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NOTE

Dodging the blades: new insights into three-dimensional space use of offshore wind farms by lesser black-backed gulls *Larus fuscus*

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ABSTRACT: GPS telemetry is improving our understanding of the way animals interact with their environment. Recent research has used this technology to assess the impact of offshore wind farms (OWFs) on seabirds, but few studies have collected fine-scale data from birds flying within OWFs. We use GPS telemetry to investigate movements of lesser black-backed gulls *Larus fuscus* in relation to OWFs from a protected site with an active breeding colony. Individual birds varied considerably in their use of OWFs; 15 out of 24 birds visited them, and time spent in these areas was 1.3% of time budgets across all birds. Two birds, for which the most data was collected, frequently entered OWFs and flew at turbine blade height; however, their overlap with the spherical 3-dimensional rotor swept volume was significantly lower than a random distribution. Although preliminary, these tracking data suggest a lack of a macro-scale (wind farm-scale) avoidance for *L. fuscus* but a potential meso-scale (within wind farm-scale) avoidance of turbines. Such data are therefore important in improving our understanding of the implications of OWFs for seabirds.

KEY WORDS: GPS telemetry · Renewable energy · Seabird · Collision risk · Avoidance · Human–wildlife conflict · Protected site

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INTRODUCTION

Technological advances are permitting ever more detailed insights into animal behaviour, ecology and conservation. A prime example is their application in the marine environment, where tracking has revolutionised the study of seabirds that spend much of their lives offshore where they are otherwise difficult to monitor (BirdLife International 2012). Marine areas are increasingly pressured by human activities, including fisheries, renewable energy developments (including offshore wind farms), pollution and climate change (Paleczny et al. 2015, Wright & Kyhn 2015). Consequently, it is imperative to identify the exposure of wildlife populations to such pressures.

Offshore wind farms (OWFs) may affect seabirds directly through collision, presenting a barrier to movement, or displacing birds from foraging areas (Furness et al. 2013). GPS telemetry has been used to investigate the spatial overlap between OWFs and movements of species (e.g. Thaxter et al. 2015) and altitude of flight to inform collision risk modelling (Cleasby et

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al. 2015, Ross-Smith et al. 2016). However, to date, the fine-scale activity of birds within operational OWFs has not been fully explored. Such information could improve our understanding of collision risk through measuring the responses of seabirds to turbines at different scales, including macro-avoidance of, or attraction to, OWFs and meso-avoidance (i.e. the last-second avoidance of rows of turbines; May 2015).

We provide initial findings of a study investigating the movements of lesser black-backed gulls *Larus fuscus* from a protected breeding colony in northwest England, located <20 km from 5 operational OWFs and a future consented site. *L. fuscus* are estimated to be at high risk of collision with OWFs (Furness et al. 2013) and are of conservation concern in the UK, with English populations declining in recent years (Ross-Smith et al. 2014). We demonstrate how GPS telemetry can illustrate the fine-scale 3-dimensional activity of individual birds within OWFs.

MATERIALS AND METHODS

Study area, catching and tagging birds

Fieldwork took place at South Walney, Cumbria northwest England (54° 40′ N, 3° 14′ W), during the 2014 breeding season (for details see Supplement 1 at www.int-res.com/articles/suppl/m587p247_supp/). A total of 24 adult lesser black-backed gulls *Larus fuscus* were captured at the nest site during incubation, and equipped with a solar-powered GPS tag (Bouten et al. 2013, Thaxter et al. 2015; Supplement 1). Tagging was undertaken under licence, approved by the independent Special Methods Technical Panel of the UK Ringing Scheme. Data collection spanned from 17 May to 1 September, covering incubation, chick-rearing, and post-breeding; the study area was defined by the foraging range of tagged birds from the colony. The 5 OWFs were Barrow, Ormonde, Walney 1, Walney 2 and West of Duddon Sands, and the consented OWF was Walney Extension (see www.4coffshore.com/offshorewind for their locations and other data).

Data processing

GPS tags recorded geographical position, ground speed and altitude above surface level (Bouten et al. 2013; Supplements 1 & 2). GPS fixes were separated into 2 categories: (1) within and (2) outside the perimeter of OWFs. The perimeter of an OWF included a buffer of 63 m around outer turbines equating to the maximum rotor radius for turbines in the study area (Supplement 1). Tags recorded 1 GPS location every 5 min, or at 10 s, 16 s or 60 s intervals ('fast-sampling') when in 'energy surplus' mode (see Supplements 2 & 3). Faster rates enabled finer-scale movements to be assessed within OWFs with reduced altitude error (Bouten et al. 2013; Supplement 2), but only occurred during daylight hours (sunrise: 03:45 to 05:06 h; sunset: 21:29 to 22:44 h) and in sunny conditions, when solar re-charging of tags was optimal. To obtain unbiased coverage of the 24 h period across all weather conditions, we sub-sampled all fast-sampling data to only include locations from 5 min intervals for assessment of altitude distributions.

Analysis

Birds were characterised as having 'connectivity' with OWFs if at least 1 GPS track was recorded within an OWF. We calculated the amount of time that all birds spent within OWFs (see Supplement 1 for details). We further investigated the movements of 2 individuals (Birds 4032 and 5026) that had the greatest number of fixes in, and overall use of, OWFs (Table 1, Table S2 in Supplement 3). For these 2 birds, we assessed the amount of time spent in flight and flight altitudes within and outside OWFs during the day and night (based on local sunrise and sunset), and 3-dimensional space use within OWFs, representative of daytime activity (see Supplements 2 & 3). Ground speed was used to delineate when birds were flying (>4 km h^{-1}), or resting at sea (≤4 km h^{-1}) (Shamoun-Baranes et al. 2011). Flight altitudes were plotted as kernel density histogram curves (Supplements 1 & 3). To assess differences between distributions, we used a bootstrap test of equality, grouping data into 4 categories by either inside or outside OWFs and by day and night. We calculated the proportion of area under each curve within the minimum and maximum heights swept by the rotor blades as a measure of overlap with the vertical rotor swept zone (vRSZ).

We analysed the movements of birds within OWFs in the spherical 3-dimensional rotor swept volume (RSV) of turbines, i.e. the horizontal rotor swept zone (hRSZ) within the vRSZ (see Fig. S1 in Supplement 1 for a schematic representation). Distributions of GPS fixes were plotted in relation to distance to nearest turbine, and altitude above mean sea level, based on RSVs for the 5 operational OWFs (Supplement 1). To visualise fine-scale daytime 3-dimensional distributions, we combined altitude and distance to the near-

est turbine for data collected at fastest intervals of 10 s (Supplement 3). Relative space use and thus overlap with the RSV was determined by kernel density estimate (KDE) utilisation distributions. A paired *t*-test was used to test whether the proportion of observed fixes within the RSV was significantly different from a null pattern of GPS points randomly redistributed in the horizontal plane within the areas of the OWFs (Supplement 3). All data processing and analyses were conducted in R 3.2.2 (R Core Team 2016).

RESULTS

Connectivity and temporal overlap with OWFs

Of the 24 birds tracked, 15 visited operational OWFs, and all birds cumulatively spent 1.3% of their total time within OWFs (Table 1). Individual birds spent up to 17% of their time (Table 1) in operational OWFs, and of the 24 birds tracked, 5 individuals interacted with all 5 operational OWFs in the area (Table 1). Birds were frequently recorded both flying and resting on the water offshore within OWFs (Fig. 1). Individuals 4032 and 5026 spent more time in flight within OWFs (51.7 and 35.7%, respectively), than in offshore areas outside OWFs (28.4 and 30.1%, respectively; see Supplements 4 & 5 for example movements of birds 4032 and 5026, respectively.

Flight altitude and 3-dimensional space use

Flight altitudes of birds 4032 and 5026 were greater within OWFs than outside (bootstrap hypothesis test of equality, $p < 0.001$; Fig. 2) and higher during the day than at night ($p < 0.001$; Table 2, Fig. 2). Overlaps with the vRSZ within OWFs were greatest during the day (76.9 and 66.1% for Birds 4032 and 5026, respectively; Table 2, Fig. 2,). Overlap with the vRSZ within OWFs during the daytime was greater than potential overlaps outside OWFs, and was lower at night than during the day (Table 2). Further analy-

Table 1. Connectivity and temporal overlaps of 24 lesser black-backed gulls *Larus fuscus* from South Walney, northwest England, with consented (C) and operational (Op) offshore wind farms, based on GPS telemetry data. Birds were characterised as having 'connectivity' with an OWF if at least 1 GPS track was recorded within its perimeter. Temporal overlaps were calculated as the proportion of total time spent in OWFs. For totals, the proportion of time spent away from the colony, offshore and in OWFs was presented as the summed time across birds in each activity expressed as a proportion of the summed tracking duration. Total connectivity was given as the maximum number of OWFs that birds interacted with

Bird	Tracking duration (d)	Time away from colony (%)	Time offshore (%)	Connectivity		Temporal overlap (%)		
				C (n = 1)	Op (n = 5)	C	Op	All
494	35.9	46.3	10.6		4		7.4	7.4
496	62.8	51.1	3.8		3		0.2	0.2
497	81.9	51.7	3.1					
499	81.8	44.5	16.3	1	5	0.1	3.2	3.3
501	85.2	47.1	29.4	1	4	<0.1	2.3	2.3
502	24.2	36.6	4.1					
503	74.0	34.5	5.8					
504	76.0	40.2	19.0		1		0.1	0.1
506	80.6	59.3	23.3	1	5	0.3	5.1	5.4
4031	35.2	34.9	11.7	1	4	0.3	1.4	1.7
4032[a]	77.2	65.3	15.8	1	5	2.7	3.2	5.9
4033	70.1	46.2	2.2					
4034	72.2	41.3	2.6					
4035	43.3	42.1	14.4		1		<0.1	<0.1
5023	84.1	42.6	6.1					
5024	74.2	35.7	13.4	1	5	0.6	8.0	8.6
5025	105.3	43.8	32.6		4		<0.1	<0.1
5026[a]	88.0	58.3	39.4	1	5	5.3	17.0	22.3
5027	92.5	64.9	4.3					
5029	60.5	57.3	4.9					
5030	99.8	52.8	11.5		1		<0.1	<0.1
5032	75.7	39.8	5.3		1		<0.1	<0.1
5033	76.7	52.6	11.0					
5034	101.7	51.1	10.4		1		<0.1	<0.1
Total	1759.0	48.5	13.5	1	5	0.6	0.7	1.3

[a]Birds 4032 and 5026 were selected for additional investigation into fine-scale space use

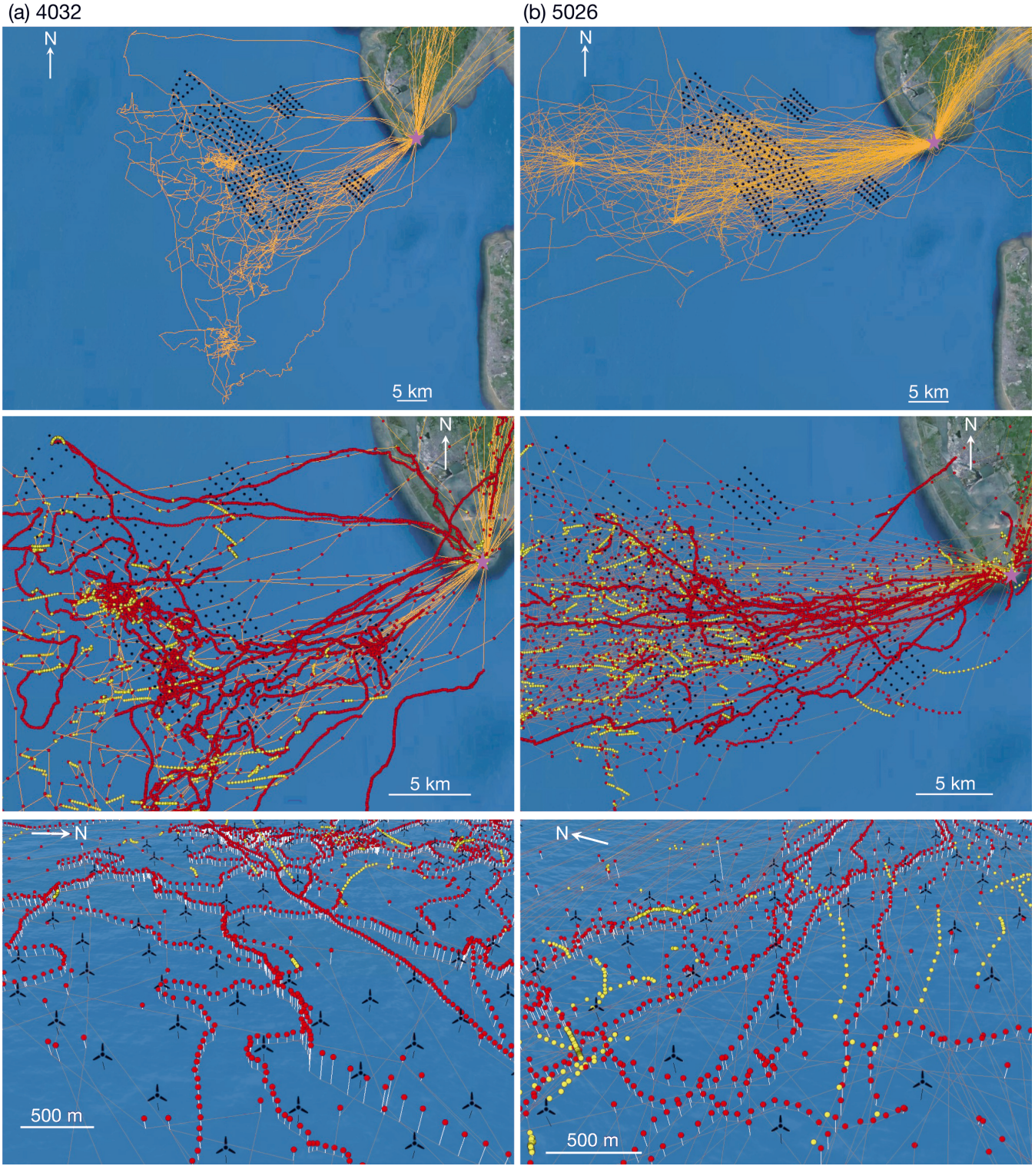

Fig. 1. Example GPS tracks showing movements of 2 *Larus fuscus* tracked from South Walney, northwest England (pink star), in relation to 5 operational offshore wind farms. (a) Left panels: Bird 4032, tracked from 17 May to 2 August, 2014; (b) right panels: Bird 5026, tracked from 17 May to 13 August, 2014. Locations are shown as likely flight (red; travel speed > 4 km h^{-1}) or likely resting, bathing or swimming (yellow; travel speed ≤4 km h^{-1}); orange lines link consecutive GPS points. Turbine locations are plotted as black dots. Top panels: wider offshore movements in and around offshore wind farms; middle panels: localised 2-dimensional movements in relation to operational wind turbines; bottom panels: visualisations of 3-dimensional movements in relation to locations of a subset of turbines, plotted at hub height (see www.4coffshore.com/offshorewind). Icons for turbine blades are not shown to scale or orientation. Wind farm turbine locations ©Crown Estate; map backgrounds ©GoogleEarth. See Supplements 4 & 5 for animated tracks for Birds 4032 and 5026, respectively

sis of 3-dimensional daytime movements revealed a small overlap (<3%) between the 95% KDE area used and the RSV (Table 2, Fig. 3). The proportion of observed fixes within the RSV was significantly lower than that expected from a random null distribution ($p < 0.001$; Supplement 1).

DISCUSSION

Although 9 of the 24 tagged lesser black-backed gulls *Larus fuscus* did not use OWFs, 8 birds spent >1% of their time in OWFs, and so did not avoid these areas. Our results match previous studies, suggesting that *L. fuscus* show no consistent avoidance of, or attraction to OWFs, whereas other species such as northern gannets *Morus bassanus*, divers and auks show a greater level of macro-avoidance (Petersen et al. 2006, Krijgsveld et al. 2011, Cook et al. 2014).

For the 2 individual birds for which results are presented (Birds 4032 and 5026), overlap with the vRSZ (inside and outside OWFs) was less at night than in the day. These results support previous findings for *L. fuscus* at a colony in eastern England, where 50% of daytime observations classed as 'marine' were within 12.8 m of sea level, in contrast to 50% within 5.6 m after dark (Ross-Smith et al. 2016). At a separate colony in Germany, *L. fuscus* also flew lower at night than during the day (boxplot inter-quartile ranges, day: 2 to 36 m; night: −2 to 8 m; Corman & Garthe 2014). However, the overlap of daytime flight altitudes with the vRSZ in OWFs in our study (>50%) was higher than in Ross-Smith et al. (2016) where 31% of *L. fuscus* daytime flights at sea were within the vRSZ (30 to 258 m), and Johnston et al. (2014), using data from boat-based surveys, where 28% (95% confidence interval 20 to 43%) of *L. fuscus* flew within a typical vRSZ of 20 to 120 m. This variation between colonies may reflect differences between commuting journeys to and from the nest site and foraging flight once further offshore. Our data indicated that *L. fuscus* spent more time in flight at higher altitudes within OWFs than outside, matching previous findings for large gulls (Krijgsveld et al. 2011, Skov et al. 2012), although ours is the first study to demonstrate this at the species level. Using laser rangefinders, Skov et al. (2012) observed that large gulls, including *L. fuscus*, on approach to the Horns Rev I OWF increased their mean flight alti-

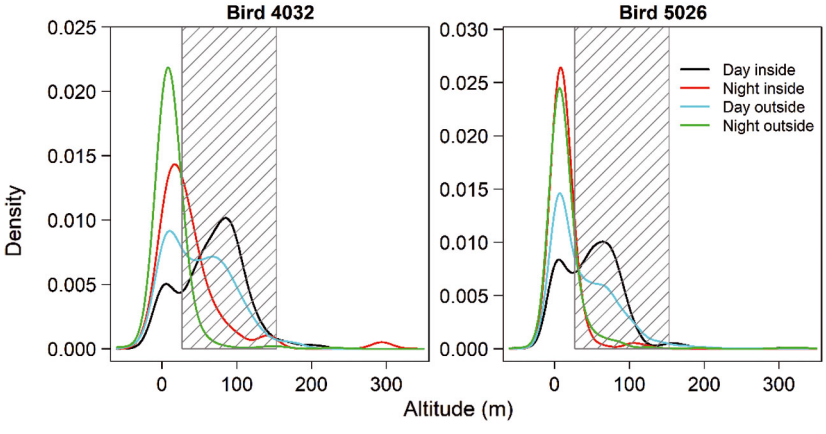

Fig. 2. Flight altitude distributions for 2 *Larus fuscus* from South Walney (left: Bird 4032; right: Bird 5026) plotted as kernel density histograms for areas within and outside offshore wind farms and separately for day and night. The shaded area represents the maximum vertical rotor swept zone (vRSZ), which was 27 to 153 m above mean sea level for offshore wind farms in this study (see 'Materials and methods')

Table 2. Characteristics of offshore flight of 2 lesser black-backed gulls *Larus fuscus* (Birds 4032 and 5026) from South Walney during day and night, within and outside offshore wind farms, showing flight altitude (m) (including modal density peak, mean ± SD and median values) and percentage overlaps with the maximum vertical rotor swept zone (vRSZ) and the 3-dimensional rotor swept volume (RSV). 'n' indicates the number of GPS fixes

Bird	Location	Period	n	Altitude (m)				Overlap (%)	
				Mode	Mean	SD	Median	vRSZ	3-dimensional RSV
4032	Within wind farm	Day	193	86.9	67.2	41.8	70.0	76.9	2.7
		Night	54	13.8	36.9	48.5	23.5	46.1	0.0
	Outside wind farm	Day	513	7.4	49.9	44.9	46.0	61.2	–
		Night	298	8.0	11.5	26.5	9.0	17.1	–
5026	Within wind farm	Day	338	65.3	49.1	39.2	50.5	66.1	1.2
		Night	144	9.2	12.3	18.0	9.0	15.1	0.0
	Outside wind farm	Day	1315	5.2	39.3	47.8	25.0	47.5	–
		Night	359	3.8	12.7	49.3	7.0	16.2	–

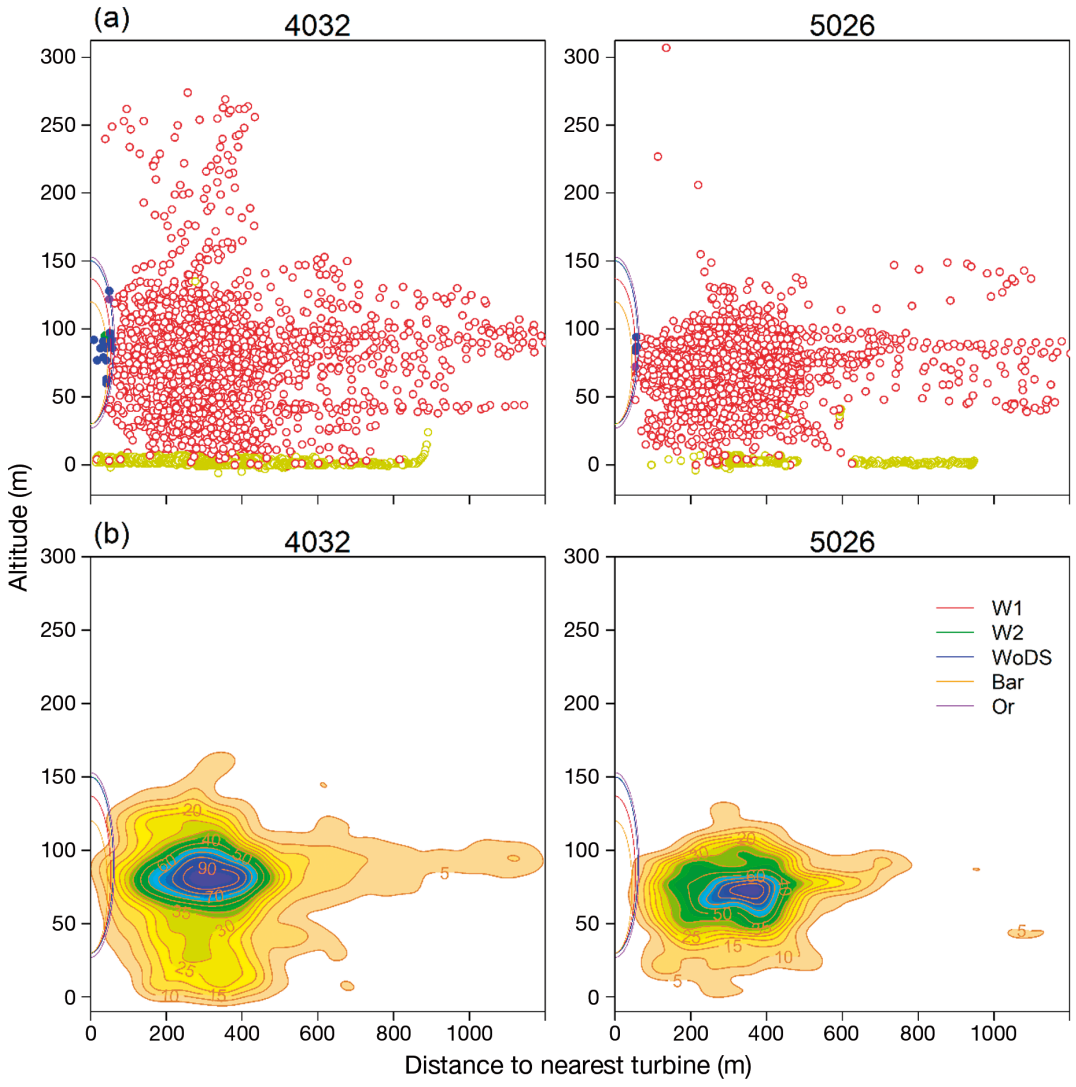

Fig. 3. Distribution of fixes of 2 *Larus fuscus* from South Walney (left panels: Bird 4032; right panels: Bird 5026) within operational offshore wind farms (OWFs) during daytime periods using data collected at a frequency of 10 s. Horizontal axes show distance from the nearest wind turbine (m); vertical axes show flight altitude (m). Coloured curves adjacent to the *y*-axes indicate 3-dimensional rotor swept volumes (RSVs) of the 5 operational OWFs in the area: Walney 1 (W1), Walney 2 (W2), West of Duddon Sands (WoDS), Barrow (Bar) and Ormonde (Or) (see inset key to colours; for locations see www.4coffshore.com/offshorewind). (a) Distance to nearest turbine and altitude for flight (red; travel speed > 4 km h^{-1}) and resting, bathing or swimming (yellow; travel speed ≤ 4 km h^{-1}) behaviours. Solid points indicate overlaps with RSVs; the colour identifies the wind farm concerned. (b) Kernel density estimation of fixes of birds in flight illustrating overlaps with the RSV determined using the 95% KDE (i.e. the area of overlap with the 5% contour line)

tude from just above sea surface to rotor height. Using visual panorama scans, Krijgsveld et al. (2011) also found that large gulls flew higher inside the Egmond aan Zee OWF, Netherlands compared to outside. Flight altitudes can vary depending on weather conditions (Dokter et al. 2013), with tailwinds creating greater lift compared to headwinds (Krüger & Garthe 2001). Wind farms may alter meteorological conditions, such as wind patterns or turbulence (Göçmen & Giebel 2016), which could influence the altitude at which the birds are flying. Alternatively, the creation of 'reef' habitats at turbine bases (Reubens et al. 2013) may increase foraging opportunities and thus alter flight activity.

Birds 4032 and 5026 frequently entered OWFs, but their use of the RSV (<3% overlap of the 95% KDE) was significantly less than expected from a null distribution. These data therefore suggest a lack of a macro-avoidance response but a potential meso-avoidance response of *L. fuscus* within OWFs. In interpreting the assessment of space use, it should be noted that our distance to nearest turbine metric is

representative of a 2-dimensional plane surrounding turbines rather than a single dimension. Consequently, the probability of occurrence along this axis is not constant. Further, the spatial overlap percentages with the RSV do not directly equate to avoidance, and are based on data collected under sunny weather conditions during the day (i.e. when birds are best able to detect turbines). Nevertheless, our approach may offer solutions to estimating 3-dimensional avoidance rates, which to date have not been determined for any species (Cook et al. 2014).

Our results are preliminary, and further investigation is needed to verify the patterns recorded. The assessment of overlap with the RSV did not account for turbine orientation, and is precautionary in assuming that all tracks were perpendicular to the rotation of the blades. Further modelling of GPS altitude measurements to account for error sources (Ross-Smith et al. 2016) and differentiation between foraging and commuting flight (Corman & Garthe 2014, Cleasby et al. 2015) would be valuable for a larger dataset.

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