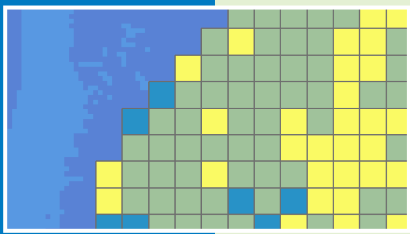
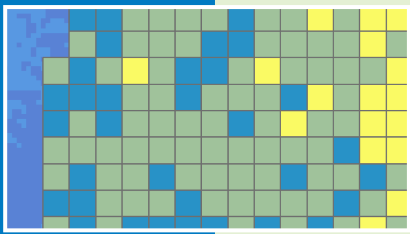
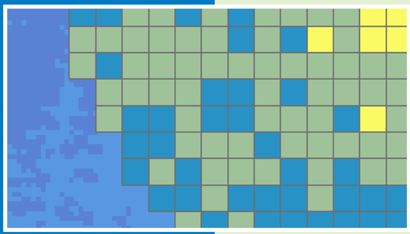
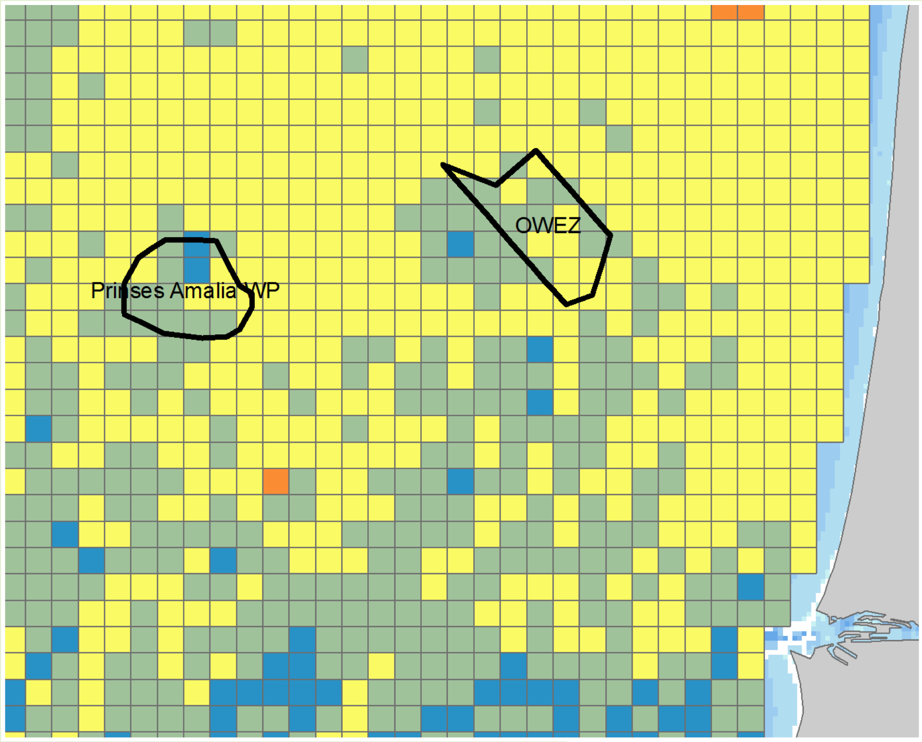
Effects of Offshore Windfarms on the behaviour of Lesser Black-backed Gulls









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Preface

ENECO, one of the operators of the Dutch offshore wind farms Luchterduinen and Princess Amalia Windpark, is interested to learn more about the behaviour of birds in and around offshore wind farms in order to gain insight into the effects offshore wind turbines can have on bird communities. In this report, we analysed GPS measurements on Lesser Black-backed Gulls (*Larus fuscus*) in the Netherlands, Belgium and United Kingdom to reveal the effects of offshore wind farms on behaviour, such as macro-avoidance or micro-avoidance through the adjustment of flight paths, flight height or flight speed.

We are profoundly grateful to several research groups for providing their UvA-BiTS GPS logger data on Lesser Black-backed Gulls and Herring Gulls and for collaborating in this study. Eric Stienen, Nicolas Vanermen (INBO - Belgium), Kees Camphuysen (NIOZ – the Netherlands), Niall Burton, Chris Taxter (BTO – United Kingdom) and overall project coordinator Willem Bouten (UvA – the Netherlands) were kind enough for providing access to their data. Our study wouldn’t have been possible without the tremendous amount of time and persistence they invested to collect the data. Mark Collier (Bureau Waardenburg) carried out the internal quality assurance.

We appreciated the feedback of Sytske van den Akker and Suzanne Lubbe on this report. The study was coordinated by Sytske van den Akker.

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1 Introduction

1.1 Motivation

Currently, there are a number of operational wind farms in the southern North Sea and a large number of new developments have been proposed. The EIA made for the Dutch ‘Kavels Borssele’ as well as the project of the Dutch government entitled ‘Framework Ecology and Cumulation’ (KEC) estimated that especially for the three "larger" gulls (Lesser Black-backed Gull, Great Black- backed Gull and Herring Gull) the cumulative mortality rates are very near or above the Potential Biological Removal of the relevant species, and as a consequence significant impacts at population level cannot be ruled out.

The underlying assessments of the potential numbers of collisions at proposed offshore wind farms were determined using the extended SOSS Band model (Band 2012) that is currently the most commonly used model to estimate collision numbers (Masden & Cook 2016). The model relies on densities of flying birds determined during diurnal ship-based or aerial surveys. The Band model further incorporates a number of species-specific parameters, including: size, flight speed, flight altitude and level of nocturnal activity. Due to the influence on numbers of birds exposed, encounter probability and collision risk, the parameters flight speed, altitude, percentage of flying birds and nocturnal activity have a large influence on the estimated number of collisions (Masden & Cook 2016). In the absence of site-specific data, these parameters are often obtained from literature, and consequently these data are often collected on flying birds without the presence of wind turbines that can have a large effect on the flight behaviour of birds (Krijgsveld *et al.* 2011; Krijgsveld 2014). For example, birds may show avoidance or attraction to wind farms, resulting in profoundly different bird densities in the area, once the wind farm is constructed. Birds could also avoid the wind farm specifically during the night, or use the wind farm area in a specific way and hence having another level of flying activity and nocturnal activity within the wind farm. Moreover, birds may also adjust their flight behaviour after entering a wind farm by adapting another flight speed or avoid the rotor-swept zone by flying higher or lower.

1.2 Current knowledge on flight behaviour

Due to the large-scale developments of offshore wind farms, there is recently increasing attention to the behaviour of large gulls, including Lesser Black-backed Gulls, in and around offshore wind farms. More and more evidence points towards Lesser Black-backed Gulls being attracted to wind farms, instead of avoiding them (Skov *et al.* 2015; Vanermen, Nicolas *et al.* 2015), although the general use of offshore habitats also seems to differ within and between years and among colonies (Thaxter *et al.* 2015; Ross-Smith *et al.* 2016). All in all, there seems to be no consensus whether the species reacts with avoidance or attraction to offshore wind farms (Krijgsveld 2014).

Despite the increasing attention to the species, there is still relatively little known about the flight behaviour of Lesser Black-backed Gulls in and around offshore wind farms. For example, estimates for flight speed are commonly based on flights tracked by land-based radars (Alerstam *et al.* 1993; Alerstam *et al.* 2007). For some species, such as gulls, flight speeds at sea may be lower than above land, especially in the vicinity of wind turbines (Krijgsveld *et al.* 2011; Ross-Smith *et al.* 2016). This can be due to avoidance behaviour of wind turbines but may also be caused by gulls foraging in and around wind farms instead of commuting through the area. Flight height profiles provide another example, as they are largely based on visual observations, which are subject to crude classifications or observer bias. Moreover, flight height profiles are measured in the absence of wind turbines and very few data exist on how birds adjust their flight height in the vicinity of wind farms. Improved estimates on flight height profiles in and around wind farms are therefore needed (Furness *et al.* 2013).

Nocturnal activity, another important parameter in collision risk modelling, is largely unknown, and published estimates of this parameter for gulls are based on few or no data (Garthe, Stefan & Hüppop 2004; Furness *et al.* 2013). Better estimates of these parameters will ensure better estimates of collision victims in EIAs for (offshore) wind farms, and specifically for larger gull species this could lead to a better understanding of the effects of proposed offshore wind farms.

1.2 GPS logger developments

Detailed measurements of flight speeds, altitudes and nocturnal activity have recently been made possible by GPS logger techniques (Bouten *et al.* 2013). Herring Gulls and Lesser Black-backed Gulls were tracked using GPS loggers as part of various studies around the southern North Sea (Camphuysen, C.J. 2010; Brabant *et al.* 2015; Thaxter *et al.* 2015; Tyson *et al.* 2015; Ross-Smith *et al.* 2016; Stienen *et al.* 2016). In order to update the currently available figures on flight speed, flight height, nocturnal activity and time spent in flight these data were recently collated and analysed (Gyimesi, A. *et al.* 2017). The study showed that adjusting the above-mentioned variables could have a large influence on the calculated number of collision victims with the extended SOSS Band model. However, it also left knowledge gaps with respect to behaviour of gulls within wind farms and on land. Namely, the newly calculated estimates by Gyimesi *et al.* (2017) on flight speed are still based on measurements under natural circumstances, although birds may adjust their behaviour in the vicinity of wind farms, as outlined above. As small modifications in e.g. the level of avoidance, flight height distribution or nocturnal activity can have a relatively large influence on the number of collision victims, this study intends to improve estimates by analysing multiple years of data on GPS logger measurements of Lesser Black-backed Gulls.

2 Materials and methods

2.1 GPS loggers

In addition to the Bureau Waardenburg data on movements of Lesser Black-backed Gulls with GPS-loggers, research groups from the NIOZ (Netherlands Institute for Sea Research), INBO (Research Institute for Nature and Forest; Belgium), BTO (British Trust for Ornithology) and University of Amsterdam (the Netherlands) provided access to their GPS logger data on Lesser Black-backed Gulls and Herring Gulls. Birds were caught on nests in breeding colonies in the UK (Orford Ness), Belgium (Zeebrugge and Oostende) and the Netherlands (Texel, Vlissingen and Volkerak) and equipped with GPS loggers. Although at the moment of catching the birds were actively breeding, the loggers were functioning for a long time period (i.e. often several years), and hence the breeding status of the birds could have changed during the data collection period. For instance, birds could have a nest failure during the same breeding period or skip breeding in the following seasons.

During the first preliminary analyses it turned out that the data of Herring Gulls is not applicable for studying behaviour in and around offshore wind farms, as birds mainly remained in the coastal zone and did not visit areas of offshore wind farms (figure 2.1). Therefore, this study focussed solely on the behaviour of Lesser Black-backed Gulls. Being able to use the joint data of all these researchers, our results were based on a large dataset on flight behaviour of Lesser Black-backed Gulls from different countries in Northwest Europe, which is of direct relevance for the European wind industry and licensing authorities in particular for the southern North Sea.

Data were collected by solar-powered GPS loggers developed by the University of Amsterdam (UvA-BiTS, for details see Bouten *et al.* 2013). The loggers were attached as backpacks using a harness and collected measurements among others on geographical position, ground speed and altitude (corrected for terrain elevation based on a Digital Elevation Model (see Bouten *et al.* 2013). The GPS logger weighed less than 3% of the birds' mass. Recording intervals were defined by the researchers and could be adjusted remotely. Measurement intervals varied between 3s to 30 min. The accuracy of the GPS-measurements depends on the log interval: the shorter the interval, the more accurate the values (Thaxter *et al.* 2011). Consequently, the mean positional error varies between 1 and 67 m, the mean speed error between 0.01 and 0.82 m/s and mean altitude error between 1 and 26 m (Bouten *et al.* 2013). Data were automatically downloaded from the GPS devices via a wireless radio network to a base station located in the colony, and then onto the UvA-BiTS database of the University of Amsterdam.

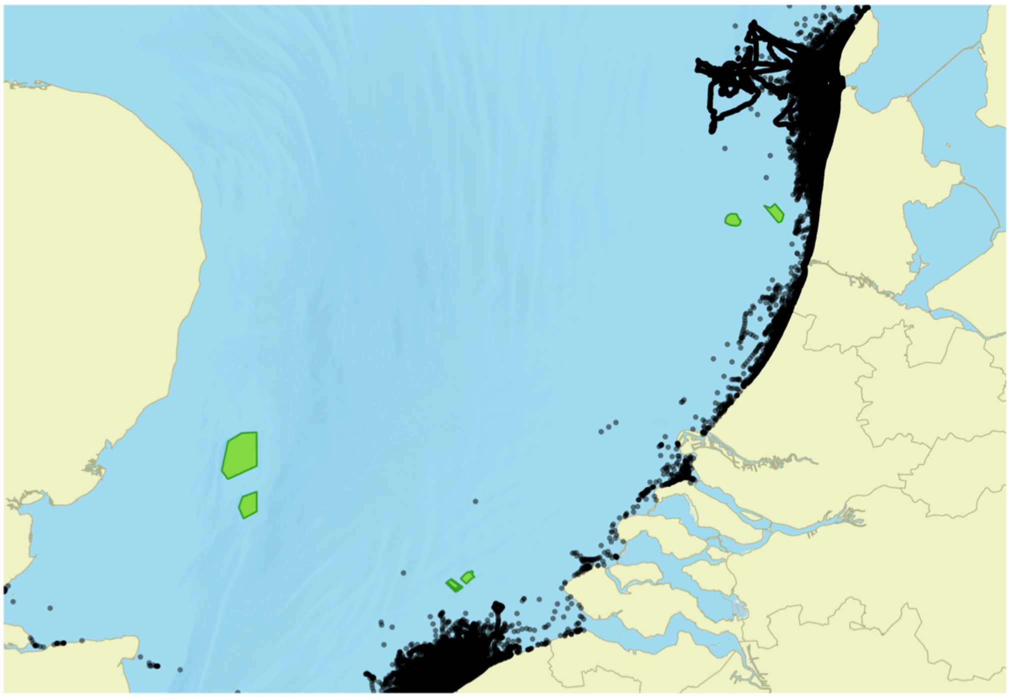

Figure 2.1 GPS positions of Herring Gulls above the North Sea ringed in the colonies of Texel (the Netherlands) and Oostende (Belgium). Green areas provide offshore windfarms included in this study.

2.2 Data selection

The total dataset contained almost 10 million GPS fixes from 2009 until 2016 from adult Lesser Black-backed Gulls and Herring Gulls equipped with a GPS logger in colonies in England, Belgium and the Netherlands The aim of this study was to estimate mean flight speed, flight height distribution, nocturnal activity and percentage of time spent flying explicitly in offshore wind farms versus offshore environments without wind farms. Therefore, several selection procedures were carried out to delineate the dataset according to the different aims of this project. The most important selection steps are highlighted below in bold and the results of the different steps summarized in a table in chapter 2.5.

As a first step for all analyses of this study, data from the Lesser Black-backed Gull colonies in Orford Ness, Texel, Vlissingen and Zeebrugge were selected **in offshore areas** (>800,000 records), based on a land-sea mask generated from country borders from Esri Data & Maps. As the current study intended to compare the behaviour of gulls in and around wind farms, we used only data in the analysis that was collected **within 20 km from offshore wind farms**, approximately 200,000 records. Birds from Lake Volkerak did not reach offshore wind farms or their 20 km buffer and hence were not part of the analysis. Due to the large distance to the colonies, Lesser Black-backed Gulls visited only sporadically areas of the wind farms Luchterduinen in the Netherlands (figure 2.2), Belwind in Belgium and English offshore wind farms other than Greater Gabbard, and hence providing insufficient data to compare behaviour inside and outside the wind farms. Therefore, the analyses of this study concentrated on the offshore wind farms OWEZ (Offshore Windpark Egmond aan Zee) and Prinses Amalia (PAWP; both the Netherlands), Thornton Bank I, II and III (Belgium) and Greater Gabbard (UK) (figure 2.3).

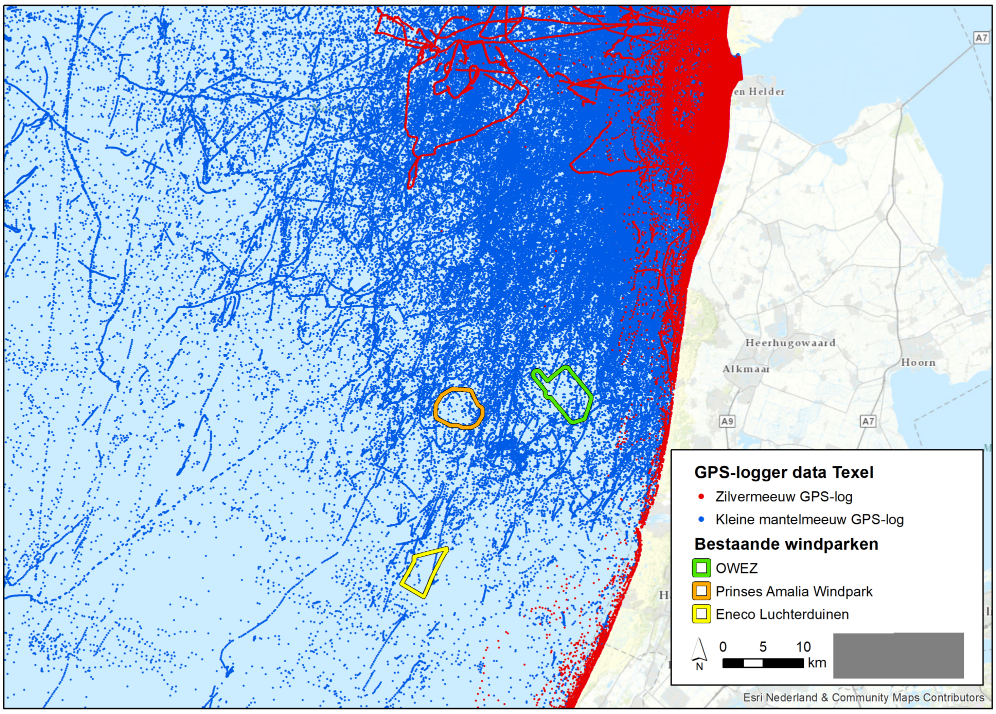

Figure 2.2 GPS positions around operational Dutch windfarms of Lesser Black-backed Gulls ringed in the colony of Texel (the Netherlands).

A comparison of behaviour before and after the completion of these wind farms was not possible due to limited time periods of the available data. Therefore, we used only data **after construction:** from 2014 onwards of the Belgian dataset (commission of Thornton Bank III) and from 2011 onwards of the English dataset (completion of most of the wind turbines of the Greater Gabbard wind farm). As the other Dutch wind farms OWEZ and PAWP were already built in respectively 2007 and 2008, all the GPS logger data from the island of Texel was collected after construction of these wind farms and could be used in the analyses.

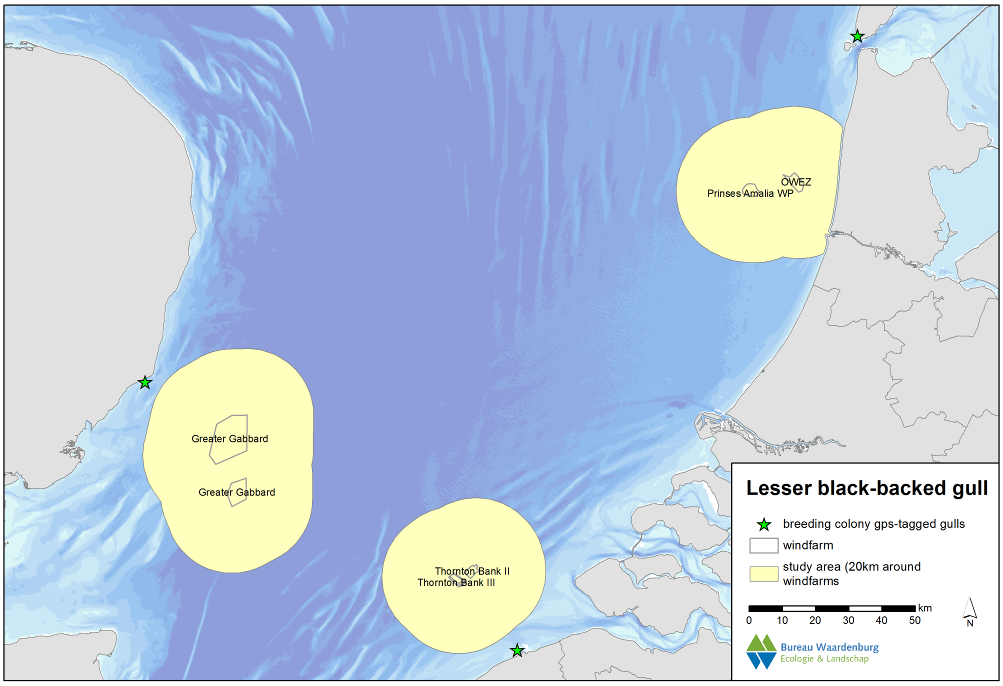

Figure 2.3 Areas around Dutch, Belgian and English offshore wind farms within which GPS logger measurements of Lesser Black-backed Gulls were included in the analysis.

2.2.1 Selections based on accuracy values

Analysis of spatial distribution

In order to use the largest possible dataset for the analysis, while also relying on reliable measurements, we made some selection steps, separately for analysing the spatial distribution and behaviour of Lesser Black-backed Gulls. These selection steps intended to limit the dataset to accurate measurements.

In order to limit the amount of data filtered out but keep adequately reliable spatial measurements, we **excluded 10% of the data with the lowest GPS accuracy** (> 22.3 m; accuracy produced by the loggers themselves). *This dataset (**n = 135,288 of 115 individuals**) in the study area of offshore wind farms was used to analyse individual tracks, and to obtain minimum distances to which Lesser Black-backed Gulls approached wind turbines.*

*For all other analyses, **the dataset was resampled for 5-minute intervals**, in order to remove the effect of individuals with a high logging frequency (cf. McLaren et al. 2016). The dataset for the analysis of spatial distribution included no further selection steps, leaving **62,291 records of 115 individuals** in the database*.

Analysis of flight speed and altitude

For the analysis of flight speed and altitude the threshold values estimated by Gyimesi et al. (2017) were used to select only accurate measurements. Therefore, **1.22 m/s was used as maximum accepted speed accuracy and 16.0 m as maximum**

accepted altitude accuracy. Only values with a better accuracy remained in the dataset. The remaining dataset contained a considerable number of altitude measurements below 0 m. In order to limit the effect of a large number of unrealistic negative altitude values, we determined a minimum height value as well. We assumed that birds cannot fly below 0 m, but a measurement at 0 m can have an accuracy error. Therefore, we took the mean altitude accuracy value below 0 m as a minimum altitude value. That resulted in -16.0 m for as minimum accepted altitude. **Records with height measurements below the minimum height value of -16.0 m were also excluded from the analysis**.

As the resulting dataset still contained a few implausible records (e.g. flight speed > 300 m/s), **0.1% of the records with the highest speed measurements were also excluded** from further analysis. For the same reason, **another 0.1% of the records with the highest altitude measurements were also excluded**. Maximum flight height in the dataset after this step was 818 m.

After the step of removing 0.1% of speed measurements with the highest values, the maximum flight speed in the resulting dataset was 23.4 m/s. This figure is lower than maximum flight speed used in previous studies (25 m/s; Dreef 2011). However, as only 0.1% of the records above these values were removed, with very high values among them, our obtained maximum values are considered realistic. The majority of the records in the resulting dataset was of very low speeds (i.e. <1 m/s), with a secondary peak occurring at around 9 m/s (figure 2.4). *The final dataset for the analysis of flight speed and flight height contained* ***30,126 records of 109 Lesser Black-backed Gull individuals*** *within a 20 km zone around offshore wind farms.*

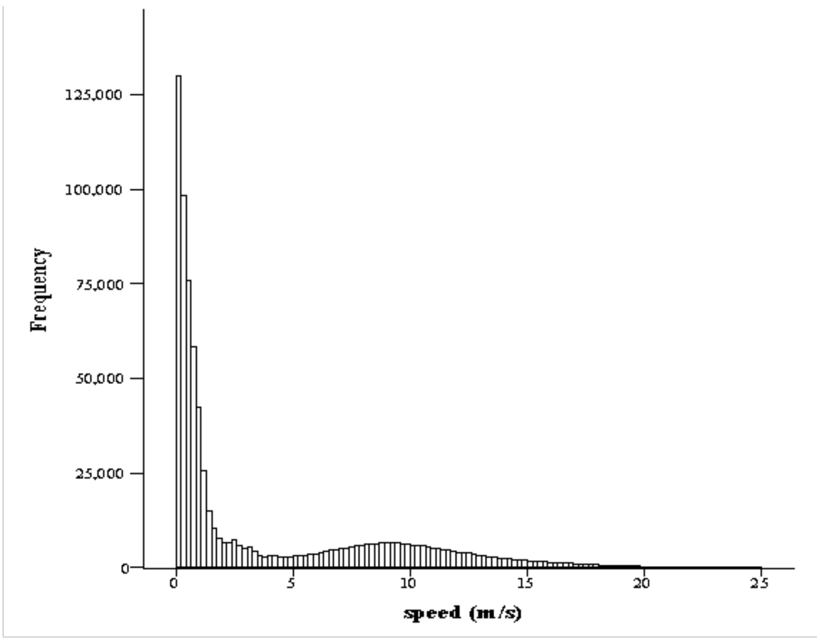

Figure 2.4 Frequency distribution (number of records) of speed measurements for Lesser Black-backed Gulls measured offshore.

2.2.3 Flight and non-flight behaviour

In order to define flight and non-flight behaviours, a minimum flight speed was also determined. Stationary behaviour (e.g. sitting; <1 m/s) was in the dataset by far the most commonly occurring behaviour (figure 2.4). Furthermore, birds at sea can exhibit behaviours of walking (on shoreline, platforms or boats) or floating on the sea surface. This latter behaviour has approximately the speed of the surface current velocity of the North Sea. The highest maximum tidal velocity during mean spring tides is reached along the coast of East-England with 1.44 m/s (figure 2.5). According to the Zuno Model (flow model of water in the southern North Sea) from Rijkswaterstaat (or the former RIKZ), the maximum mean current velocity in the southern North Sea over the entire tidal cycle is 1.18 m/s. The strongest near-surface tidal currents are measured around inlets, as for example the Marsdiep tidal inlet with 1.8 m/s (Buijsman 2007).

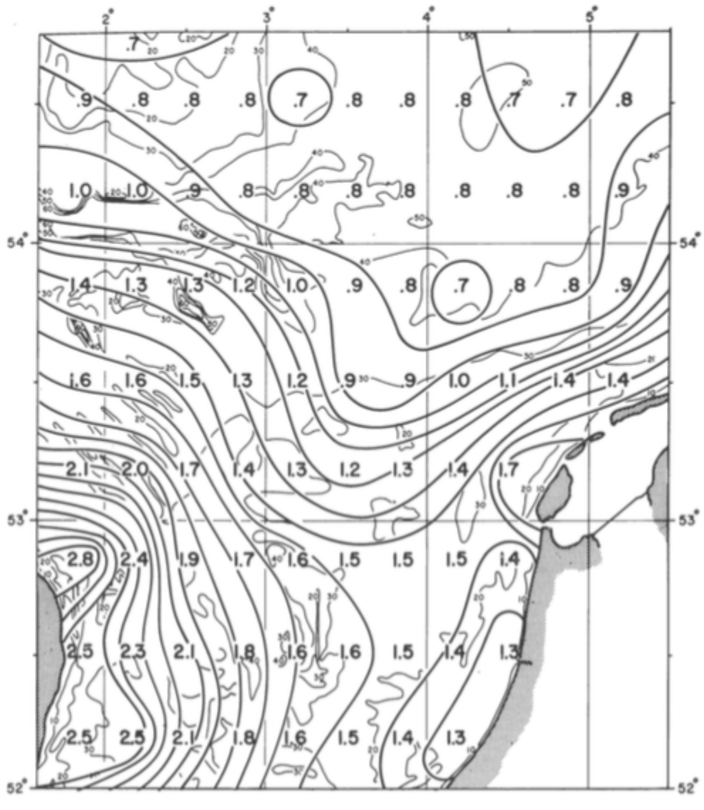

Figure 2.5 Maximum tidal velocities (mean spring tide) in knots (1 knot = 0.51 m/s), and lines of equal velocity as deduced from the atlas of tidal streams (source: Deutsches Hydrographisches Institut, Hamburg, published by Creutzberg et al. (1984)).

Shamoun-Baranes *et al.* (2011) used the aerodynamic theory to ascertain a minimum flight speed of 1.1 m/s. Dreef (2011) used a threshold of 1.39 m/s, based on an explanatory analysis of data. Figure 2.6 shows that this value (solid vertical line) is not an obvious cut-off point. More recently, McLaren *et al.* (2016) determined 2.5 m/s as the minimum flight speed, based on accelerometer measurements of the same GPS loggers as used in the current study. Based on the above-mentioned current velocity values, the maximum speed gulls can eventually reach during floating does not exceed the 2.5 m/s used by McLaren *et al.* (2016) as minimum flight speed. Moreover, speed measurements for a subset of data occurring above land in the Netherlands (i.e. excluding floating behaviour) for gulls from the colony at Texel, showed the majority of records occurring around 0 m/s. With increasing speed the number of records decreased steadily, to stabilize around 2.5 – 3 m/s. Very few records had a speed between approximately 2.5 m/s and 5.0 m/s (less than 0.1% of the records per 0.1 m/s speed class). Therefore, based on our own analysis and previous research by McLaren *et al.* (2016), we also used a minimum speed of 2,5 m/s for distinguishing flight from other behaviour.

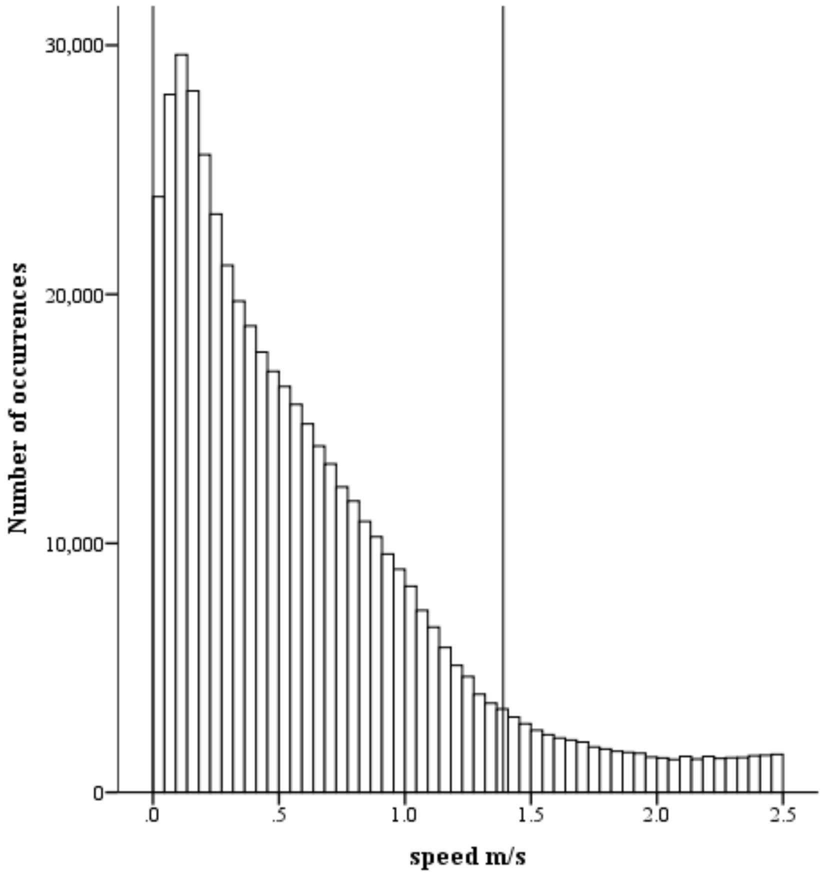

Figure 2.6 Frequency distribution (number of records) of speed measurements of Lesser Black-backed Gulls. Scale of speed limited to < 2.5 m/s. Vertical solid line is minimum flight speed of 1.39 m/s determined by Dreef (2011).

2.3 Analysis of wind farm area use

All the measurements left in the final dataset were plotted on a grid of 1x1 km, resulting in 6,170 grid cells in and around offshore wind farms, of which the Dutch wind farms OWEZ and PAWP, the Belgian wind farms Thornton Bank I, II and III and the English wind farm Greater Gabbard were included in the analyses. The parameters of these offshore wind farms are presented in table 2.1.

Table 2.1 Date of commission and physical parameters of Dutch, Belgian and English wind farms included in the analyses (country codes NL, B and UK, respectively).

wind farm	country	commission	number turbines	number turbines / km^2	closest distance to colony (km)	hub height (m)	rotor diameter (m)	tipheight (m)	lower tipheight (m)
OWEZ	NL	2007 Jan.	36	1,5	46	70	90	115	25
PAWP	NL	2008 July	60	3,5	55	59	80	99	19
Thornton Bank I	B	2009 May	6		28	94	126	157	31
Thornton Bank II	B	2013 Jan.	30	2,5	26	95	126	158	32
Thornton Bank III	B	2013 Sept.	18	2,6	26	95	126	158	32
Greater Gabbard	UK	2013 Aug.	140	1,0	25	77.5	107	131	24

Statistical analyses

The number of records was summed for each grid cell. The dataset consisted of 6,170 grid cells (1 x 1 km) with the number of records per grid cell calculated from GPS tracking data (resampled for one value per 5 minutes). Because of the high degree of collinearity among variables such as *water depth*, *distance to the coast* and *distance to the colony*, we selected in the final models only *distance to colony (km)* as a predictor. Moreover, the dataset contained a strong pattern of spatial autocorrelation (Moran's I of 0.23 with $p < 0.001$) and there was a strong spatial pattern in the residuals of the zero-inflated models without spatial autocorrelation. As the zero-inflated model cannot be simply expanded to include a correction for spatial autocorrelation, we constructed a separate model that takes into account the spatial dependence of bird distribution. However, these models could not be combined to include all countries together, likely due to the different spatial distributions of Lesser Black-backed Gulls relative to the offshore wind farms in the vicinity (see chapter 3.1). Namely, OWEZ and Prinses Amalia lay within the common foraging distribution of Lesser Black-backed Gulls, the Thornton Bank wind farms just at the edge of it, while Lesser Black-backed Gulls from Orford Ness forage mainly to the north of Greater Gabbard and not commonly in the direction of the wind farm.

Therefore, we constructed a zero-inflated model without spatial autocorrelation, using a checklist to select the most appropriate model. First, we checked whether the simplest model that might fit the data (Generalised Linear Model with Poisson distribution) was adequate: it was not due to the data being overdispersed (too many zeros, too many high values). Also a GLM with a quasi-poisson distribution did not properly account for overdispersion. A GLM with a negative binomial distribution adequately accounted for the overdispersion, but did not account for the overabundance of zeroes in the dataset. Therefore, we selected a zero-inflated model that consisted of two parts: structural zeroes were predicted using a binomial model and zeroes and positive numbers were drawn from a negative binomial distribution. In this model the predicted number of zeroes (1,541) adequately matched the actual number of zeroes (1,574). We used Z-tests to test the significance of predictors.

The statistical analyses were performed using R v3.4 (R Core Team 2013) with packages *lattice, pscl, ggplot2, boot, tidyr, MASS* en *nlme*.

2.4 Estimation of behavioural variables

In order to gain insight in eventual change in bird behaviour within wind farms, estimates were derived for various behavioural variables, inside and outside wind farms, as described below.

Based on measurements that were categorized as flight (see chapter 2.2.2), general estimates for flight speed and flight altitude were produced, as well as separately for during day and during the night. The **flight speed** measurements had a Poisson distribution, rather than a normal distribution. Therefore, we determined also median values besides mean values.

Besides changing their flight behaviour by adjusting flight speed and flight height, a behavioural response to wind farms may also comprise of using the wind farm area in another way, such as generally a different activity level during the night or a different level of flying activity inside wind farms.

Therefore, we compared the level of nocturnal activity and percentage of flying birds inside and outside wind farms. For these estimates both flight and non-flight data were used. **Nocturnal activity** was estimated based on the fraction of measurements in each grid cell that was recorded during the night, relative to the total number of measurements in that grid cell. This method of estimating nocturnal activity was not sensitive to the difference in logging intervals during day and night as only the fractions of night measurements were compared between grid cells within and outside wind farms.

Finally, we also determined **flying activity** by calculating the percentage of measurements indicating flying birds (speed > 2.5 m/s) during daylight and night relative to all measurements.

Statistical analyses
The effect of a wind farm on flight speed and flight altitude of Lesser Black-backed Gulls was tested in a Generalized Linear Model with a Gamma distribution. As described above ‘distance to the coast’ and ‘distance to the colony’ were correlated but in contrast to the analysis of wind farm use, we chose here to include distance to the coast in the analysis, as we expected that this could have more of an influence on

flight behaviour. Therefore, in the full model distance to the coastline was added as covariate, and daylight period (dawn, day, dusk, night) and whether or not within the wind farm as factors.

Finally, also an analysis on behaviour inside wind farms relative to around wind farms on the level of individual tracks was carried out for the wind farms OWEZ, Prinses Amalia and Thornton Bank, as turbine positions for these wind farms were readily available. Moreover, distances of bird positions relative to the wind turbines were also measured. As these analyses were carried out on the level of the individuals, and not in-between individuals, all measurements were used (i.e. no resampling for 5-minute intervals was carried out) and no other accuracy selection step was adapted than the one on GPS accuracy (i.e. excluding measurements with an accuracy lower than 22.3 m) leaving *135,288 records* in the database. Measurements were categorized based on their position to “within wind farm”, in “buffer zone” and “open sea”. The buffer zone was defined as the area three kilometres around wind farms. This zone width approximately corresponded with the width of the wind farms. Subsequent measurements within 10-minute time periods were connected to form tracks. The analysis focussed on tracks that crossed both the buffer zone and the wind farm and on eventual changes in behaviour within these tracks. In the analyses, speed and altitude were compared as continuous measurements and whether or not flying as nominal measurements. As the data was not normally distributed and in some cases the data within wind farms had a different distribution than outside the wind farm, most of these analyses were conducted with pairwise non-parametric tests. For the altitude measurements just outside and inside the wind farm a square-root transformation was applied to fulfil the requirements of a paired t-test. Altitude measurements with a negative value were excluded from this analysis.

2.5 Summary of selection steps and analyses

As our study had different aims (estimating behavioural variables and spatial distribution in offshore areas), we carried out several different selection procedures and corresponding analyses. Below, in table 2.2, we summarize which selection steps and datasets were used for the different analyses.

Table 2.2 Selection steps and datasets used for the different analyses presented in this report.

Analysis	chapter	selection steps	type measurements	# measurements	# individuals
wind farm area use	3.1.1-3.1.4	5 min. intervals; <22.3m GPS accuracy	grid cells	62,291 summed in 6,171 grid cells	115
control areas	3.1.5	5 min. intervals; <22.3m GPS accuracy	GPS point records	4,912	78
distance to turbines	3.1.6	<22.3m GPS accuracy	GPS point records	135,288	115
behavioural variables	3.2.1-3.2.4	5 min. intervals; <22.3m GPS accuracy; < 16m height accuracy; <1.22 speed accuracy	GPS point records	30,126	109
tracks	3.2.5	<22.3m GPS accuracy	tracks	1,934 records in 66 tracks	29

3 Results

This study focussed on GPS logger measurements of adult Lesser Black-backed Gull individuals within a 20 km zone around offshore wind farms, providing information on flight speeds and flight heights with a high-accuracy GPS position. After the selection procedures (see chapter 2.2), the final dataset contained 62,291 records with 5-minute intervals of 115 Lesser Black-backed Gull individuals and a relatively high GPS accuracy for the analysis of spatial distribution. The final dataset for the analysis of flight speed and flight height contained 30,126 records of 109 adult individuals. The loggers were functioning often for several years and thus based upon the yearly decisions of the birds to breed or not to breed the dataset could include both active breeders and non-breeders. Moreover, the loggers were functioning year-round, so data were collected both during and outside the breeding season. However, as NW-European Lesser Black-backed Gulls leave their breeding grounds during late summer and only come back at the end of March-early April (Gyimesi *et al.* 2011; Shamoun-Baranes 2017), 95% of the measurements around offshore wind farms in the southern North Sea were recorded in the period April-July and 99.9% in the period March-August. A paired analysis on the mean number of measurements per wind farm grid cell per month compared with the mean in grid cells in the open sea per month seemed to suggest that Lesser Black-backed Gulls occur relatively more often in wind farms in June, but the difference was not significant ($t_5 = 2.1$; $p > 0.08$). Hence, a further analysis on seasonal differences was not carried out.

In this chapter we first provide insights in the wind farm area use of Lesser Black-backed Gulls separately for the Netherlands, Belgium and the United Kingdom. In addition to a general description, a statistical analysis on spatial distribution, an analysis on the occurrence in wind farms relative to control areas and general observations on the distance gulls approach wind turbines are examined. In the second part of the results chapter behavioural differences inside wind farms relative to outside wind farms are analysed, based on general interpretations of all the data together and on the level of individual tracks.

3.1 Wind farm area use

In this chapter we describe wind farm area use by Lesser Black-backed Gulls first per country and then through a statistical analysis in combination for all wind farms. The effect of wind farms on the spatial distribution of gulls in offshore habitats was tested by dividing up the area within a 20 km zone around offshore wind farms in 1x1 km grid cells and summing the number of measurements per grid cell.

Below, the results of this spatial analysis are presented, respectively for the Dutch (OWEZ and Prinses Amalia), the Belgian (Thornton Bank wind farms) and the English wind farms (Greater Gabbard). The maximum distance measured from the colony where birds still occurred in a grid cell differed between the Dutch colony (79 km) and the Belgian and English colonies (respectively 65 and 66 km). Hence, all wind farms included in the analysis were theoretically in the range of the relevant colonies.

3.1.1 Dutch offshore wind farms

The longest data range was available from the Dutch colony on the island of Texel. The colony lies approximately 48 km and 57 km to the northeast from OWEZ and PAWP, respectively. In figure 3.1.1, it is clearly visible that the number of measurements decreases from northeast to southwest. Within the distribution of Lesser Black-backed Gulls certain “gaps” are noticeable, clearly within the boundaries of OWEZ and PAWP (see also figure 2.2).

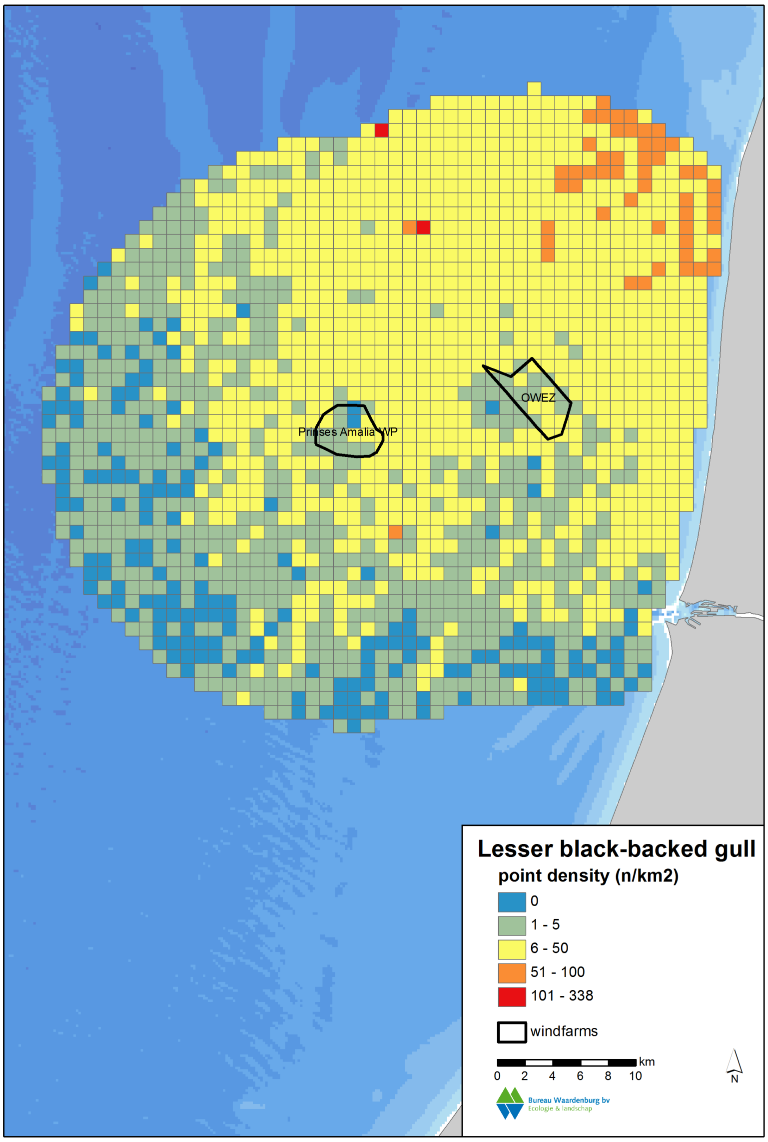

Figure 3.1.1 Number of records per grid cell (1 x 1 km) 20 km around the Dutch offshore wind farms PAWP and OWEZ of Lesser Black-backed Gulls equipped with a GPS logger in the colony of Texel (the Netherlands) from 2009 onwards.

The density of tracks along the wind farms seems to indicate that birds fly around the wind farms, namely around OWEZ, which lies both closer to the colony and the shoreline. Lesser Black-backed Gulls from birds seem to have a frequently visited “hotspot” southwest to the OWEZ wind farm, i.e. even farther from the colony than the wind farm itself.

3.1.2 Belgian offshore wind farms

The analysis on the data for the Belgian offshore wind farms focused on measurements from birds tagged in the colonies at Zeebrugge and Vlissingen from 2014 onwards, after the completion of Thornton Bank III. Although the original dataset contained measurements from earlier years, most of the data originated from 2014. Moreover, as Thornton Bank III is built around Thornton Bank I (western areas in figure 3.1.2), and Thornton Bank II (eastern area in figure 3.1.2) next to Thornton Bank I and II, during a timeframe of four years, the effects were impossible to be disentangled directly per windfarm and hence only overall effects were measured from 2014 onwards. The colony at Zeebrugge, providing most of the data in the Belgian wind farms, lies approximately 28 km to the east from the Thornton Bank wind farms. It is clearly visible in figure 3.1.2 that the number of measurements decreases with the distance from the coast. The majority of the measurements occurred within 30 km from the coast, and thus roughly up to the boundaries of the Thornton Bank wind farms. Although, still a considerable number of the measurements were recorded farther offshore, with a maximum distance of 65 km from the colony, Lesser Black-backed Gulls visited the Belwind wind farm and its surroundings (at ca. 46 km from the coast) only sporadically (figure 3.1.2) and hence this wind farm was not included in the further analyses.

The maximum number of measurements per grid cell (i.e. 97) within the Thornton Bank wind farms was much higher than in any other wind farm analysed in this report, probably due to the closer distance to the colony. However, such a high number of measurements occurred only in one grid cell. The second highest value was 16 measurements in a grid cell and all the rest below 5 measurements per grid cell. Moreover, similarly to the Dutch offshore wind farms, the rest of the area of the Thornton Bank wind farms was hardly utilized by Lesser Black-backed Gulls, while offshore areas “behind” the wind farms, and thus even farther from the colony, were more often visited.

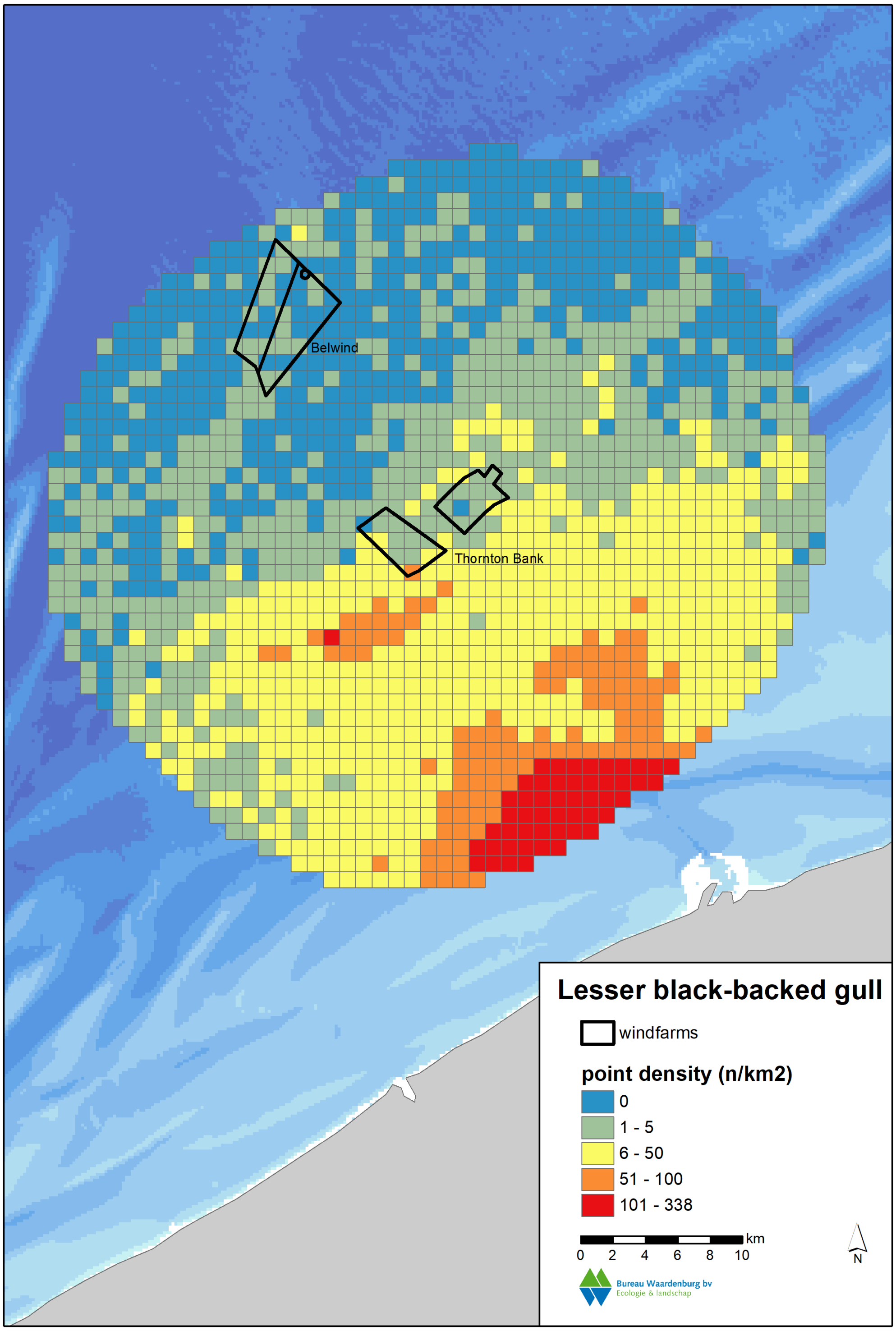

Figure 3.1.2 Number of records per grid cell (1 x 1 km) 20 km around the Belgian offshore wind farms of Lesser Black-backed Gulls equipped with a GPS logger in the colony of Zeebrugge (Belgium) and Vlissingen (the Netherlands). Records are from 2014 onwards. In the analyses only the Thornton Bank windfarms were included.

3.1.3 English offshore wind farms

Lesser Black-backed Gulls equipped with a GPS logger in the English colony at Orford Ness frequented offshore areas mainly to the southeast of the colony, to a maximum distance of 66 km. In that direction the offshore wind farm Greater Gabbard at a distance of approximately 33 km lies in the reach of the gulls. Other offshore wind farms that lie to the east or south of the colony, like London Array and Thanet, were only sporadically visited. Therefore, data analysis was limited to the Greater Gabbard wind farm.

The majority of the data from the Orford Ness colony was collected in 2010 and 2011. Although the wind farm was only fully commissioned in the summer of 2013, in 2011 April 109 of the 140 turbines were already installed. In order to include as much data as possible, the analysis focused on measurements from 2011 onwards, when most of the turbines were already installed.

In figure 3.1.3 it is clearly visible that most of the measurements occurred in the northern part of the study area, less in and around Greater Gabbard but again a substantial amount farther offshore, “behind” the wind farm, with a maximum distance of 66 km from the colony. Within this spatial distribution certain “gaps” are noticeable, similarly to the other offshore wind farms, also the area of the Greater Gabbard wind farms was hardly utilized by Lesser Black-backed Gulls, despite the fact that offshore areas “behind” the wind farms, and thus even farther from the colony, were still frequently visited.

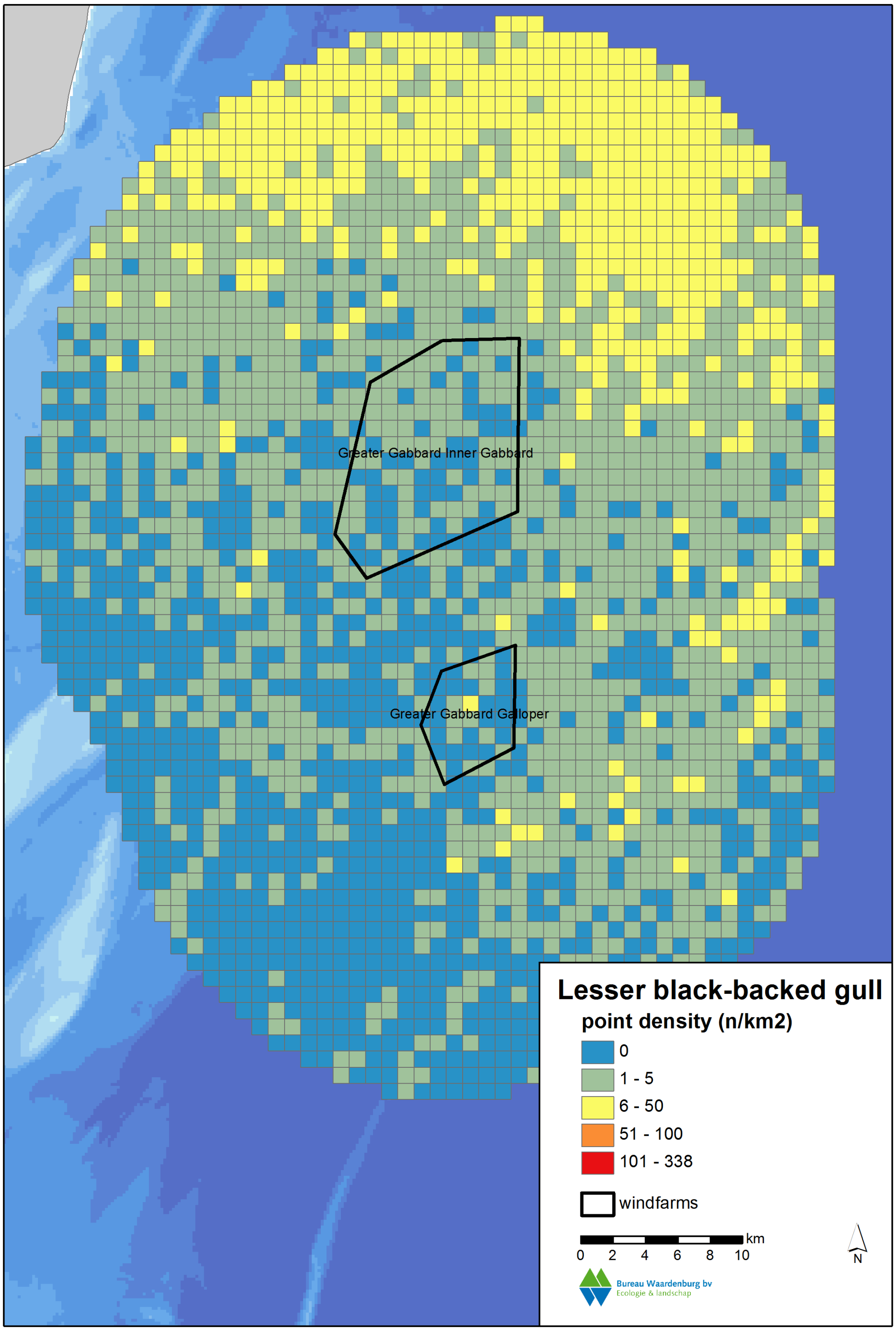

Figure 3.1.3 Selected data 20 km around the English offshore wind farm Greater Gabbard of Lesser Black-backed Gulls equipped with a GPS logger in the colony of Orford Ness (England). Records are included from 2011 onwards.

3.1.4 Statistical analysis

The effect of the presence of a wind farm on the spatial distribution of Lesser Black-backed Gulls was analysed with a dataset of measurements 20 km around offshore wind farms. The analysis was carried out based on the number of measurements within 6,170 grid cells, of which 205 fell within the boundaries of the studied offshore wind farms. The average number of measurements per grid cell was only 2.3 within wind farms against 9.7 outside wind farms. Moreover, there were relatively more cells within wind farms completely avoided than outside wind farms: 35% of the grid cells within wind farms had a value of 0, against 25% of grid cells outside wind farms, even though these latter also included grid cells very far from the colony and the coast, where due to a pure distance effect less birds occur.

Zero-inflated model without spatial autocorrelation

(a) Distance to wind farm (km)

The distance to the wind farm significantly affected the number of GPS measurements of Lesser Black-backed Gulls per grid cell, both in the binomial ($P = 0.002$) as well as in the negative binomial part of the model ($p < 0.001$). The strength of this effect varied among countries. In both model parts the distance to the colony was a strong predictor ($p < 0.001$) as well.

(b) Occurrence in wind farm (yes or no)

The number of GPS measurements was lower in wind farms ($p < 0.05$) than outside wind farms, but only in the count model and not in the binomial part ($p > 0.7$): the location of a grid cell within a wind farm or not could not predict whether the cell had a 0 value or not, but the location did have an effect on the actual value of the cell. Besides the ones within the wind farm there were numerous other grid cells with zero values, namely farther away from the colony. This is also highlighted by the significant effect the *distance to the colony* in both model parts ($p < 0.001$). The effect of wind farm varied also in this model among countries.

Difference between wind farms

As described above, offshore wind farms seem to be largely underused by Lesser Black-backed Gulls relative to the surrounding areas. In the analysis, an in-between difference among wind farms was also detected but this was largely due to the high number of observations within the Thornton Bank wind farms. As pointed out in chapter 3.1.2, this large number of records in Thornton Bank was caused by one grid cell with 97 observations. If we would ignore this one cell, the rest of the measurements were not different among the wind farms. In figure 3.1.4 it is clearly visible that the median number of measurements within all wind farms is lower than five. These values were on average 17% - 72% lower per wind farm compared with the number of measurements per grid cell outside wind farms (i.e. considering all grid cells, even those very far from the colony and the coast). Regarding these differences, it is especially interesting that within PAWP, in which the turbines are positioned closer to each other than in other wind farms, the number of measurements per grid cell within the wind farm was not lower than in the other wind farms (figure 3.1.4).

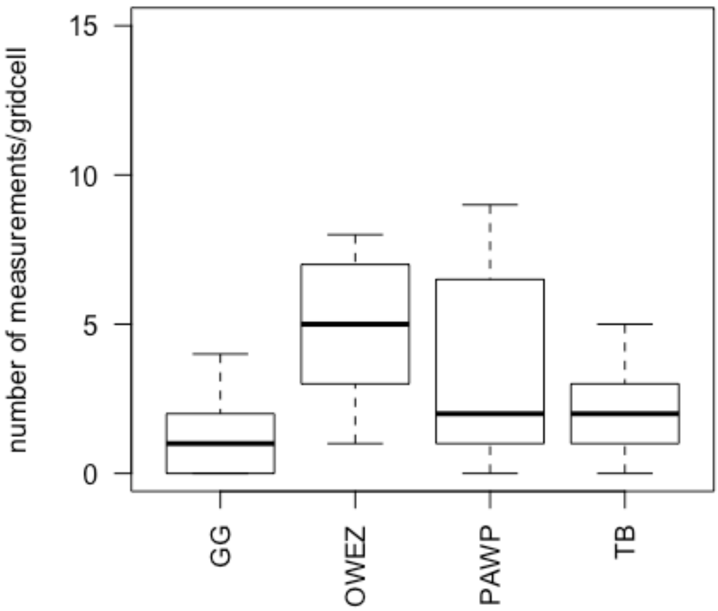

Figure 3.1.4 Number of measurements of Lesser Black-backed Gulls per grid cell within wind farms. Bold horizontal lines provide medians, boxes 25 and 75% percentiles, T-bars roughly a 95% confidence interval. GG = Greater Gabbard; TB = Thornton Bank wind farms).

3.1.5 Analysis of control areas

In addition to the statistical analysis, a spatial analysis was also carried out by using control areas on two sides of the wind farms lying at the same distance from the colony as the wind farm itself. These control areas had the same shape and surface area, as the wind farm area, and hence the numbers of records within these control areas could be directly compared with the number of records within the wind farms.

This analysis clearly showed that areas around the wind farms were much more frequented than the wind farms themselves (figure 3.1.5). The number of records within the wind farms was 39% (Thornton Bank) to 88% (OWEZ) lower than the mean number of records in the two control areas of the wind farms. In other words, 39 to 88% less records occurred within the boundaries of the wind farms than on average in the control areas. Taking the different number of measurements per wind farm into account, the number of records was in wind farms altogether **70%** lower than in the control areas. This measure is representative of the so-called *macro-avoidance* of wind farms.

Interestingly, the number of individuals crossing the wind farm areas (mean per windfarm = 14.4 ± 5.1SD) was not significantly lower compared with to the number of individuals occurring in the control areas (mean per control area = 16.4 ± 4.4SD;

paired t-test per windfarm: $t_4 = 0.9$; $p > 0.4$). Hence, wind farm attendance was not dependent on a few individuals, but on a comparable number of individuals as in the surroundings, only they visited wind farm areas less often (paired t-test per windfarm: $t_4 = 3.2$; $p < 0.05$). Lesser Black-backed Gull individuals occurred in any of the wind farm areas on 133 different days, whereas control areas were visited on 329 different days. An analysis on the time duration of individual tracks in the wind farms presented in chapter 3.2.5 revealed that gulls also spent less time within the windfarms compared with the surroundings.

The reduction in the number of measurements within the wind farms was in the case of Greater Gabbard (81%) comparable with that of OWEZ and in the case of Prinses Amalia (39%) with that of Thornton Bank. The difference in between the two pairs of wind farms is large but the only similarity between these wind farms seems to be that Prinses Amalia and Thornton Bank have a higher density on wind turbines than OWEZ and Greater Gabbard.

Moreover, except for Thornton Bank, for all other wind farms more measurements occurred in a control area (with the same surface area as the wind farm) ‘behind’ the wind farm (i.e. relative to the position of the colony) than in the respective wind farm. In other words, nearly all areas around wind farms, irrespective of the distance to the colony, were more often used than the wind farm area itself. Therefore, this spatial analysis also underlines that wind farm areas are relatively underused by Lesser Black-backed Gulls.

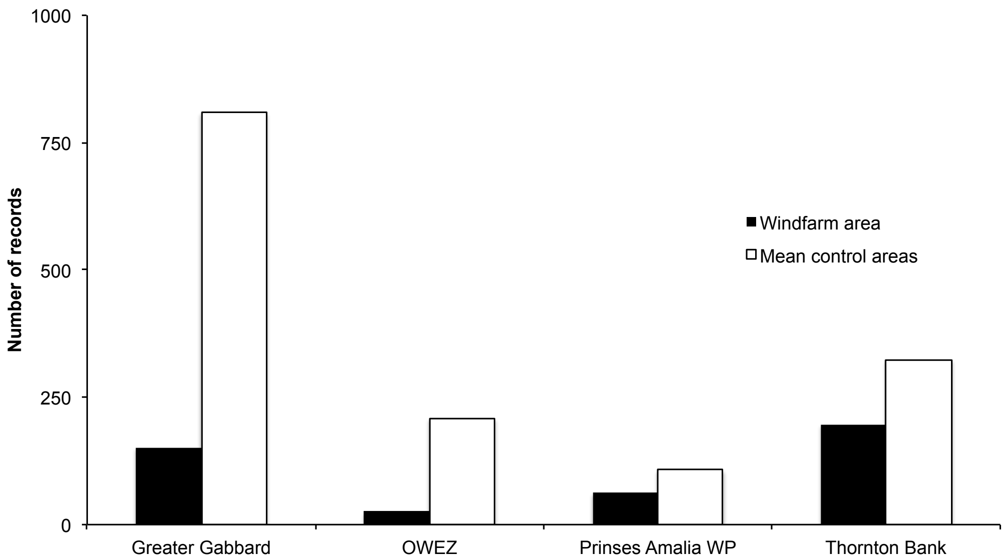

Figure 3.1.5 Number of records within wind farms and in control areas around the wind farms, with the same shape and surface area. Only measurements with 5-minute intervals are included.

3.1.6 Distance to windturbines

Besides the general effect of wind farms on the distribution of Lesser Black-backed Gulls, we could also carry out an analysis on the distances of birds to the nearest wind turbines in the wind farms OWEZ, PAWP and Thornton Bank.

For this analysis, all measurements were used with a GPS accuracy < 22.3 m, thus not only the ones resampled to 5-minute intervals, as the effect of an individual was irrelevant. Based on around 300 records per wind farm, we can conclude that at the moment of measurement only 16 individuals were within 100 m of a wind turbine. Of these only 5 *flying* individuals approached wind turbines to within rotor distance (i.e. considering explicitly the rotor diameters per wind farm, see table 2.1), resulting in 6 measurements in flight within Thornton Bank and 3 measurements in flight within OWEZ, but none in PAWP (table 3.1.1). Thus, altogether 9 of the 886 measurements within the wind farms in the Netherlands and Belgium occurred within the reach of the rotors of the turbines. That translates to 1% of all measurements within the three wind farms together. In other words, 99% of all the measurements within the wind farms occurred too far from the turbines to form a risk for collisions. This measure could give an indication of the so-called *micro-avoidance* of individual wind turbines. Moreover, only 3 of these birds seemed to fly at rotor height, the rest below the rotor-swept zone, thus the above figures can be considered as a worst-case scenario. In Thornton Bank the birds seemed to approach wind turbines to closer distances than in the other wind farms (table 3.1.1). In contrast to other wind farms, turbines of Thornton Bank have jacket foundations where Lesser Black-backed Gulls and other gulls species are known to regularly rest and forage (Vanermen, N. *et al.* 2017).

Considering that in wind farms 70% less records were found than in control areas (see chapter 3.1.5), the *overall avoidance* for Lesser Black-backed Gulls can be calculated at 99.7%. Nevertheless, it has to be noted that this calculation relies on the actually measured GPS positions, and we have no information on how close birds approached wind turbines in between two measurements. If measurements were spread randomly within the wind farm area, the chance was much smaller that a GPS measurement would occur within the rotor-swept zone, as the rotor-swept zone is small relative to the total wind farm area. However, measurements are not spread randomly due to conscious avoidance, and hence 1% of measurements within the rotor-swept zone (see above) has to be considered as a minimum.

The distances to wind turbines were generally larger during the night (table 3.1.1). However, the number of measurements during the night was much smaller, also due to settings of the GPS loggers (see chapter 2.1). Only one measurement of a flying bird was recorded within the rotor-swept zone during the night. Mostly, non-flying birds, which could comprise of birds floating on water or birds at the foot of the turbines, approached wind turbines to closer distances than flying birds (table 3.1.1). However, these birds were due to their position naturally out of reach of the blades.

Table 3.1.1 Minimum distances (m) to wind turbines and in brackets their mean measurement errors (m) of Lesser Black-backed Gull positions within OWEZ, PAWP and Thornton Bank (TB) in flight and non-flight both during day and night. All measurements with a GPS accuracy < 22.3 m are included, n = refers to the number of measurements available per windfarm. The rotor radius per wind farm provides the distance within which birds might collide with blades.

	rotor radius (m)	n =	day		night	
			non-flying	flying	non-flying	flying
OWEZ	45	304	64 (±19)	32 (±9)	19 (±9)	54 (±14)
PAWP	40	275	26 (±9)	49 (±4)	89 (±10)	100 (±10)
TB	63	307	0 (±5)	8 (±10)	107 (±5)	122 (±5)

3.2 Behaviour within offshore wind farms

Besides the number of measurements occurring within or outside wind farms, this study also intended to investigate whether Lesser Black-backed Gulls change their behaviour within wind farms relative to areas without wind farms. One of the aims of these analyses was to test whether mean values of behavioural variables in offshore areas used in collision risk models, such as the Band model, should be adjusted. Therefore all data outside wind farms was used, as a description of the general behaviour, compared with measurements within wind farms. As described in chapter 3.1, a large avoidance effect of offshore wind farms was detected. Consequently, out of the 30,126 measurements within the dataset, only 224 occurred within wind farms. From these measurements, only 60 were in flight, of which only two during the night. Therefore, one has to bear in mind that below analyses are based upon a rather limited the dataset.

3.2.1 Flight speed

Within vs. outside wind farms

The first preliminary analysis on speed measurements (i.e. including also non-flight behaviour) seemed to point towards a lower recorded speed within wind farms relative to outside wind farms (figure 3.2.1). In an offshore habitat this could indicate relatively more inactive (e.g. floating) birds inside wind farms, and this will be examined in chapter 3.2.3. Here we will further concentrate explicitly on speeds recorded in flight within wind farms.

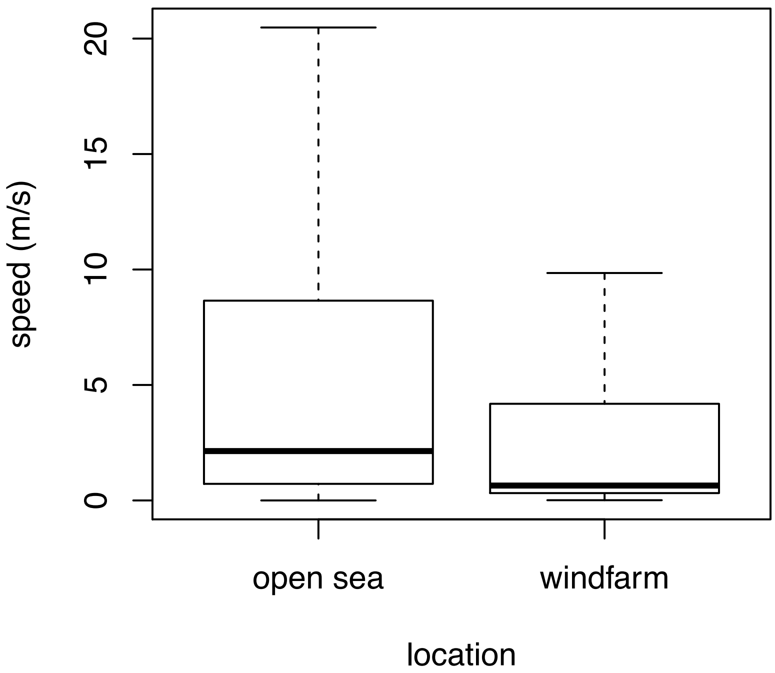

Figure 3.2.1 Speed (m/s) of Lesser Black-backed Gulls (including also non-flight behaviour) outside and inside wind farms. Bold horizontal lines provide medians, boxes 25 and 75% percentiles, T-bars roughly a 95% confidence interval.

After **excluding non-flight behaviour** (i.e. <2.5 m/s), gulls seemed to fly faster through wind farms than their average speed outside wind farms. However, the median flight speed outside wind farms was remarkably low and inside wind farms more resembled the expected flight speeds (9.4 m/s; Gyimesi, A. *et al.* 2017). A further analysis on the **frequency distribution of flight speeds** revealed that *outside wind farms* a considerable peak occurred between speeds of 3.5 m/s and 5 m/s: 17% of the data fell within this speed range (figure 3.2.2). In contrast, *within wind farms*, only 8% of the data occurred within this range (figure 3.2.2). Lesser Black-backed Gulls frequently follow fishing trawlers at sea that commonly have a speed around 3.5 m/s (Camphuysen, C. J. 1995), which could clarify the peak in speed measurements around this value *outside* wind farms. On the other hand, fishing trawlers are either not allowed to enter wind farms or fishermen are not willing to enter due to safety reasons, which could clarify the lack of a peak at speeds around 3.5 m/s *within* wind farms.

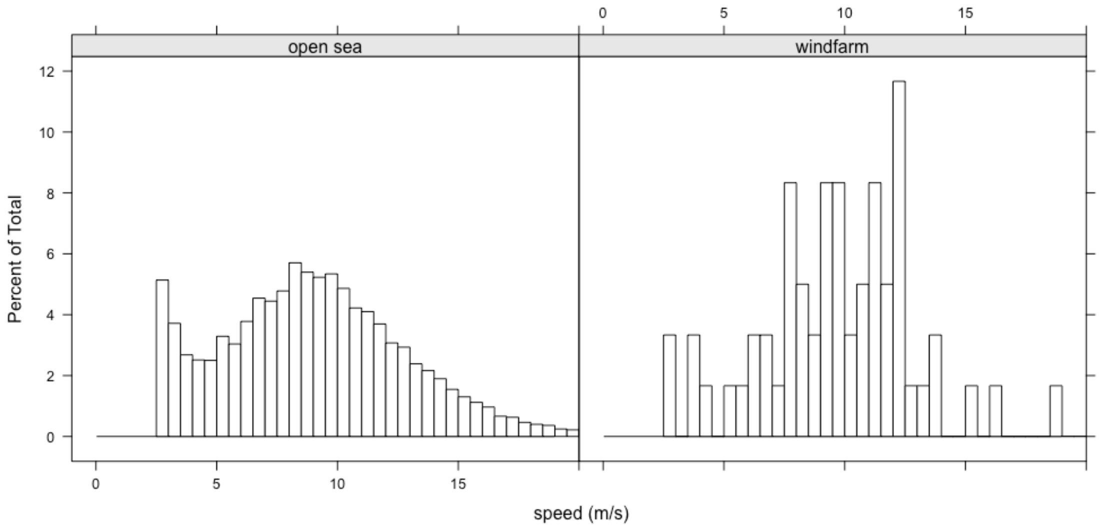

Figure 3.2.2 Frequency distribution of flight speed (i.e. > 2.5 m/s) measurements (m/s) of Lesser Black-backed Gulls recorded by the GPS loggers outside (left panel) and inside wind farms (right panel).

In order to analyse the true travel speed of Lesser Black-backed Gulls inside and outside wind farms, i.e. **excluding birds after fishing trawlers**, the flight speed analysis was carried out on a data subset with speed measurements above 3.5 m/s (n = 58). These remaining speed measurements had a comparable median of 9.9 m/s and 9.3 m/s respectively inside and outside wind farms, and also the distribution of the data was similar (figure 3.2.3).

Statistical analysis

A statistical analysis on this dataset, which included in addition to the effect of the presence of a wind farm also other factors such as distance to the colony, distance to the shore and altitude, did not detect a significant difference between flight speeds inside and outside wind farms ($p > 0.2$). Nevertheless, period of the day did affect flight speed, which will be discussed in chapter 3.2.4. Also a comparison of speed measurements within the wind farms and in control areas (see chapter 3.1.5) showed no significant difference ($F_{5, 27} = 1.4$; $p > 0.2$).

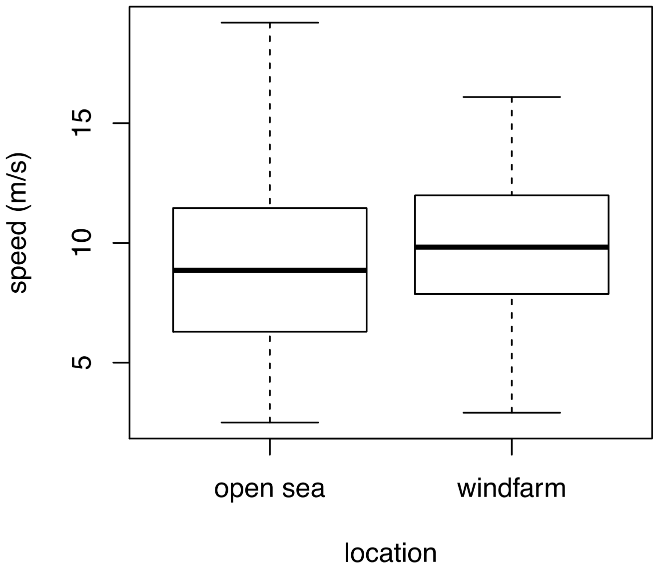

Figure 3.2.3 Flight speed (m/s) of Lesser Black-backed Gulls above 3.5 m/s recorded by the GPS loggers outside and inside wind farms. Bold horizontal lines provide medians, boxes 25 and 75% percentiles, T-bars roughly a 95% confidence interval.

3.2.2 Flight altitude

Comparably to the flight speed within and outside wind farms, also flight altitude was analysed. Generally speaking, altitude measurements have a lower accuracy than speed measurements (Bouten *et al.* 2013). Therefore, based on the accuracy values produced by the loggers themselves, we limited our analysis to measurements with an accuracy better than 16 m, and hence to a reasonably reliable dataset. For the analysis of flight altitude evidently only measurements in flight, i.e. speed > 2.5 m/s, were used. Based on the results of the flight speed analysis, the flight altitude analysis was also further limited to data with flight speed > 3.5 m/s.

Within OWEZ and Greater Gabbard, most of the birds flew below rotor height, and the fractions at rotor height were highly similar (table 3.2.1). The fraction of flying birds was also in PAWP the highest below rotor height. However, relatively more birds flew at rotor height. Moreover, in the Belgian Thornton Bank wind farms even more birds occurred at rotor height within the boundaries of the wind farm than below. Note that the sample sizes per wind farm are fairly low (table 3.2.1).

Statistical analysis

The statistical analysis of flight altitudes showed no significant difference ($p > 0.9$) between measurements within and outside wind farms (figure 3.2.4). Therefore, based on the limited number of measurements within wind farms it cannot be concluded that Lesser Black-backed Gulls would adjust their flight height once entering a wind farm. The analysis did reveal a significant effect of period of day (see chapter 3.2.4) and of distance to the coast (both $p < 0.0001$). Previously, it was shown that birds above land fly higher (Gyimesi, A. *et al.* 2017), which could cause that birds closer to the coast still fly higher than farther away (figure 3.2.5). Also a comparison of altitude measurements within the wind farms and in control areas (see chapter 3.1.5) showed no significant difference ($F_{5, 60}$ = 1.2; $p > 0.2$).

Table 3.2.1 Frequency distribution of flight altitudes (m) of Lesser Black-backed Gulls with a speed > 3.5 m/s recorded by the GPS loggers inside wind farms relative to the rotor height. The Belgian Thornton Bank wind farms were pulled together due to nearly identical lower tip heights (i.e. 31 and 32 m).

	lower tip height (m)	upper tip height (m)	fractions relative to rotor height below	at	above	n =
Greater Gabbard	24	131	75%	17%	8%	12
OWEZ	25	115	82%	18%	0%	11
PAWP	19	99	50%	38%	12%	8
Thornton Banks	32	158	38%	58%	4%	26
mean			**61%**	**33%**	**6%**	**57**

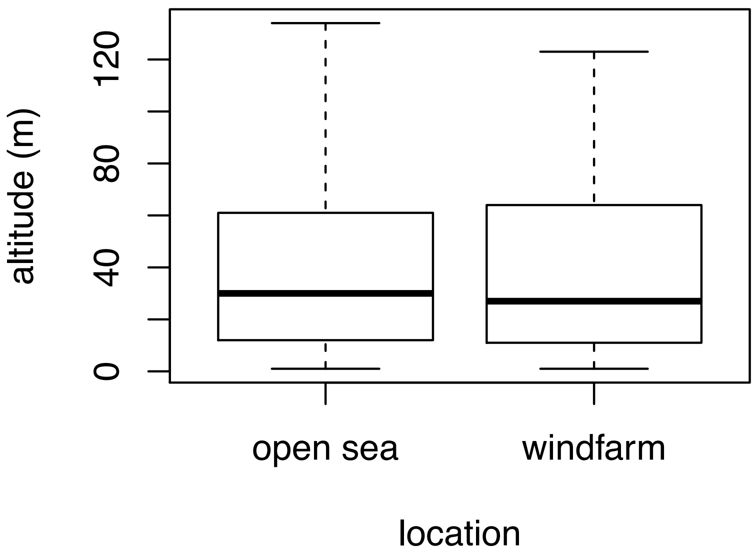

Figure 3.2.4 Flight altitude (m) of Lesser Black-backed Gulls above 3.5 m/s recorded by the GPS loggers outside and inside wind farms. Bold horizontal lines provide medians, boxes 25 and 75% percentiles, T-bars roughly a 95% confidence interval.

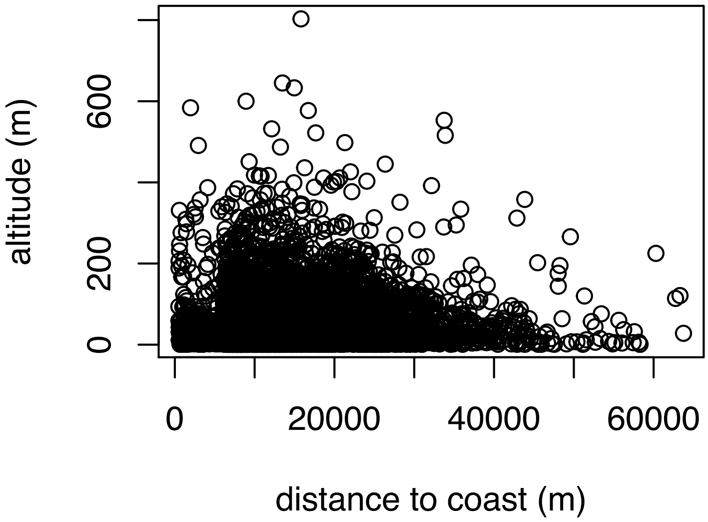

Figure 3.2.5 Flight altitude (m) of Lesser Black-backed Gulls relative to the distance to the coast, recorded by GPS loggers. Only data points with a speed > 3.5 m/s were included. Due to the selection of grid cells 20 km around wind farms, the minimum distance to the coast was 5 km for Greater Gabbard and 7 km for Thornton Bank, resulting in an increasing amount of measurements at those distances.

3.2.3 Percentage of flying

In the previous chapters we discussed the speed and altitude of birds in flight. Besides birds adjusting their flight behaviour, it might also be possible that Lesser Black-backed Gulls use wind farm areas in another way than the open sea, for instance by resting here more. The data exploration of percentage of flying birds within wind farms concerns birds either resting at the foundations of wind turbines, floating on the water or flying, based on in total 412 records.

Considering all measurements, birds inside wind farms seemed to spend approximately the same amount of time inactive (i.e. speed < 2.5 m/s) as outside wind farms: 44% against 51%, respectively. Of these there were only 33 measurements (8% of all measurements) within 5 m of the wind turbines, suggesting that inactive birds within windfarms were mainly floating on the water rather than resting at the turbine foundations. However, there was a considerable variation among wind farms, with 80% of the measurements in Greater Gabbard concerning flying birds but only 19% in the Thornton Bank wind farms and the other wind farms in between these extremes. These differences may occur due to gulls using the wind farms in a different way. For instance, birds have been observed in Thornton Bank regularly resting and foraging on the jacket foundations of the turbines (Vanermen, N. *et al.* 2017), whereas Greater Gabbard seems not to be part of the regular foraging range (see figure 3.1.3), and hence could be crossed predominantly during commuting.

Also a comparison of percentage of birds in flight within wind farms and the control areas around the wind farm did not show a general pattern of that Lesser Black-backed Gulls behaving in a different way in wind farms than outside (table 3.2.2).

However, the large variation among wind farms was also in this analysis obvious. In three of the four wind farms the percentage of measurements in flight was lower within the wind farms than in the control areas, but in Greater Gabbard it was just the opposite (table 3.2.2). All in all, the variation among wind farms is rather large to draw hard conclusions (see also chapter 3.2.5).

Table 3.2.2 Percentage of Lesser Black-backed Gulls in flight within wind farms and their control areas (see chapter 3.1.5) with the same shape and at the same distance from the colony as the wind farm.

	percentage in flight		
	control areas		WP
	left	right	area
Greater Gabbard	47	54	80
OWEZ	44	49	38
Prinses Amalia	40	52	38
Thornton Bank	38	51	19
mean	40	53	44

3.2.4 Nocturnal activity

Finally, we also compared nocturnal activity among grid cells within and outside wind farms. Comparably to the percentage of flying birds, also **this analysis could not reveal clear differences in nocturnal activity between areas inside and outside wind farms** (figure 3.2.6). However, while in three of the wind farms a few per cent (3% - 6%) less measurements per grid cell occurred within wind farms than outside wind farms during the night, within Thornton Bank the nocturnal activity was ca. 15% higher than outside the wind farm area. As logging interval could be different during the day and during the night (i.e. usually lower during the night to save battery power), the values presented in figure 3.2.6 should not be interpreted as the actual nocturnal activity.

In addition to the general nocturnal activity levels described above, in previous chapters we have referred to significant effects of ‘period of day’ both on flight speed and flight altitude. In other words, Lesser Black-backed Gulls did generally change their flight behaviour during the night, only not in a different way inside and outside wind farms: both mean **flight speeds and flight altitudes were lower during the night** compared with other periods during the day (figures 3.2.7 and 3.2.8). Consequently, although the nocturnal activity level of Lesser Black-backed Gulls within wind farms seems not to diverge from outside wind farms, their collision risks are different due to a lower flight speed and lower flight altitude (cf. Ross-Smith *et al.* 2016).

Moreover, not only did the flight behaviour change during the night, also **flight activity in general decreased during the night**. As described in chapter 3.2.3, outside wind farms 52% of Lesser Black-backed Gulls were recorded in non-flight behaviour. However, splitting that up to different periods of the day reveals that during the daylight period only 48% of the birds was inactive outside wind farms, against 91% during the night. This latter value was hardly different within wind farms (i.e. 87%), again suggesting that birds do not behave in a different way within wind farms, but general patterns can be detected in their behaviour.

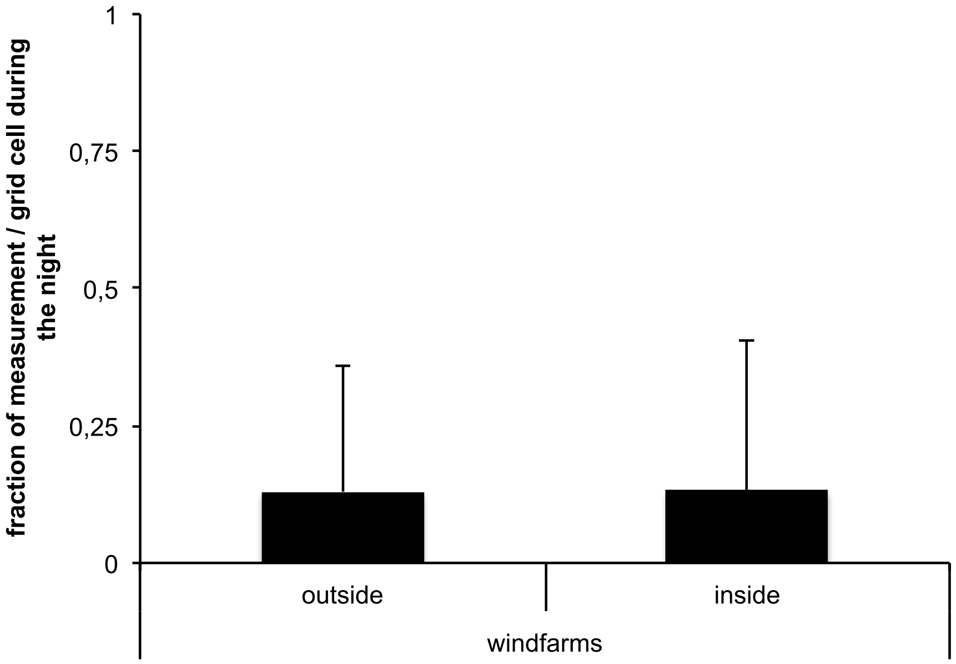

Figure 3.2.6 Fraction of measurements of Lesser Black-backed Gulls recorded during the night in grid cells outside and inside wind farms, relative to all the measurements in the same grid cells. Bars provide means, error bars standard deviations.

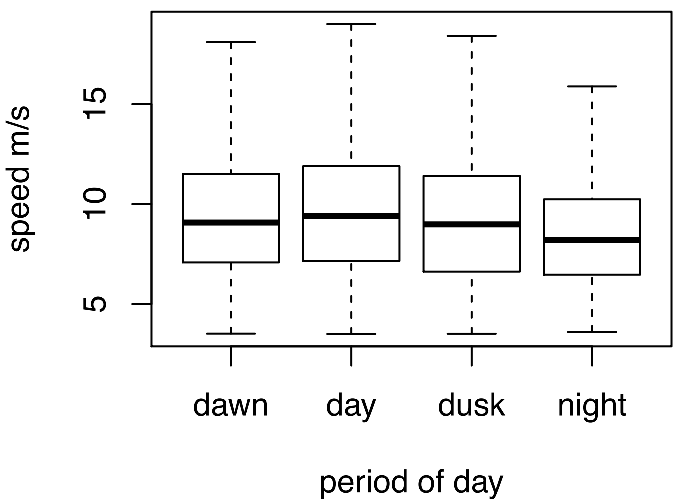

Figure 3.2.7 Flight speeds (m/s) of Lesser Black-backed Gulls above 3.5 m/s recorded by the GPS loggers during different periods of the day. Bold horizontal lines provide medians, boxes 25 and 75% percentiles, T-bars roughly a 95% confidence interval.

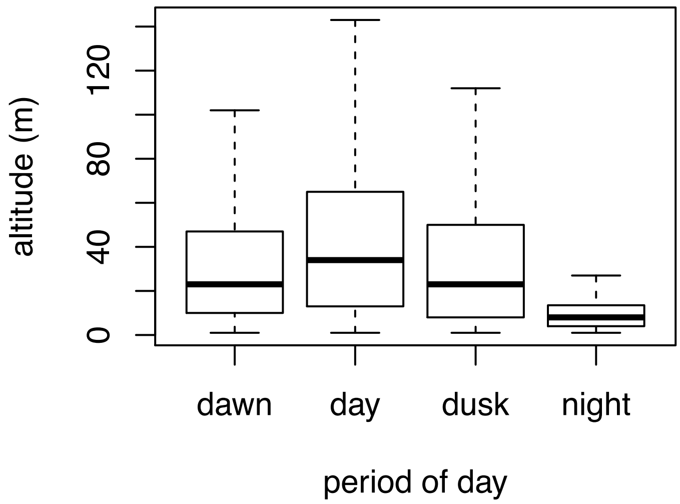

Figure 3.2.8 Flight altitudes (m) of Lesser Black-backed Gulls above 3.5 m/s recorded by the GPS loggers during different periods of the day. Bold horizontal lines provide medians, boxes 25 and 75% percentiles, T-bars roughly a 95% confidence interval.

3.2.5 Track analysis

Measurements were categorized based on their position to “within wind farm”, in “buffer zone” and “open sea” (see also chapter 2.4 in Methods). The buffer zone was defined as the area three kilometres around wind farms. This zone width approximately corresponded with the width of the wind farms. In total 66 tracks of 29 individuals were identified that comprised of measurements both within a wind farm (i.e. 34 in OWEZ, 17 in Prinses Amalia and 15 in Thornton Bank) and in the buffer zone around it (see figures in Appendix). The number of measurements within the tracks also underlines that Lesser Black-backed Gulls spent more time in the buffer zone than in the wind farm area: 417 measurements occurred within the wind farm, while 1,517 measurements in the buffer zone, considering the same tracks. Moreover, of the 66 tracks nearly the half had only one measurement within the wind farm, while in the buffer zone this was the case for only 6% of the tracks. All the maps of the tracks of the three wind farms, separately for the different flight variables, are included in the Appendix. All the below analyses were conducted pairwise, i.e. segments or point measurements of the same track were compared within the wind farm with outside the wind farm.

Flight behaviour

A first visual examination of the tracks through the wind farms revealed a few cases when Lesser Black-backed Gulls abruptly stopped flying as soon as they entered a wind farm (see e.g. figure 7.1.2 in the Appendix). In order to test the hypothesis that birds could lower their flight activity within the wind farms to avoid collisions, first a general comparison was conducted of the fraction of measurements in flight inside the wind farm relative to the buffer zone within the same track.

The analysis provided no evidence for the hypothesis: within the wind farms 74% of the measurements was in flight, while 60% of the measurements of the same tracks was in flight in the buffer zone. Comparing these fractions within the tracks, only in 26% of the tracks was the fraction of measurements in flight higher in the buffer zone than in the wind farm. In another 23% of the tracks was the fraction of measurements in flight equal inside the wind farm and in the buffer zone. Consequently, for 51% of the tracks the fraction of measurements in flight was higher in the wind farm than in the buffer zone.

Flight speed

Due to the higher flight activity within wind farms, also the average speed of measurements was higher in the wind farms than in the buffer zone within the same track. However, when considering only measurements in flight (i.e. >2.5 m/s), the mean flight speed of measurements within the same track was comparable inside wind farms (9.8 m/s ± 2.8SD) and in the buffer zone (9.6 m/s ± 3.0SD). Also a statistical comparison showed no significant difference in speed between segments of the same track within the wind farm and in the buffer zone (Wilcoxon signed rank test; $p > 0.2$). In other words, when birds were flying, they did not seem to change their flight speed after entering a wind farm, which could for instance happen if the birds intended to cross the wind farm area quickly.

Flight altitude

Corresponding to the previous comparisons, due to the higher flight activity, also the mean altitude was higher in wind farms than in the buffer zones within the same tracks. However, when considering only measurements in flight (i.e. >2.5 m/s of 61 tracks), the mean flight altitude of measurements within the same track was comparable inside wind farms (42 m ± 45SD) and in the buffer zone (38 m ± 45SD). Of these tracks also the ones that according to the flight altitude were approximately at rotor height (25 – 100 m) did not considerably change their flight altitude (53 m mean flight altitude in buffer zone vs. 55 m in wind farm). Also a statistical comparison showed no significant difference in flight altitude between segments of the same track within the wind farm and in the buffer zone (Wilcoxon signed rank test; $p > 0.6$).

Changes along wind farm borders

The analyses mentioned above focussed on average values of transects in the wind farm and in the buffer zone within the same track of the same individual. In order to analyse whether sudden changes would take place along the border of the wind farms that are masked by average values, we compared in pairwise analyses subsequent measurements of just outside the wind farm and just inside the wind farm. For these analyses all the above-mentioned variables were tested, but none of the tests showed a significant difference between within the wind farm measurements with outside the wind farm measurements. In other words, we found no evidence that the chance that a bird is flying or floating would be different (McNemar-test; $p > 0.1$), the flight speed would be different (Wilcoxon signed rank test; $p > 0.2$), or the flight altitude would be different (paired-$t_{107=}1.0$; $p > 0.3$). An extra control was carried out on a subset of the data, to see whether a difference occurred when birds entered a wind farm (i.e. excluding data when birds left the wind farm). Nonetheless, this was not the case either (both speed and altitude $p > 0.1$).

Spatial distribution within wind farms

In addition to the analysis on behavioural parameters, a visual analysis is conducted on how far birds enter a wind farm, relative to the outer border of the wind farm. The wind farms OWEZ and Thornton Bank have a block design, with approximately four lines of turbines along the widest width (see figures in the Appendix). The area in-between the two outer lines we considered as the edge zone of the wind farm and in-between the two inner lines as the centre zone. Contrastingly, Prinses Amalia has a round shape, but also approximately four lines (circles) of turbines. Consequently, the number of tracks was summed in the inner half (centre zone) and outer half (edge zone; table 3.2.3) of the wind farms. Note that tracks evolved by connecting subsequent GPS measurements with a straight line, and hence the lines of the tracks can pass through areas where birds not necessarily occurred if they did not fly in a straight line. Nevertheless, there was no obvious difference in the number of birds crossing the centre of wind farms and the outer zone of the wind farms. Even in Prinses Amalia, with the highest density of wind turbines, approximately half of the tracks crossed the inner half of the wind farm.

Table 3.2.3 Percentage of Lesser Black-backed Gulls tracks through the centre- (inner half) or edge zone (outer half) of wind farms.

	centre zone	edge zone
OWEZ	62	38
Prinses Amalia	53	47
Thornton Bank	40	60

Time spent in wind farms

Based on the tracks crossing the wind farms, it could be calculated how much time birds approximately spent within the boundaries of the wind farms. Note that these calculations are based on the first and the last measurement of the same track within the wind farm, and hence the given periods should be considered as minimum time lengths. Namely, birds had always crossed the border of the wind farm before the first measurement and had needed some time to reach the border of the wind farm after the last measurement. Nevertheless, the periods provide insights in the order of magnitude of the time spent by Lesser Black-backed Gulls in a wind farm.

The time periods of Lesser Black-backed Gulls within wind farms ranged from half a minute (crossing of OWEZ with two measurements) to 5.5 hours (a non-mobile bird in Thornton Bank). The length of the periods depended on the behaviour of the birds. Lesser Black-backed Gulls that flew through the wind farm spent on average 8 minutes in the wind farm. Birds that were partly floating or resting and partly flying spent on average 37 minutes within the boundaries of the wind farm. Finally, the birds that were non-mobile (floating on water or resting at man-made structures) for the whole period on average 80 minutes.

4 Discussion

In our study we revealed first of all a large-scale non-attendance of Lesser Black-backed Gulls of offshore wind farms. This held for all studied wind farms, although we found a large in-between wind farm variation in the level of reduction relative to areas outside the wind farms. This is also highlighted by the discrepancy in previous studies: most authors have concluded that Lesser Black-backed Gulls either do not avoid offshore wind farms (Petersen *et al.* 2006; Krijgsveld *et al.* 2011; Skov *et al.* 2015) or are even attracted to them (Vanermen, Nicolas *et al.* 2015), although in Germany also avoidance of offshore wind farms is documented (see summary in Krijgsveld 2014; Mendel *et al.* 2014). These differences may be due to the situation of the wind farm relative to the colony, the distance to the shore and foraging opportunities in the vicinity. Such differences are also obvious among the wind farms studied in the current study, where Vanermen *et al*. (2017) have reported resting and foraging gulls at the foundations of the Thornton Bank wind farms, while the foraging areas of the Lesser Black-backed Gulls in England obviously lay further to the north than the Greater Gabbard wind farms.

As in most coastal colonies around the North Sea Lesser Black-backed Gulls are largely orientated on feeding on discards of fishing vessels during offshore foraging flights (Camphuysen, C. J. 1995; Garthe, S. *et al.* 1999; Camphuysen, C.J. 2010), it remains a question whether gulls are not simply following fishing vessels that are either prohibited to enter wind farms or avoid entering due to other reasons. Therefore, the "avoidance" of offshore wind farms by Lesser Black-backed Gulls may simply be an artefact of birds following their food source. Also our counterintuitive result of lower avoidance of wind farms with a higher wind turbine density (PAWP and Thornton Bank) suggests that Lesser Black-backed Gulls do not necessarily see wind turbines as a hazard. Our results on the distances gulls approach wind turbines show that Lesser Black-backed Gulls are well capable of avoiding individual turbines. Out of 886 measurements only 9 were flying within the horizontal distance of the rotor radius, of which most birds were likely below the rotor-swept zone. Moreover, turbines could have been out of function at the moment of measurement or the blades standing parallel to the flight direction. Visual measurements in the OWEZ wind farm also established that at such moments more birds approached wind turbines in flight (Krijgsveld *et al.* 2011).

All our data analysis depended on the basic assumption that the GPS loggers provide reliable measurements. The UvA-BiTS GPS loggers have a mean positional error between 1 and 67 m, a mean speed error between 0.01 and 0.82 m/s and a mean altitude error between 1 and 26 m (Bouten *et al.* 2013). In order to ensure a reasonably reliable database for our analysis, we limited our analysis to measurements with accurate measurements, based on the accuracy values produced by the loggers themselves (see Chapter 2). Generally speaking, the vertical accuracy of GPS loggers is lower than the horizontal accuracy (Cook *et al.* 2012). However, a recently GPS height measurements were shown to have a similar general pattern of flight height distribution as optical laser range finder measurements (Borkenhagen *et al.* 2018), and a modeling study indicated that the error in GPS height measurements can be directly accommodated analytically (Ross-Smith *et al.* 2016). Therefore, GPS measurements can provide high quality, cost-effective and accurate information on seabirds' flight altitude, especially when compared with the inaccuracy of flight height estimates from boat surveys and the more restricted weather conditions they represent, as well as the possibility that birds altered their flight behaviour in the presence of boats (Ross-Smith *et al.* 2016).

Recently, more and more evidence is provided that although Lesser Black-backed Gulls are considered generalists in their selection of prey (Cramp & Simmons 1978), there is strong individual specialization (Gyimesi, Abel *et al.* 2016; Isaksson *et al.* 2016; Ross-Smith *et al.* 2016; Juvaste *et al.* 2017), which also varies with the season (Thaxter *et al.* 2015). In that sense, it is important to note that our study concentrated on adult gulls. It might be that actively breeding birds during the breeding season focus in offshore areas on following fishing vessels, in order to collect discards, a nutritious food source for raising chicks (Camphuysen, C.J. 2013). Adult non-breeding birds, immatures and birds during migration and wintering may make other choices. The competition for food behind fishing vessels is enormous and only the strongest birds can collect enough food to make this food source profitable (Camphuysen, C. J. 1995; Camphuysen, C.J. 2013). As breeding birds are commonly considered dominant over non-breeding birds (MacRoberts & MacRoberts 1972), it could be that foraging behind fishing vessels in spring and summer is only accessible to adult breeding birds. Consequently, Lesser Black-backed Gulls observed in offshore wind farms might originate from the large pool of adult floaters (Gyimesi, A. & Lensink 2012) or from immature birds. In addition, some studies have focused on other periods of the year, such as the autumn and winter surveys at Luchterduinen (Skov *et al.* 2015), and hence could have exposed shifting preferences throughout the year (cf. Thaxter *et al.* 2015).

If so, this could have large consequences for assessing the effects of wind farms on Lesser Black-backed Gulls. Namely, strong avoidance during the breeding season by adult breeding birds shall result in a lower number of collision victims from the breeding population, which has a direct effect on the survival of chicks as well. Moreover, also colonies within Natura 2000-areas would be less affected by collision mortality. On the other hand, the question can be raised whether the non-attendance of breeding Lesser Black-backed Gulls is equal to habitat loss, or it has to do with a redistribution of resources, in this case fishing vessels.

5 Conclusions and recommendations

5.1 Conclusions

Main conclusion: Lesser Black-backed gulls caught and equipped with GPS loggers in colonies of the Netherlands, Belgium and England frequented offshore wind farms significantly less often than expected based on their general distribution. Based on our results, the macro-avoidance of offshore wind farms can be on average as large as 70% (range: 39% – 81%).

Distance of effects: The lower number of measurements per grid cell was not limited to only the wind farm boundaries but extended to the surroundings, highlighted by the significant effect of distance in kilometres to wind farms on the number of measurements per grid cell.

Differences among wind farms: Although the lower numbers within the wind farm boundaries held for all studied wind farms, there were relatively large differences among wind farms, in nearly all studied variables.

Occurrence within rotor-swept zone: 99% of all the measurements within the wind farms occurred outside the rotor-swept zone. Gulls seemed to approach wind turbines in Thornton Bank to closer distances than in other wind farms.

Flight speed and altitude: Flight speed and flight altitude of Lesser Black-backed Gulls seemed not to be different inside and outside wind farms. However, considering all measurements, flight altitude and flight speed were lower during the night than during the day, affecting the collision risk of birds during the night.

Flight- and nocturnal activity: Percentage of measurements in flight and nocturnal activity appeared not to be generally different within and outside wind farms. In addition to lower flight speed and altitude during the night, also the general activity level, in terms of percentage of flying, decreased during the night, leading to a lower number of flying birds prone to collision.

Change in behaviour on the level of individuals: Also the analysis at the level of individual tracks showed that birds do not seem to change their flight speed or flight altitude. However, within the same tracks birds seemed to be more in flight within the wind farm than in the buffer zone of the wind farm.

Spatial distribution with the wind farm: Based on the analysis of the individual tracks, there was no obvious difference in the number of birds crossing the centre of wind farms and the outer zone of the wind farms.

Time spend in wind farms: Depending on their behaviour, Lesser Black-backed Gulls spent on average 8 minutes in the wind farm when flying to 80 minutes when floating on the water resting at wind farm structures.

5.2 Application of results in SOSS Band model

Assessments as to the potential numbers of collisions at proposed offshore wind farms are commonly determined using the SOSS Band model. This model incorporates a number of species-specific parameters, including flight speed, flight altitude and level of nocturnal activity. Our current study provides new insights in these variables, specifically for Lesser Black-backed Gull in offshore wind farms through the use of modern tracking techniques. Based on the results, there seems to be no reason to use other values for these behavioural variables in the current practice of modelling than previously reported by Gyimesi et al. (2017) generally for offshore environments: once in a wind farm the birds do not appear to behave in a profound different way than outside the wind farm. However, the main conclusion of the current study is that Lesser Black-backed Gulls occur in much lower numbers in wind farms than in the surroundings. Future studies with detailed GPS measurements within wind farms should confirm the conclusions of our study regarding micro-avoidance.

Moreover, our study also highlighted that there is both a large spatial and temporal variation in gull behaviour. Spatial effects were mainly detected in avoidance levels and temporal differences were revealed between behaviour during the day and night. Such differences currently do not form a regular part of the modelling exercise but can be easily incorporated and can make a large effect on the outcome of the models.

5.3 Recommendations

Our study resulted in clear insights how Lesser Black-backed Gulls can be affected by offshore wind farms. Nevertheless, the question remains how far this study is limited to adult breeding birds and whether other age groups, birds with another status or during migration might show a different response to offshore wind farms. Especially, that several studies have led to different conclusions regarding avoidance/attraction of wind farms by Lesser Black-backed Gulls. Therefore, it would be important to find out more of the origin of gulls within offshore wind farms.

In addition, our present study could not give answer to whether Lesser Black-backed Gulls were truly avoiding wind farms or were simply following fishing vessels that are absent in wind farm areas. By doing a spatial comparison of offshore fishing intensity with the distribution of the gulls could provide new insights that could put the absence of breeding gulls in wind farms in perspective.

6 Literature

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7 Appendix

7.1 Tracks in OWEZ

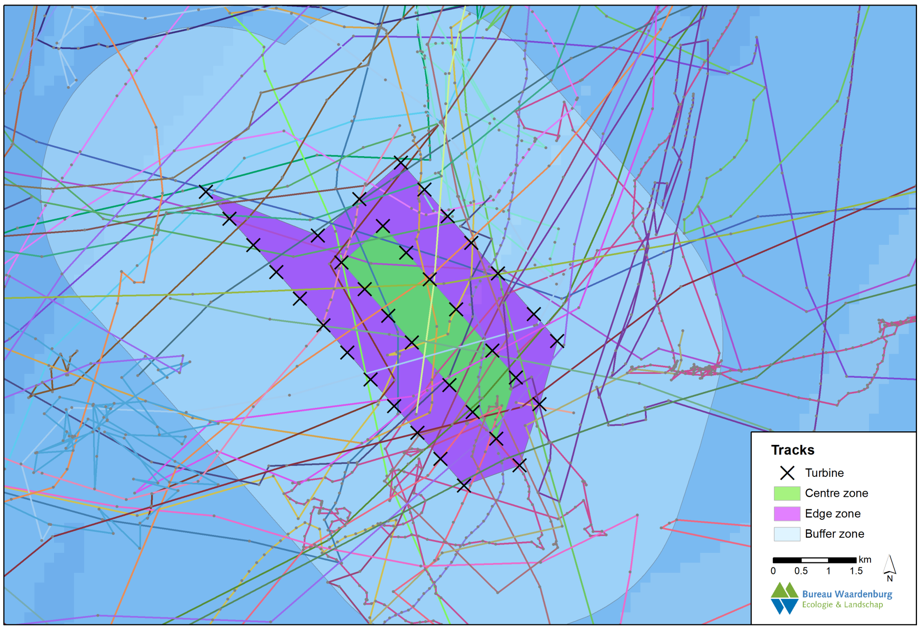

Figure 7.1.1 All individual tracks of Lesser Black-backed Gulls crossing through the Dutch OWEZ wind farm. In addition to the position of the turbines, also the buffer zone (3 km around the wind farm) used in the analysis is shown.

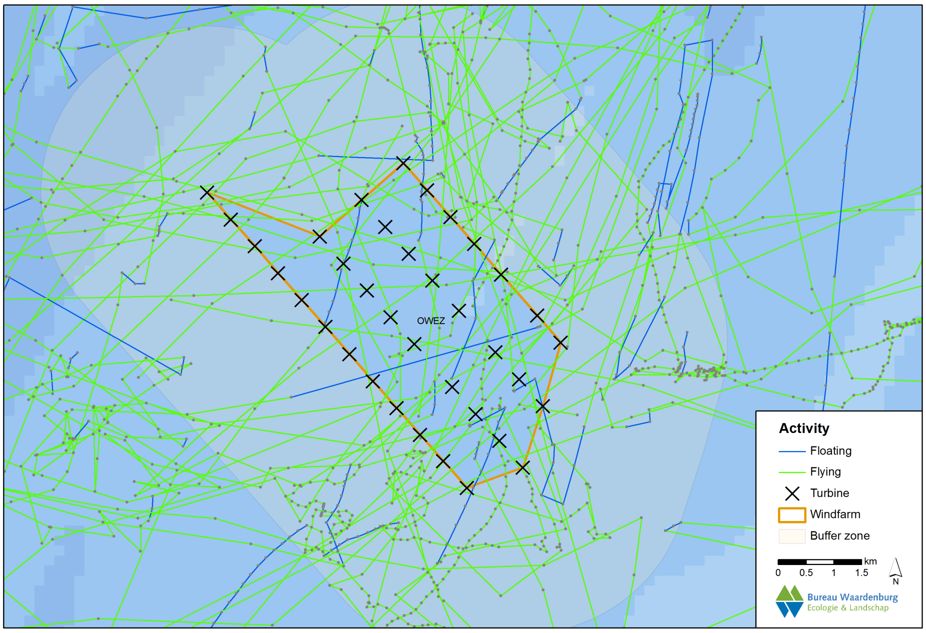

Figure 7.1.2 Tracks of Lesser Black-backed Gulls in OWEZ in flight (>2.5 m/s) or non-flight (i.e. floating; < 2.5 m/s). In addition to the position of the turbines, also the buffer zone (3 km around the wind farm) used in the analysis is shown.

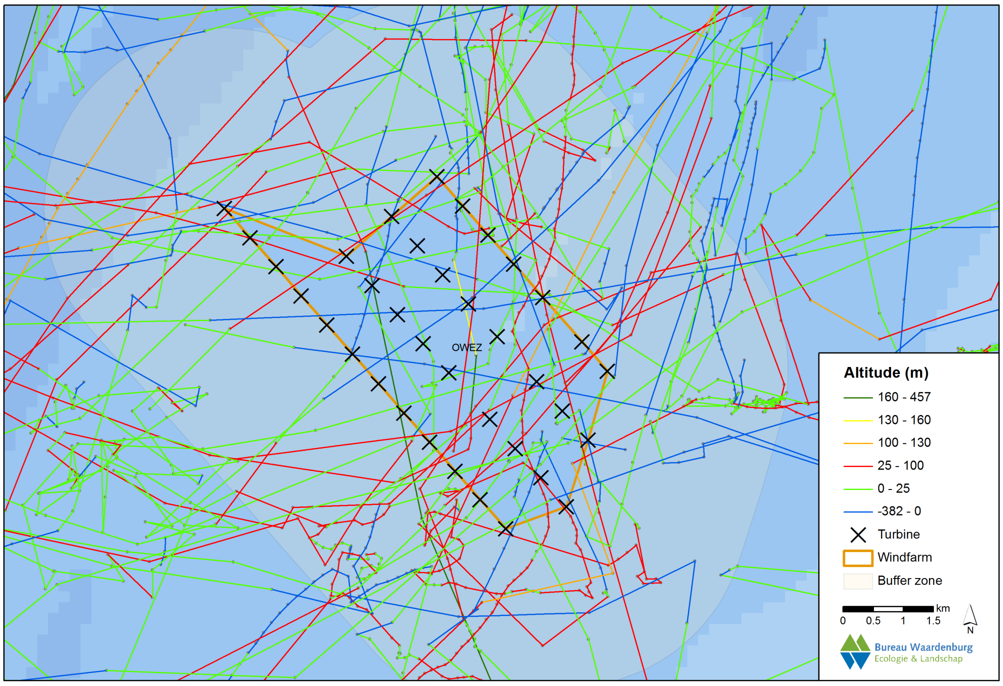

Figure 7.1.3 Altitude (in m classes) of Lesser Black-backed Gulls tracks in the OWEZ wind farm. In addition to the position of the turbines, also the buffer zone (3 km around the wind farm) used in the analysis is shown.

7.2 Tracks in Prinses Amalia

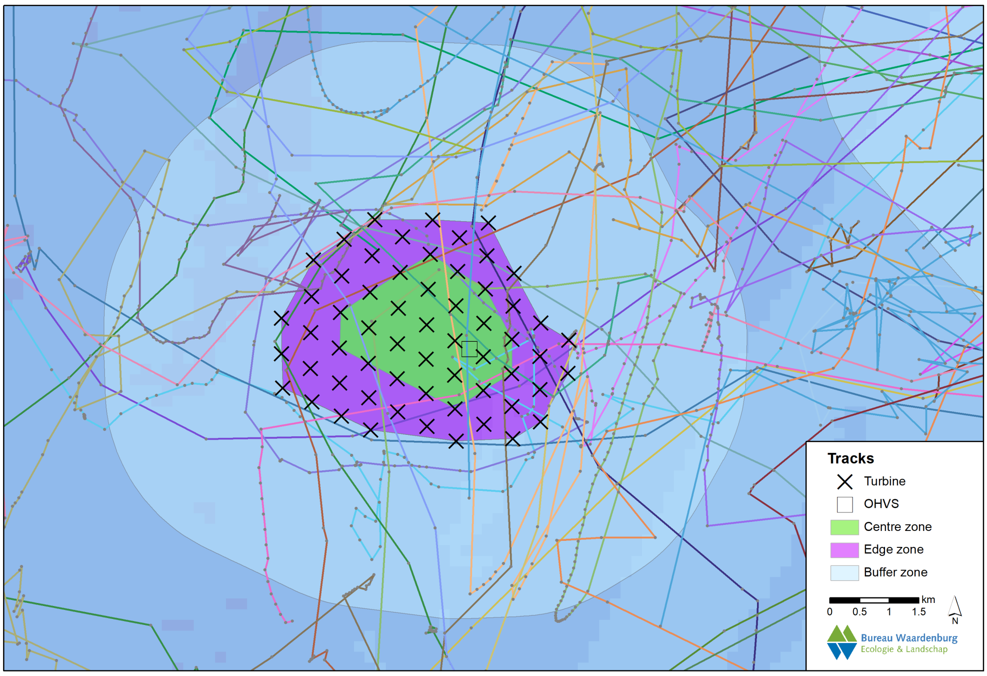

Figure 7.2.1 All individual tracks of Lesser Black-backed Gulls crossing through the Dutch Prinses Amalia wind farm. In addition to the position of the turbines, also the buffer zone (3 km around the wind farm) used in the analysis is shown.

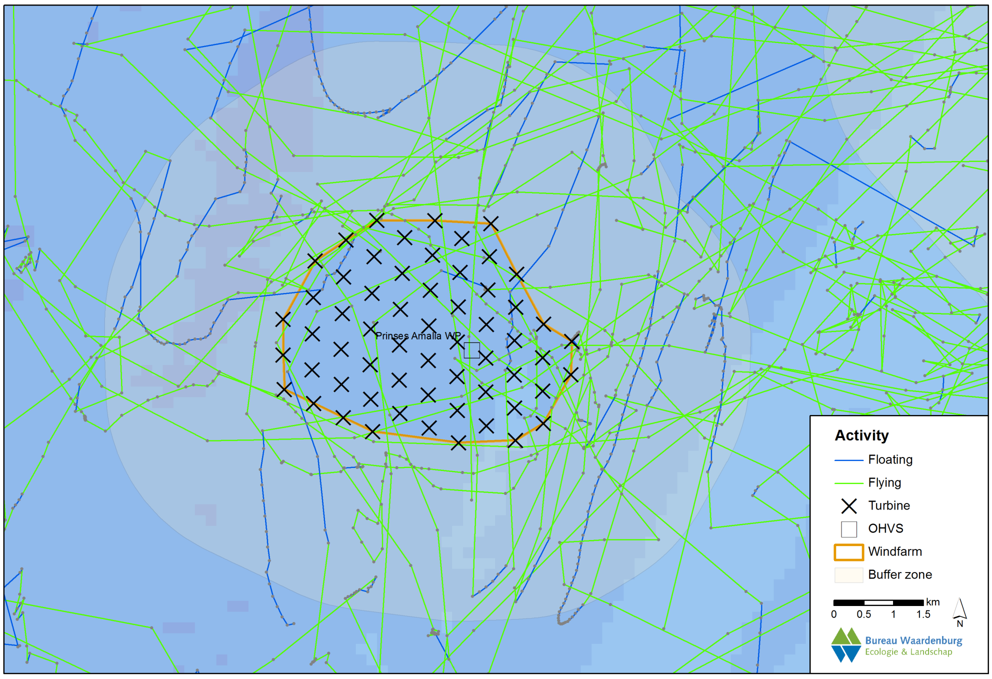

Figure 7.2.2 Tracks of Lesser Black-backed Gulls in Prinses Amalia in flight (>2.5 m/s) or non-flight (i.e. floating; < 2.5 m/s). In addition to the position of the turbines, also the buffer zone (3 km around the wind farm) used in the analysis is shown.

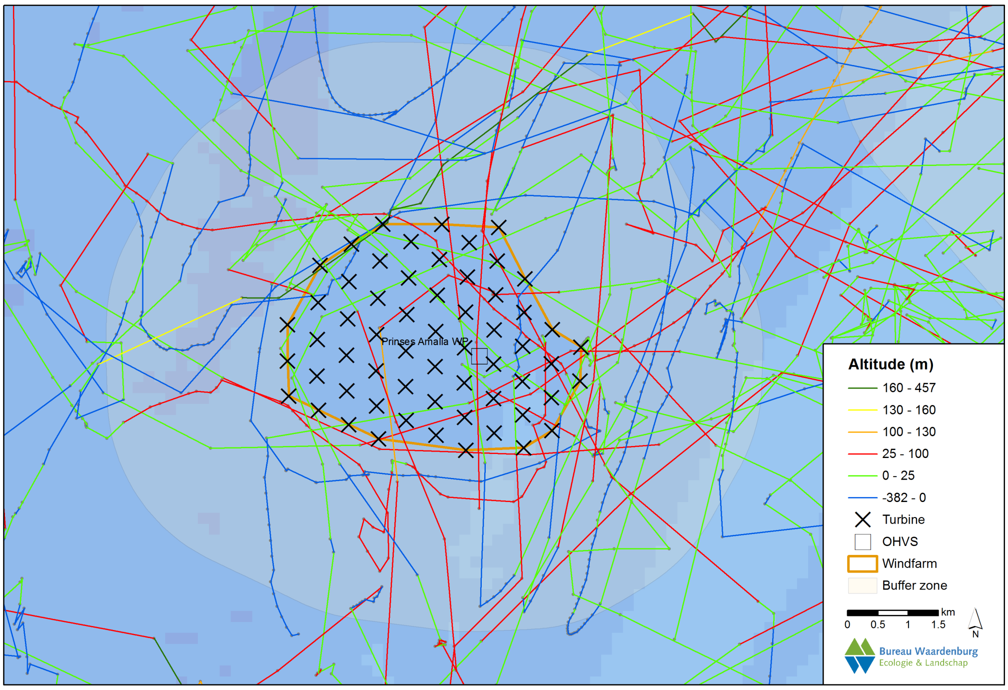

Figure 7.2.3 Altitude (in m classes) of Lesser Black-backed Gulls tracks in the Prinses Amalia wind farm. In addition to the position of the turbines, also the buffer zone (3 km around the wind farm) used in the analysis is shown.

7.3 Tracks in Thornton Bank

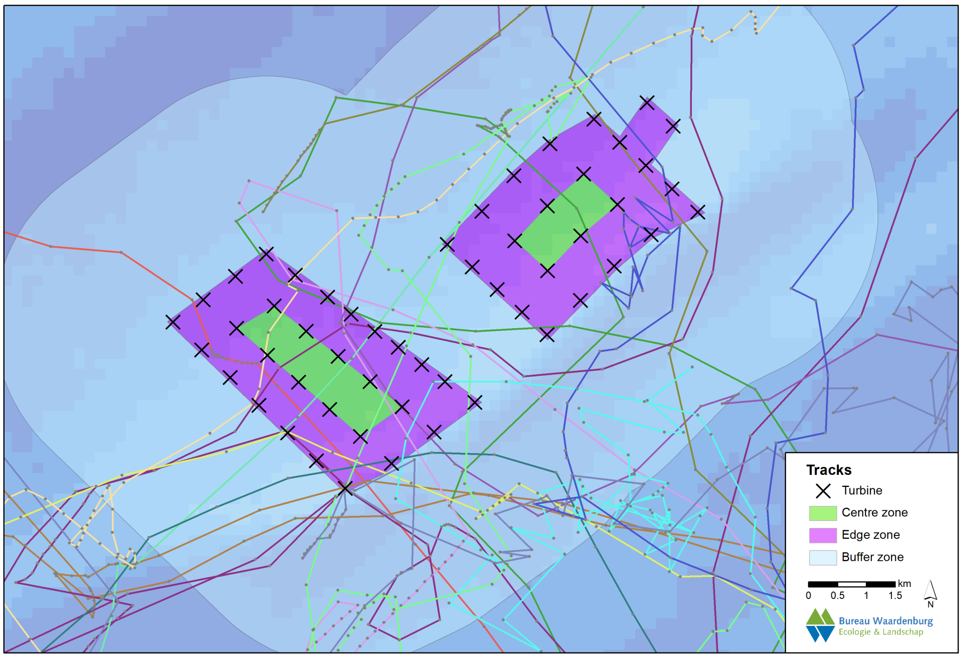

Figure 7.3.1 All individual tracks of Lesser Black-backed Gulls crossing through the Belgian Thornton Bank wind farm. In addition to the position of the turbines, also the buffer zone (3 km around the wind farm) used in the analysis is shown. 2

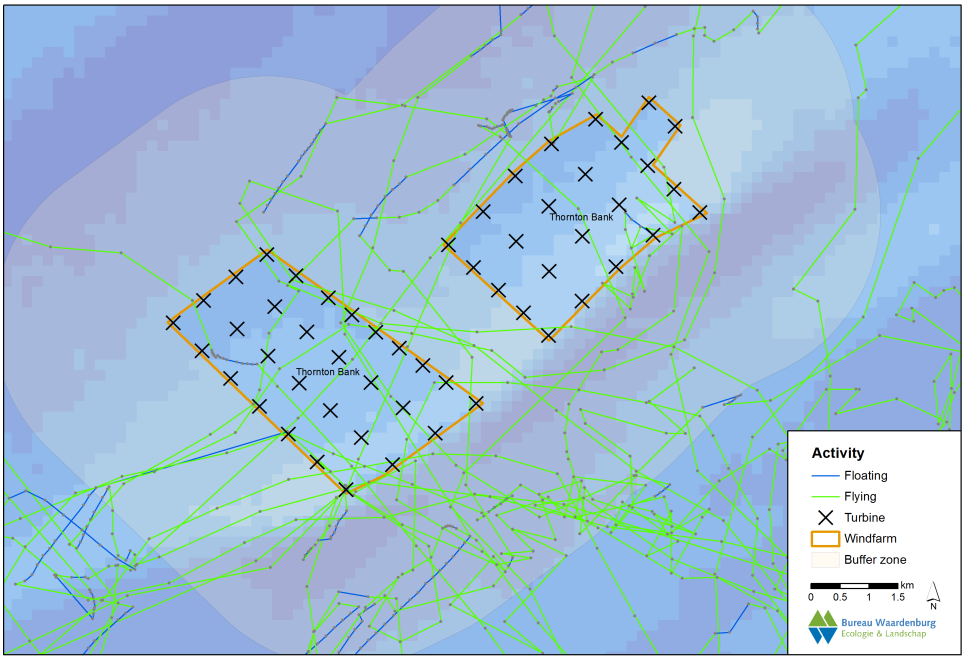

Figure 7.3.2 Tracks of Lesser Black-backed Gulls in Thornton Bank in flight (>2.5 m/s) or non-flight (i.e. floating; < 2.5 m/s). In addition to the position of the turbines, also the buffer zone (3 km around the wind farm) used in the analysis is shown.

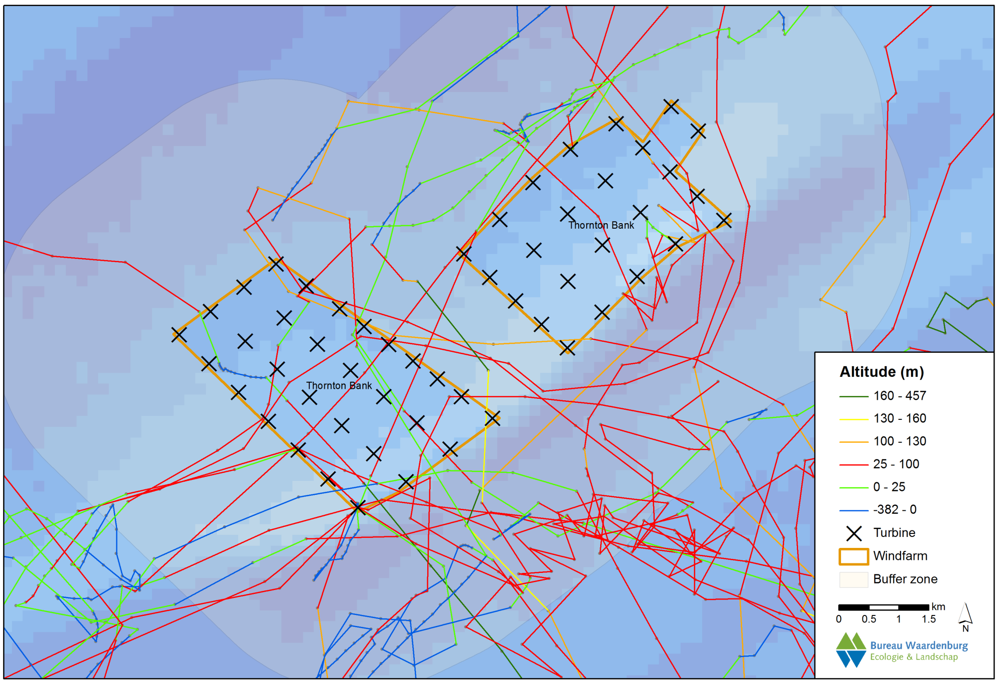

Figure 7.3.3 Altitude (in m classes) of Lesser Black-backed Gulls tracks in the Thornton Bank wind farm. In addition to the position of the turbines, also the buffer zone (3 km around the wind farm) used in the analysis is shown.

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