a significant attraction behaviour towards a wind farm. The modified migratory behaviour was also significantly different from the behaviour at nearby reference sites. The attraction was inversely related to distance to the wind farm and was primarily recorded during periods of adverse wind conditions. The attraction behaviour suggests that migrating raptor species are far more at risk of colliding with wind turbines at sea than hitherto assessed.

## 1. Introduction

Several species of raptors and storks have small populations with *K*-strategic life histories and are among the species of birds most frequently exposed to wind farms [1], and owing to unfavourable conservation status [2] are prioritized conservation targets [3]. Soaring species employ thermal migration with alternating soaring and gliding [4] and display strong avoidance towards crossing large expanses of open water. This leads to both a funnelling effect and a potential for attraction of birds to wind turbines when crossing the sea (the 'island effect', [5]). Several studies have reported attraction of birds to offshore structures [6]. However, no empirical data have yet been available on avoidance and attraction rates and behavioural reactions of soaring migrants to marine wind farms. Post-construction studies at a marine wind farm in the Baltic Sea (Rødsand II) offered a unique opportunity to assess the potential attraction of soaring migrants to a marine wind farm, as the wind farm is located at a different angle (S–SE) from the main migration direction (SW) of raptors heading towards the German coast (figure 1).

## 2. Material and methods

We used a combination of radar and laser rangefinder tracking (table 1) to measure the migration flight directions of raptors during the autumn migration in 2010 and



**Figure 1.** Location of study and reference sites. The locations of Rødsand II (studied wind farm) and Nysted offshore wind farms, the closest point (Fehmarn) on the German coast for raptors migrating from the Danish coast during autumn, as well as radar (dashed lines) and rangefinder (solid lines) tracking ranges are indicated. The map in the lower right panel shows examples of radar tracks of migrating raptors recorded at the study site at Hyllekrog. (Online version in colour.)

**Table 1.** Specifications for the radar and rangefinder equipment, and protocols used for tracking of migrating raptors.

type	surveillance radar	tracking radar	laser rangefinder
stations	study site 2010–2011, Rødbyhavn reference site 2010	Rødbyhavn reference site 2009	study site 2010–2011, Gedser reference site 2011
brand	FR2127	Superfledermaus	Vectronix Vector 21 Aero®
type	X band	X band	powered laser with 8× zoom
tracking range	6 km	6 km	3 km
power output	25 kW	150 kW	—
pulse repetition frequency	500 Hz	2082 Hz	—
number of tracking days	study site 37, Rødbyhavn ref. site 19	Rødbyhavn ref. site 37	study site 37, Gedser ref. site 12
time of tracking	study site Aug–Oct, Rødbyhavn ref. site July–Nov	Rødbyhavn ref. site July–Nov	study site Aug–Oct, Gedser ref. site Aug–Oct
tracking method	groups of raptors	groups of raptors	groups of raptors

2011. The radar station at the study site was placed on Hyllekrog ( $54.6100^{\circ}$  N,  $11.4575^{\circ}$  E), Denmark. The reference sites where no marine wind farms are installed in proximity were located at Gedser ( $54.5752^{\circ}$  N,  $11.9181^{\circ}$  E) and Rødbyhavn ( $54.6504^{\circ}$  N,  $11.3561^{\circ}$  E).

A variable defining the flight direction in relation to wind direction was created for each time step (segment) of the track defining whether the bird was flying in ahead wind (within a range of  $90^{\circ}$  degrees;  $135^{\circ}$ – $315^{\circ}$ ) or tail wind ( $316^{\circ}$ – $134^{\circ}$ ).

Circular statistics were applied using Oriana v. 4.2 (Kovach Computing Services). The position and heading angle were

determined for each pair of way-points representing a track-segment in the radar and rangefinder recordings. Prior to analyses, tests were undertaken to ensure that all data followed a von Mises distribution [7]. The difference in the overall pattern of migration directions between the study and the reference sites at Rødbyhavn and Gedser was tested using circular Mardia–Watson–Wheeler tests [7–9]. The test is a non-parametric test for determining whether two or more distributions are identical. Samples are pooled together sorted by angle, and then evenly distributed around the circle by circular ranks. Any significant difference between the resultant vector lengths  $R$  will lead to a

**Table 2.** Sample sizes (number of raptor group tracks recorded by radar and laser rangefinder) and proportion of headings towards SE (headings between 90° and 180°, i.e. in the direction of the wind farm) at study and reference sites during autumn migration in 2009, 2010 and 2011.

species	study (impact) site 2010–2011		Gedser reference site 2011		Rødbyhavn reference site 2009–2010	
	<i>N</i>	% headings towards SE	<i>N</i>	% headings towards SE	<i>N</i>	% headings towards SE
all raptors	4368	48.98	5417	22.82	553	17.18
buzzards	1610	33.79	890	24.49	279	27.96
sparrowhawk	1083	45.34	2578	24.67	166	6.02
kites	746	48.66	434	12.44	10	20.00
harriers	468	54.06	272	8.46	43	0.00
falcons	404	65.10	1169	25.66	14	7.14

large *W* test statistic and rejection of the null hypothesis of identical distributions. The effect of the distance to the offshore wind farm on flight directions of raptors was tested using circular–linear correlation coefficients [10] between bearing and distance to wind farm. Flight directions were calculated at the level of each segment of the radar and rangefinder tracks. The circular–linear correlation is analogous to the Pearson product–moment correlation with a coefficient range from  $-1$  to  $+1$ .

Avoidance rates (AR) were estimated for four raptor species, which could be tracked by radar equipment over longer distances from the wind farm, enabling a description of flight behaviour; intersecting/non-intersecting wind farm perimeter marked by the outer turbines on approach to the marine wind farm (within 1 km distance from wind farm perimeter)

$$AR = \frac{(N \text{ tracks non-intersecting}) - (N \text{ tracks intersecting})}{(N \text{ tracks non-intersecting}) + (N \text{ tracks intersecting})}$$

As the collected data did not allow confidence intervals of the AR to be estimated empirically, these were simulated using Monte Carlo tests. The tests were based on sampled means and standard deviations derived from ranges of AR observed in raptors at land-based wind farms [11].

### 3. Results

Mardia–Watson–Wheeler tests between the study site and the two reference sites showed significant ( $p < 0.0001$ ) differences in the distribution of migration directions with resulting large *W* values; Hyllekrog/Gedser *W* 159.5 for all raptors, 30.8 for buzzards, 143.3 for sparrowhawk, 117.0 for kites, 177.4 for harriers and 223.5 for falcons, Hyllekrog/Rødbyhavn *W* 111.2 for all raptors, 18.6 for buzzards, 125.3 for sparrowhawk, 35.4 for harriers and 24.4 for falcons. Owing to small sample size at Rødbyhavn, the difference for kites was not significant, with a *W* value of 8.94 ( $p = 0.011$ ). Raptors at the study site were more often recorded migrating with a bearing between south and east when compared with the reference sites. The proportion of all raptors with migrating directions between S and E recorded at the study site was 49.0%, compared with 22.8% at the Gedser reference site (table 2), and 17.2% at Rødbyhavn reference site (table 2). The recorded pattern of migration directions at the study and the Gedser reference site in 2011 was clearly different for all groups of raptors (figure 2). The difference in mean directions was mainly recorded during periods of head winds.

The spatial pattern of tracked raptors at the study site indicated a gradual attraction of raptors and flight directions

changing from SW (direction towards closest point Fehmarn on German coast) to S-E (direction towards wind farm) with decreasing distance to the marine wind farm (figure 2). The effect of the distance to the marine wind farm on flight directions of raptors was highly significant ( $p < 0.001$ ) for all five species groups of raptors: buzzards ( $r$  0.371), sparrowhawk ( $r$  0.285), kites ( $r$  0.445), harriers ( $r$  0.193) and falcons ( $r$  0.273).

For all four species of raptors analysed for macro avoidance the majority of tracks entered the wind farm perimeter. This leads to negative macro avoidance (attraction) rates; common buzzard  $\bar{x} - 0.04$  (95% confidence interval  $-0.025$  to  $-0.055$ ), honey buzzard  $-0.14$  ( $-0.125$  to  $-0.155$ ), red kite  $-0.17$  ( $-0.185$  to  $-0.160$ ) and marsh harrier  $-0.05$  ( $-0.065$  to  $-0.040$ ).

### 4. Discussion

Our investigations of behavioural responses of migrating raptors to a marine wind farm in the Baltic Sea provided, we believe, the first evidence of attraction of soaring bird species to marine wind farms as measured by migration directions. As the attraction behaviour is inversely related to the distance to the wind farm and is most significant during periods of head winds, it is likely that this behaviour is triggered by adverse weather conditions. Birds are attracted to offshore structures for various reasons [12–14]. However, an ‘island effect’ similar to the process that causes attraction of landbird species to small islands [5] is perhaps the most likely driver behind the attraction behaviour. The attraction leads to macro AR values, that are very different from those reported for waterbirds and seabirds, which typically indicate that more than 90% of the birds avoid marine wind farms [15]. The AR values estimated in our study also show that behavioural reactions by soaring migrants at marine wind farms differ significantly from those recorded at land-based wind farms, where high AR values of several species of raptors have been reported [16]. Behavioural details recorded at the Rødsand II marine wind farm further indicate low migration speed of raptors and complex movement patterns when they cross the wind farm [17,18].

The attraction of soaring migrants to marine wind farms will markedly enhance their risk of collision, as the migration heights of most species often overlap with the height of the rotor-swept zone [19]. The migration height is however dependent on both wind conditions and visibility, with a higher proportion of birds flying at risk during adverse weather conditions [19]. As many species of raptors and

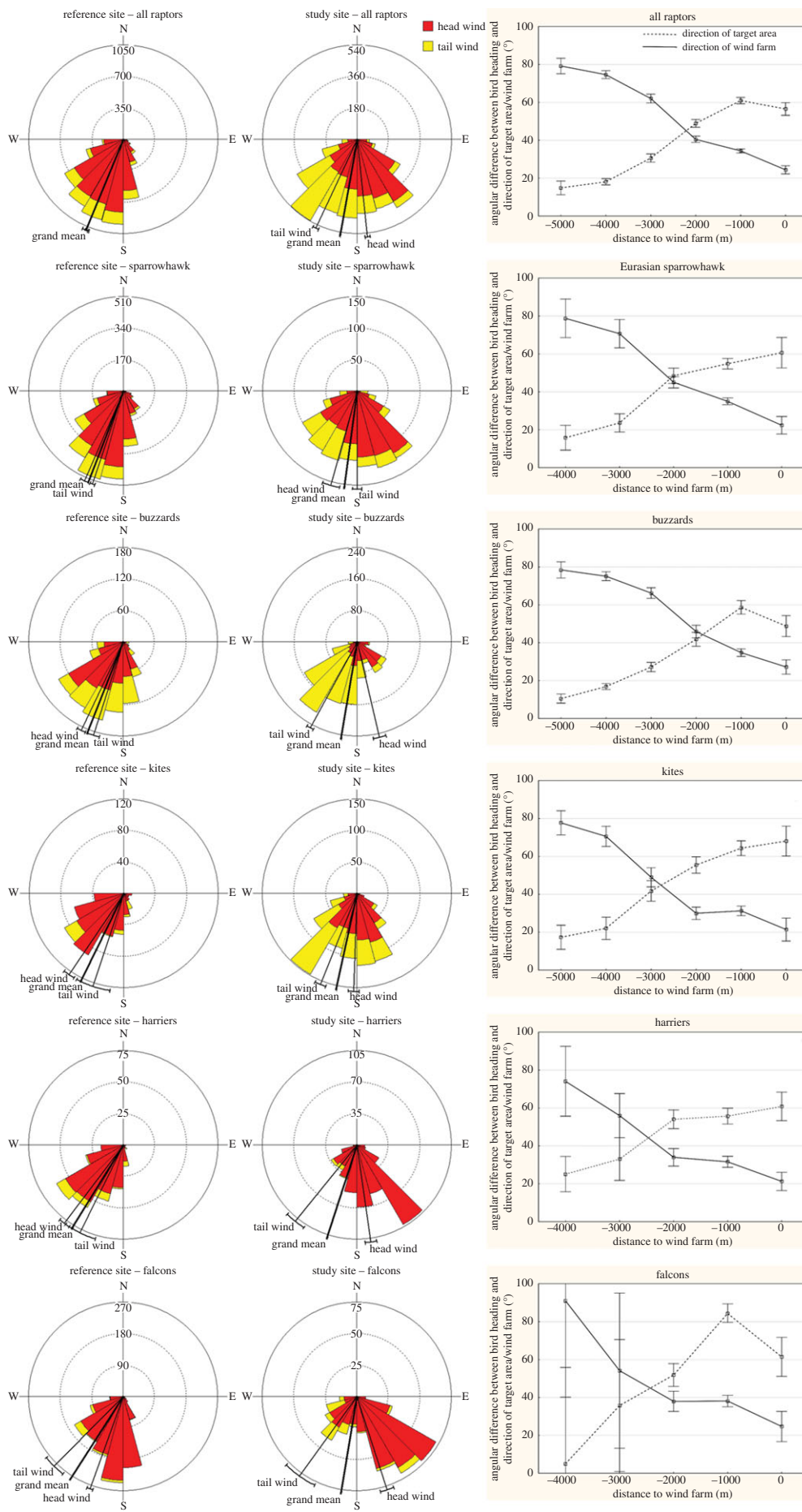


Figure 2. (Caption opposite.)

**Figure 2.** (*Opposite.*) Directional histograms demonstrating differences in migration directions of raptors between study and Gedser reference sites in 2011 (left panel), and relationship between migration direction of raptors at study site and distance to marine wind farm (right panel). Numbers on the Y-axes of histograms refer to sample size (number of tracks recorded by radar and laser rangefinder). Each wedge represents a sector of 15°. The mean direction in tail and head winds is indicated by the black lines running from the centre of the graph to the outer edge; the grand mean indicates the mean direction across all wind directions. The arcs extending to either side represent the 95% confidence limits of the mean directions. The two lines shown in the right panel reflect the angular difference between bird heading and the direction of the wind farm as a function of distance to the wind farm. Mean and 95% confidence intervals of angular differences are shown. All raptor species changed their mean migration direction as they approached the marine wind farm. Mean migration directions were initially towards the SW (direction towards closest point on German coast) at 4–5 km distance, and shifted towards the marine wind farm located in the S and SE direction when the raptors reached a distance to the marine wind farm of less than 2 km.

other soaring migrants have *K*-strategic life-history characteristics, the increased risk of added mortality at marine wind farms means that population impacts may occur unless proper planning of the development and siting of marine wind farms takes place in the future.

**Ethics.** All measurements were undertaken in accordance with relevant protocols for safe use of radar and laser rangefinder.

**Data accessibility.** Radar and laser rangefinder track data: Dryad <http://dx.doi.org/10.5061/dryad.4t8h5> [20].

**Authors' contributions.** H.S., M.D. and J.A.K. developed the concept of the paper. J.A.K., B.L. and H.S. organized the field investigations. J.A.K.,

S.H. and R.Z. undertook the data processing and analyses; H.S. performed the circular statistics. H.S. and M.D. wrote the manuscript, with input from all authors. All authors approved the final version of the manuscript and agree to be held accountable for the content therein.

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