Offshore space use
of lesser black-backed gulls (*Larus fuscus*)
from the Schiermonnikoog
breeding population

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1. Introduction

1.1 Background

Gemini offshore wind farm is located in the Dutch part of the North Sea, 85 km north of the coast of Groningen, 60 km north of the island Schiermonnikoog. The Gemini wind farm consists of 150 wind turbines, totalling 600 MW and two offshore high voltage stations. Start of construction was mid-2015. Gemini is fully operational since 2017.
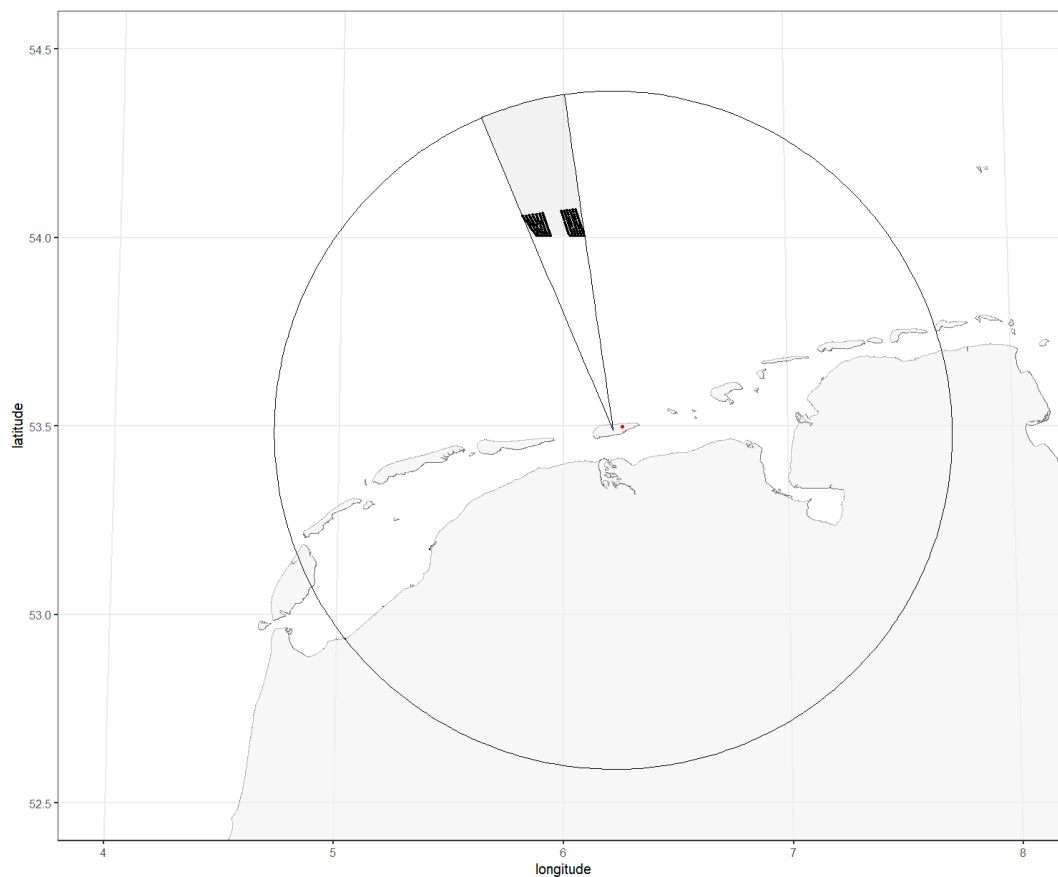
Figure 1: Overview of study area: Circle area indicating the 100km foraging range assessed in the Appropriate Assessment of Gemini for lesser black-backed-gulls breeding on Schiermonnikoog. Black dots show turbine locations of Gemini wind farm. Red dot indicates colony where lesser black-backed gulls were tagged.

The Environmental Impact Assessment for Gemini indicated that, as a result of collision risk, the cumulative effects of Gemini and neighbouring wind farms could possibly raise the additional mortality for lesser black-backed gulls *Larus fuscus* (LBBG) in the area. A small effect on the population size of the LBBG in the Nature 2000 area *Waddenzee* could not be ruled out beforehand (Gemini EIA, 2012)

The additional mortality of LBBG from collision risk on the breeding colonies in the *Waddenzee* was studied in detail in an Appropriate Assessment of Gemini. Assuming a maximum foraging distance from the breeding colonies of 100 km and a model for the distribution of LBBG at sea, it was estimated for the various breeding colonies which fraction of the foraging flights would pass through the wind farm, contributing to a collision. The Appropriate Assessment concludes that for the LBBG breeding colonies in the *Waddenzee* the maximum effect on additional mortality is approx. 0.7% and that significant negative effects can be ruled out (Gemini AA, 2012).

As part of Gemini's environmental monitoring program, the distribution of LBBG (and other bird species) in and around the wind farm area was surveyed on a monthly basis for one year, before construction of the wind farm commenced. Lesser black-backed gulls were most numerous during the summer surveys, from April through August, reaching the highest densities, of over 3 birds per km^2, in July. Even though 95% of all LBBG seen were aged as "adults", at that time - which coincides with the end of the breeding season - most birds in the area appeared to be loafing, non-breeding birds that had no clear connection to any colony as the surveyors never observed early morning arrival or evening departures towards land (van Bemmelen *et al.* 2015). The authors point out that without marked, GPS-logged birds it is not possible to be certain whether breeding birds from adjacent colonies (e.g., Schiermonnikoog) do reach the Gemini area, but that from their observations it would appear that breeding birds did not reach the Gemini area in any significant numbers.

The apparent low numbers of breeding birds from adjacent colonies at the site of the wind farm prompted the project design of the LBBG research during the operational phase of the wind farm to focus less on the presence of LBBG's in the wind farm and the impact of the wind farm on the breeding colonies, and more on developing understanding of lesser black-backed gull behaviour, breeding biology, and response to environmental drivers. A project was therefore developed to conduct research into LBBG behavioural ecology alongside their potential interactions with Gemini wind park using GPS tracking. Of the several *Waddenzee* populations considered in the Appropriate Assessment, Schiermonnikoog is one of the nearest populations to Gemini and the estimated impact of Gemini wind park on the Schiermonnikoog population was one of the highest. For this reason, alongside more practical considerations of tagging and monitoring feasibility, the study focuses upon the Schiermonnikoog population. Consequently, the project "Offshore space use of Lesser Black-backed Gulls (Larus fuscus) from the Schiermonnikoog breeding population" (GEM-40-107) was funded and this document provides an executive summary of the project, in addition to the annual summaries, the PhD thesis of Elspeth Sage (Sage 2022, see supplementary file S1) and scientific publications (Sage *et al.* 2019; Sage *et al.* 2022). Using GPS tracking and systematic breeding bird monitoring, the main aims of the project were to: (1) quantify the space use of Lesser Black-backed gulls associated with the breeding colony at Schiermonnikoog; (2) identify the commuting routes and flight altitudes between foraging areas and the breeding colony; (3) determine how birds adjust their flight altitudes and airspeed in response to atmospheric conditions; (4) assess flight behaviour within the wind farm; (5) integrate available information to estimate collision risk. During the project operation it became apparent that GPS data within Gemini wind farm was sparse, limiting the scope for quantifying collision risk, which resulted in the final main emphases of the research focusing on questions 1-4.

1.2   Lesser black-backed gull ecology and interactions with wind farms

Lesser black-backed gulls are long lived generalist seabirds that display enormous behavioural plasticity from the individual to species level, resulting in high variability in their movement behaviour. These birds have a generalist diet, feeding on a wide range of natural and anthropogenic food resources from marine and terrestrial habitats, which results in high variability in their foraging movements. Some of their foraging resources are highly linked to human landscape use, such as agricultural fields, refuse sites, and fishery discards (Ramírez *et al.* 2015; Tyson *et al.* 2015; Isaksson *et al.* 2016; Langley *et al.* 2021), and whilst lesser black-backed gulls are often regarded as a highly

adaptable species with the capacity to shift between different strategies, this is not without cost (Bicknell *et al.* 2013; Langley *et al.* 2021). Lesser black-backed gulls have a long history of responding to human pressures with both positive and negative effects (Camphuysen 2013) so it remains important to monitor the impacts of the landscape on their movements and to understand how lesser black-backed gulls make decisions with respect to the landscape. This also extends to the need to understand how lesser black-backed gulls make decisions in response to the atmospheric landscape.

In relation to the specific case of monitoring the impacts of wind farms on bird species, lesser black-backed gulls are a species of interest. They have been identified as a species at risk of collision with individual turbines (Furness *et al.* 2013; Marques *et al.* 2014; Potiek *et al.* 2022) and show variability in their attraction to wind farm areas (Cook *et al.* 2018; Vanerman *et al*. 2020). Therefore, there is a specific need to understand the degree of variation in lesser black-backed gull movement behaviour and the drivers of gull movement in the context of their interactions with wind farms. There is a lot that can be learnt from lesser black-backed gull movements which will support informed decision-making regarding landscape development, providing we have the right tools to investigate the dynamic interactions between the landscape, the atmosphere, and animal movement.

1.3   Aims of this report

The primary aim of this report is to provide an overview into the offshore space use of lesser black-backed gulls in line with the original project aims and in addition to the research presented in the PhD thesis written as the main output of this project (Sage, 2022). The research presented here is divided into the following sub aims in the following chapters:

1. In Chapter 2 we present insight into the monitoring efforts that were undertaken, firstly in the GPS tagging and tracking of individual lesser black-backed gulls from the Schiermonnikoog colony, and secondly in the breeding monitoring efforts that were carried out at the Schiermonnikoog colony to investigate broader breeding success and diet. We present an overview of the data collected and a summary of breeding success.
2. In Chapter 3 we present a brief overview of the aims and conclusions of the main output of this project, the PhD thesis Sage 2022, entitled: [Wind energy for all! The dynamic flight of gulls in human-engineered landscapes](). This chapter is modified from parts of Sage 2022 (Chapter 6).
3. In Chapter 4 we explore the three-dimensional space use of lesser black-backed gulls from Schiermonnikoog, presenting 2D maps of space use throughout the study period and across periods of the breeding season, and examining the range of flight altitudes used by gulls at sea. We also examine flight speeds, proportion of time spent at sea, and comment on how flight altitude may interact with turbine heights.
4. In Chapter 5 we build upon the knowledge presented in Chapter 4 to carry out a case study into the overlap between Gemini wind farm area and Schiermonnikoog lesser black-backed gulls. This case study is carried out as a comparison with the original appropriate assessment conducted prior to wind farm construction as a way of identifying where assumptions of the appropriate assessment model can be improved and discussing the added value GPS tracking data can provide.
5. In Chapter 6 we take a more detailed view of three-dimensional flight within the Gemini wind farm area and present maps of flight in relation to speed, altitude and distance from turbines. We identify the different behaviours observed by tracked gulls within the wind farm and comment on how these behaviours may relate to collision risk.
6. In Chapter 7 we present a summary of the knowledge gaps addressed in this project and provide an overview of offshoot research that uses data or themes arising from this project.

2. Monitoring effort

The data collected for this project consisted primarily of GPS tracking data gathered from individual tagged lesser black-backed gulls, and breeding monitoring data collected at the breeding colony on Schiermonnikoog. In this chapter we give an overview of these two key data collection efforts and provide summaries of the data gathered.

All work conducted in the field to fit GPS loggers and to carry out breeding monitoring was carried out with approval from and in accordance with the Dutch ethics committee on animal experiments (DEC) of the Royal Netherlands Academy of Arts and Sciences (KNAW). Permission to work in the colony was granted by Natuurmonumenten.

Lesser black-backed gulls breed across Schiermonnikoog, often in mixed colonies with herring gulls. The focal colony for this project was a mixed colony of mainly lesser black-backed gulls and a minority population of herring gulls, located among the dunes along the north edge of the island, within the protected National Park area (Figure 1).

Figure 1: A view of the Schiermonnikoog study colony

2.1 GPS tracking of individual lesser black-backed gulls

In order to track individual lesser black-backed gulls from the Schiermonnikoog colony, UvA-BiTS loggers were deployed on 28 adult gulls in the spring of 2017 and 2018. The UvA-BiTS system consists of individual solar powered trackers which record and store biologging data on internal memory (Bouten *et al.* 2013). This biologging data includes GPS position, 3D acceleration, instantaneous speed and altitude, and in later logger hardware devices (deployed in 2018) pressure sensors. UvA-BiTS loggers download data to users by communicating with a base station, either directly or via a local relay of antennas. The base station, consisting of a single antenna and internet connected laptop with the UvA-BiTS base station software, receives data from the loggers and transmits it to a central database. Via the base station measurement settings can also be altered on individual or multiple loggers (provided the logger in question comes into contact with the base station). On

Schiermonnikoog, three relays were set up in the breeding colony where tagging took place (Figure 2a) and the base station was set up in a beach restaurant approximately 5km down the coast, with a direct line of sight. This system was set up every year, usually in February or March, to gather data from returning gulls, and was taken down in July, when most breeding gulls have departed from the area.

To deploy tags on individuals, gulls were captured during the late incubation stage of breeding, when attraction to the nest is high, using a walk-in trap (Figure 2b). The egg clutch was removed and stored safely to avoid damage, whilst decoy eggs were placed on the nest. Gulls caught in the trap could be then safely removed and fitted with a UvA-BiTS logger, affixed using a Teflon wing harness that sits under the feathers (Figure 2c). Alongside affixing the logger, a metal ring and colour rings were fitted to the legs so that individuals could be resighted visually. Biometrics of each individual were taken: mass, alongside wing, tarsus, beak and head length, which could be used for sexing individuals (Camphuysen 2013). Photographs were also taken of the wing from above in order to estimate wing area and birds were then immediately released. The entire process was timed to ensure that a bird was not handled for more than approximately 20 minutes.

Measurement settings were uploaded to UvA-BiTS tags with a goal of getting uninterrupted information on individual movements, with a specific focus of measuring fine-scale flight behaviour within the Gemini wind farm area. Different measurement regimes were carried out throughout 2017 – 2021 based around these goals and around individual tag performance. Within the UvA-BiTS system geographic fences can be used to change measurement regimes in different locations; tags deployed in 2017 had the capacity to use one geographic fence whilst tags deployed in 2018 had the capacity to use three. These fences were mainly used to change the time interval of measurements; GPS measurements were always taken on these intervals followed by an accelerometer measurement, and then (only in the case of 2018 tags) a pressure measurement.

For tags deployed in 2017 the single geographic fence was placed around Gemini wind farm, allowing high resolution (typically 3 second interval) measurements to be captured. From 2018 onwards it was determined that overall sea movements were infrequent enough that the fence could be extended to include a wider at sea area, including Gemini wind farm, without draining battery life. This wider sea fence was used for subsequent years, incorporating most of the Schiermonnikoog marine foraging area, unless a tag was not working to its full functionality. Outside of the high-resolution fence, 10-minute measurement intervals were typically assigned, with a 5-minute E+ setting when battery life was high. At the end of the breeding season, before gulls departed the area, wintering settings were set, with 60-minute measurement intervals and 30-minute E+ measurement intervals.

For tags deployed in 2018, three fences were consistently used. Firstly, a high resolution 6 second interval was used, following the same sea and wind farm area as used by the 2017 tags. This 6 second interval had to be used rather than 3 seconds as 2018 tags carried an additional pressure sensor, which increased the time needed for all measurements (GPS, accelerometer and pressure) to be taken. A second fence covered the breeding colony, within which 15-minute measurements were taken (gulls are typically sitting on the nest and moving little within the colony, so lower resolution measurements save battery). The largest fence covered the entire breeding area; most of the Netherlands and surrounding sea areas, within which 10-minute measurement intervals were taken. Beyond this fence the same winter settings as the 2017 deployed tags were used.

Figure 2: a) UvA-BiTS relay set up in Schiermonnikoog colony, b) field set up for capturing adult lesser black-backed gulls on the nest, with decoy eggs and a walk-in trap, c) an adult lesser black-backed gull having been fitted with a UvA-BiTS logger.

Lesser black-backed gulls tagged in previous years were monitored for their return in subsequent years. Some individuals did not return, whereas some individuals returned every year (Table 1). In some cases, gulls were not picked up on the UvA-BiTS station but were re-sighted in the colony, either having lost their tag, or the tag being present but presumed broken. Many individuals were also re-sighted on migration through the European colour-ring birding platform (Euring 2022)

Table 1: Overview of breeding season GPS measurements per year of tracking, departure and arrival dates are given for birds within a distance of 1km of the center of the colony

year	number of individuals	Tags deployed	Number of measurements	Total time (hours)	Minimum arrival date	Mean arrival date	Last departure date	Mean departure date
2017	20	20	161118	24483	NA	NA	2017-08-10	2017-07-14
2018	23	9	357501	37407	2018-03-21	2018-04-05	2018-08-17	2018-07-04
2019	13	0	378266	28054	2019-03-15	2019-04-03	2019-07-25	2019-07-11
2020	11	0	448803	30011	2020-03-12	2020-04-01	2020-08-07	2020-07-24
2021	6	0	88959	13289	2021-03-24	2021-04-06	2021-07-31	2021-07-07

Table 2: Overview of breeding season GPS measurements per tracked individual, departure and arrival dates are given for birds within a distance of 1km of the center of the colony

individual	Deployment year	Years with data	Number of measurements	Total time hours	Minimum arrival date	Mean arrival date	Last departure date	Mean departure date
5519	2017	5	70221	9046	24-apr	4-mei	10-aug	23-jul
5524	2017	4	110577	10842	19-mrt	26-mrt	10-aug	2-aug
5525	2017	3	104850	7543	21-mrt	29-mrt	6-aug	1-aug
5526	2017	5	45582	8147	24-mrt	4-apr	28-jul	22-jun
5527	2017	3	76280	4707	3-apr	8-apr	17-jul	27-jun
5528	2017	1	2645	553	NA	NA	18-jun	18-jun
5531	2017	1	8822	1524	NA	NA	26-jul	26-jul
5532	2017	5	293770	10697	23-mrt	27-mrt	8-aug	8-jul
5533	2017	4	63425	5427	29-mrt	4-apr	14-jul	13-jun
5551	2017	2	12620	2287	18-apr	18-apr	1-jul	27-jun
5552	2017	2	27760	3902	24-mrt	24-mrt	7-aug	15-jul
5554	2017	4	149978	9983	13-mrt	19-mrt	7-aug	21-jul
5555	2017	3	72596	7248	5-apr	6-apr	7-aug	2-aug
5556	2017	1	12548	1511	NA	NA-NA	26-jul	26-jul
5559	2017	2	29724	4410	5-apr	5-apr	10-aug	31-jul
5560	2017	5	114946	11056	29-mrt	2-apr	7-aug	22-jul
5561	2017	5	42895	10549	19-mrt	1-apr	24-jul	9-jul
5562	2017	1	8122	1416	NA	NA	26-jul	26-jul
5564	2017	1	8504	1462	NA	NA	24-jul	24-jul
5566	2017	2	21990	2119	3-apr	3-apr	16-jun	12-jun
5709	2018	4	51545	9133	21-mrt	28-mrt	17-aug	31-jul
5711	2018	1	1113	189	NA	NA	8-jun	8-jun
5762	2018	1	999	168	NA	NA	7-jun	7-jun
5763	2018	2	27474	2426	12-mei	12-mei	25-jul	17-jul
5773	2018	1	4877	954	NA	NA	12-jul	12-jul
5780	2018	3	55642	4142	3-apr	10-apr	12-jul	24-jun
5781	2018	1	10524	934	NA	NA	12-jul	12-jul
5783	2018	1	4618	867	NA	NA	20-jul	20-jul

2.2   Breeding monitoring efforts

In parallel with the efforts to monitor individual adult lesser black-backed gulls via GPS tracking, monitoring was carried out to measure colony wide breeding success. Broader colony breeding monitoring efforts provided complementary contextual knowledge for the GPS monitoring, such as breeding timing and success, as well as the opportunity to compare breeding success at Schiermonnikoog with other nearby colonies where long-term breeding monitoring is carried out, such as Texel. Monitoring protocols at Schiermonnikoog were therefore based upon the existing protocols at Texel, in order to maximise the comparability of the breeding outcomes between the two islands.

Breeding monitoring began towards the end of April, around the beginning of the egg laying season. Throughout the breeding season the colony was visited every third day for nest monitoring. The colony area was divided into three sections (west, middle and east) and monitoring work was only ever carried out in one section at a time, to minimise disturbance to across the colony area. Transects were carried out in each section at a time, walking systematically to identify nests with eggs. Upon finding a nest, nest location was recorded with a hand-held GPS logger and market with a labelled bamboo cane. Eggs were labelled (A, B or C according to their order of appearance, where A is the first egg to be found in a nest) and their widest length and width was measured. On subsequent visits to an egg, egg condition was recorded, noting the warmth of the egg in the hand, which gives an indication of

the egg viability, as well as recording any signs of cracking or pipping. The fate of each egg was recorded as hatched when a chick was found or presumed alive, failed where the egg had failed to hatch, and predated when an egg/chick was missing and presumed dead. Hatching dates were estimated within the last three days based on the condition of the chick. Visual identification of gulls as they flew from or returned to the nest, and camera traps placed in the field, were used to identify whether a nest belonged to herring or lesser black-backed gulls.

Efforts were also made to specifically identify the nests of returned tagged birds. Despite receiving positional information from tagged individuals, the positional error on GPS measurements (around to 7 m) and the variable density of nests, which can be much less than 7 m, means that identification of tagged bird's nests cannot be done with tagged GPS data alone. GPS data was used to get an indication of where in the colony a tagged bird may be nesting. Visual observations in the colony were then used to attempt to identify tagged birds on the nest, usually using their colour rings. Finally, camera traps placed near the nest were used to identify whether nests belonged to a tagged gull. Attempts to identify every tagged bird's nest were not exhaustive and were mainly carried out in 2018 and 2019.

In order to monitor chick growth and success, a subset of the colony nests was chosen at random for further monitoring beyond hatching. Typically, twenty lesser black-backed and twenty herring gull nests were chosen at random for monitoring, alongside any tagged bird nests that had been identified, which were monitored but not included in the overall colony breeding success metrics as they were not randomly selected. Towards the end of the incubation period, enclosures were erected around the nests selected for chick monitoring. These enclosures were built small enough that only one or two nests were incorporated within them so that chicks from these nests could easily be captured and identified on each colony visit, but large enough that chicks had freedom to roam, spaces to hide, and space for parents to land within the enclosure and feed chicks. Enclosure areas were typically $2 - 6\ m^2$ in area, and built from bamboo canes and chicken wire, staked to the ground with metal or wooden pegs. When a chick within an enclosure area was identified, it was fitted with a unique metal leg ring, and biometric measurements were taken every visit (mass, tarsus, primary wing, head and beak length). The fate of the chick was assigned as dead (when found dead) predated (usually young chicks who disappeared) or fledged (disappeared chicks who were deemed large enough to fly, or any chick surviving past 38 days).

Alongside breeding success monitoring, dietary samples were gathered from nests in 2017, 2018 and 2019, in order to gain a deeper insight into the dietary trends of the Schiermonnikoog colony. Samples were taken from enclosures of lesser black-backed gulls and typically consisted of pellets from indigestible parts of prey, regurgitates of large prey parts, a bolus (usually food thrown up by a bird being handled, due to stress), or chick food that is left close to the nest to feed the chicks. Samples were bagged and labelled according to the nest they were found at and the date they were identified, before being frozen for storage. In 2017 and 2019 samples were taken mainly during the chick rearing period of breeding from specific enclosure nests, whilst in 2018 samples were also taken in the incubation period as part of a bachelors thesis project from a geographical sample area.

Breeding outcomes from the monitored Schiermonnikoog colony from 2017-2020 are presented in Tables 3, 4 and 5 for lesser black-backed gulls, tagged lesser black-backed gulls and herring gulls respectively. Figure 3 presents raw chick growth curves for lesser black-backed gulls, tagged lesser black-backed gulls and herring gulls in the years 2017-2019.

Table 3: Breeding success of lesser black-backed gulls on Schiermonnikoog, 2017 - 2020

	Random sample 2017	Random sample 2018	Random sample 2019	Random sample 2020
Nest monitoring				
first egg laying	28-4-17	02-05-18	29-04-19	28-04-20
median egg laying	16-5-17	17-05-18	17-05-19	17-05-20
mean clutch size	2.8	2.8	2.8	2.6
±sd clutch size	0.5	0.4	0.5	0.7
(n) eggs	244	244	219	200
(n) nests	87	84	78	76
mean 3 egg volume	223.12	224.59	221.74	215.67
sd 3 egg volume	15.01	18.32	15.66	24.49
(n) nests	74	77	65	57
first egg hatching	28-5-17	01-06-18	29-05-19	22-05-20
median egg hatching	12-6-17	10-06-18	13-06-19	12-06-20
(n) eggs	244	244	219	200
failed clutches (%)	16	11	10	14
(n) nests	87	84	78	76
egg fates				
accident (%)	0.82	1.6	0.46	0.5
failed (%)	11.89	9.40	8.68	9.0
hatched (%)	75.41	79.50	83.56	80.5
predated (%)	11.89	9.40	7.31	10.0
(n) eggs	244	244	219	200
Enclosure monitoring				
(n) hatchlings	28	54	46	NA
(n) nests monitored	20	22	22	NA
chick fates				
fledged (%)	21.43	7.41	34.78	NA
dead (%)	17.86	29.60	43.48	NA
predated (%)	60.71	62.96	21.74	NA
first fledging	11-07-17	13-07-18	10-07-19	NA
fledglings per pair	**0.3**	**0.16**	**0.73**	**NA**

Table 4: Breeding success of tagged lesser black-backed gulls on Schiermonnikoog, 2017 - 2019

	Newly tagged 2017	Newly tagged 2018	Returned tagged birds 2018*	Returned tagged birds 2019*
Nest monitoring				
first egg laying	01-05-17	08-05-18	11-05-18	08-05-19
median egg laying	16-05-17	11-05-18	17-05-18	17-05-19
mean clutch size	3	2.9	3	3
±sd clutch size	0	0.3	0	0
(n) eggs	60	26	21	24
(n) nests	20	9	7	8
mean 3 egg volume	220.99	222.38	219.28	212.17
sd 3 egg volume	13.86	8.13	16.07	14.92
(n) nests	20	8	7	8
first egg hatching	28-05-17	04-06-18	10-06-18	07-06-19
median egg hatching	09-06-17	13-06-18	13-06-18	13-06-19
(n) eggs	60	26	21	24
failed clutches (%)	7	44	14	12.5
(n) nests	20	9	7	8
egg fates				
accident (%)	0	0	0	0
failed (%)	25.00	11.50	4.76	4.17
hatched (%)	46.67	42.30	80.95	83.33
predated (%)	28.33	46.25	14.29	12.50
(n) eggs	60	26	21	24
Enclosure monitoring				
(n) hatchlings	24	11	17	20
(n) nests monitored	20	9	7	8
chick fates				
fledged (%)	25.00	18.18	5.88	30
dead (%)	37.50	9.09	41.18	30
predated (%)	37.50	72.72	52.90	40
first fledging	11-07-17	25-07-18	31-07-18	16-07-19
fledglings per pair	**0.3**	**0.22**	**0.14**	**0.75**

*2018: Of the 20 birds tagged in 2017, 15 returned, and 7 of these birds were identified as nesting

***2019:** Of the 20 birds tagged in 2017, 11 returned, and 7 were identified as nesting (including 2 broken/missing loggers). Of 9 birds equipped in 2018, 4 returned (1 with missing logger) and 2 were identified as nesting. One nest was parented by 2 logger birds (one from 2017 and one from 2018).

***2020**: Due to COVID-19 enclosure monitoring was not carried out and loggerbird nests were not identified in 2020.

Table 5: Breeding success of herring gulls on Schiermonnikoog, 2017 - 2020

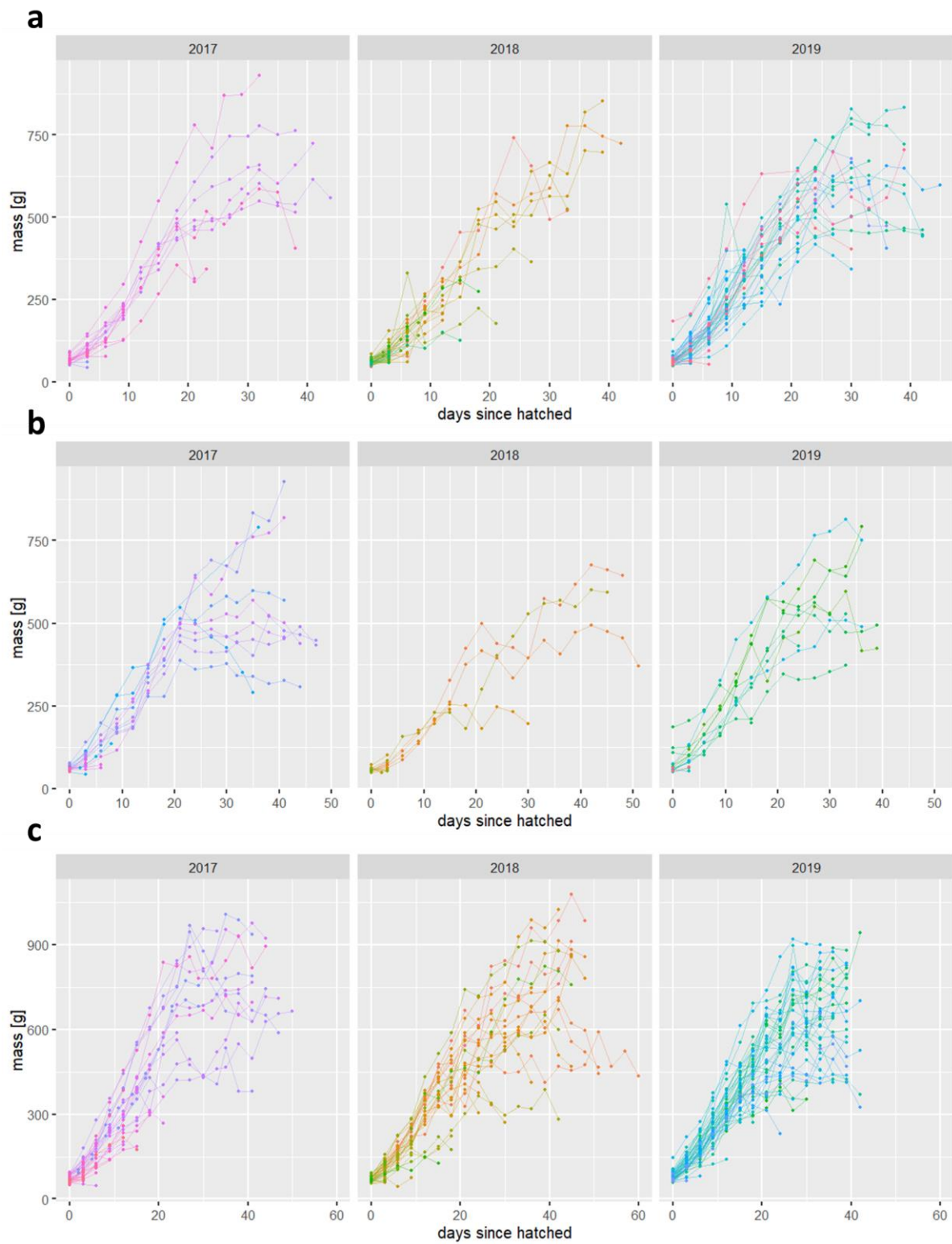|	Random sample 2017	Random sample 2018	Random sample 2019	Random sample 2020
Nest monitoring				
first egg laying	04-05-17	02-05-18	02-05-19	01-05-20
median egg laying	13-05-17	14-05-18	14-05-19	10-05-20
mean clutch size	2.7	2.72	2.74	2.8
±sd clutch size	0.61	0.58	0.54	0.55
(n) eggs	108	87	63	55
(n) nests	40	32	23	20
mean 3 egg volume	254.78	253.11	254.26	256.72
sd 3 egg volume	17.55	27.80	26.16	17.15
(n) nests	31	25	19	16
first egg hatching	28-05-17	29-05-18	01-06-19	25-05-20
median egg hatching	09-06-17	10-06-18	10-06-19	06-06-20
(n) eggs	108	87	63	55
failed clutches (%)	15	16	4	15
(n) nests	40	32	23	20
egg fates				
accident (%)	0.93	0	0	0
failed (%)	19.44	12.64	12.70	20.0
hatched (%)	77.78	80.46	87.30	74.55
predated (%)	1.85	6.90	0	5.45
(n) eggs	108	32	23	20
Enclosure monitoring				
(n) hatchlings	41	45	48	NA
(n) nests monitored	20	20	21	NA
chick fates				
fledged (%)	29.27	33.33	68.75	NA
dead (%)	24.39	46.67	29.17	NA
predated (%)	46.34	20.00	2.08	NA
first fledging	11-07-17	01-07-18	25-06-19	NA
fledglings per pair	**0.6**	**0.75**	**1.57**	**NA**

Figure 3: Chick growth curves from 2017 -2019 for a) random sample of lesser black-backed gull nests, b) nests of tagged lesser black-backed gulls c) random sample of herring gull nests

3. The dynamic flight of gulls in human-engineered landscapes

The primary output of this project is a PhD thesis entitled 'Wind energy for all! The dynamic flight of gulls in human engineered landscapes' (Sage 2022). The aim of this thesis was to gain a deeper insight into how atmospheric conditions influence the movement behaviour of lesser black-backed gulls, particularly in human-engineered landscapes in the context of wind farm development. This research was achieved by studying GPS tracked lesser black-backed gull flight behaviour at different scales, across and within populations, and by measuring and modelling flight behaviour and atmospheric dynamics on very fine scales.

The research presented in Sage 2022 provide fundamental ecological insight into the flight behaviour and decision making of lesser black-backed gulls as well as the impact of interactions between landscape structure and atmosphere on lesser black-backed gull behaviour. These fundamental insights are also applied to specific knowledge gaps surrounding the potential impact of offshore wind farms on lesser black-backed gulls, from developing new metrics to measure movement range in impact assessments to understanding how atmospheric environments can influence flight height in offshore wind farms.

The outputs of the PhD thesis are in many ways broader than the original project description and for a comprehensive overview of the project this thesis should be referred to directly (see supplementary file S1). However, as a brief overview for this report, below we provide a summary of the key thesis findings across the four research chapters of the thesis.

In Chapter 2 of the thesis, we measured movement range across colonies throughout the lesser black-backed gull range and examined how variability across relatively simple movement metrics could influence spatial conservation outcomes.

In Chapter 3 of the thesis, we found that lesser black-backed gulls respond to orographic lift in their terrestrial surroundings on a fine-scale and demonstrate knowledge of predictable corridors of uplift. We discuss how knowledge of uplift corridors can contribute to the spatial planning of new developments such as onshore wind farms (Sage *et al.* 2019).

In Chapter 4 of the thesis, we learnt that lesser black-backed gulls also regularly undertake thermal soaring and identified how the mechanics of different flight behaviours, such as circling and gliding, interact with the spatio-temporal dynamics of the thermal landscape to facilitate energy efficient flight (Sage *et al.* 2022). As in Chapter 3, knowledge of atmospheric landscapes can contribute to spatial planning of the landscape including onshore wind farms.

In Chapter 5 of the thesis, we quantified thermal soaring in lesser black-backed gulls over the North Sea, identified the environmental conditions under which thermal soaring occurs in a marine landscape where soaring opportunities are expected to be scarce, and made links between thermal soaring and flight altitude in the context of interaction with offshore wind farms.

Overall, the knowledge in the thesis (Sage 2022) can be used to better understand how human behaviour, even on very fine-scales, influences the flight environment for a generalist bird species, and can therefore also be applied to shaping future landscape engineering decisions.

4. Spatial distribution and flight metrics of lesser black-backed gulls from Schiermonnikoog

In this chapter we examine the breeding season movements of lesser black-backed gulls from Schiermonnikoog, focusing upon recording their spatial distribution, flight altitudes and flight speeds. By mapping the spatiotemporal distribution of lesser black-backed gulls it is possible to gain some insight into where lesser black-backed gulls are most commonly occurring and their potential for overlap with wind farm areas, specifically Gemini wind farm.

Breeding season GPS data was distinguished based on the first arrival of an individual within 1km of the colony after March 1st, until the last occurrence of an individual within 1km of the colony until August 31st. Within this dataset there were a small number of long-range exploratory movements which occurred (with individuals travelling back towards Belgium, across to the UK, or up to Norway before returning within the breeding season) which were removed from the dataset so that localised movements could be focused on.

4.1 Spatial overview

In Figure 4 we present a two-dimensional spatial raster map of GPS tracked lesser black-backed gulls from Schiermonnikoog as a density distribution. All data presented in this section was resampled to hourly time intervals to reduce the effect of spatiotemporal autocorrelation. The most regularly utilised areas can be identified alongside the overall gull distribution. Outside of the breeding colony (the mostly highly utilised cells in the centre of the distribution), occurrence was highest inland, distributed over several favoured foraging areas. Popular inland foraging destinations inland included agricultural areas in the province of Groningen, the Lauwersmeer, Groningen city, and a waste site in Drenthe. At sea gull distributions were more sparse, mostly occurring directly north of the colony and spreading out over a wide geographic area. Several areas of high utilisation occurred at the very north and western edges of the movement range.
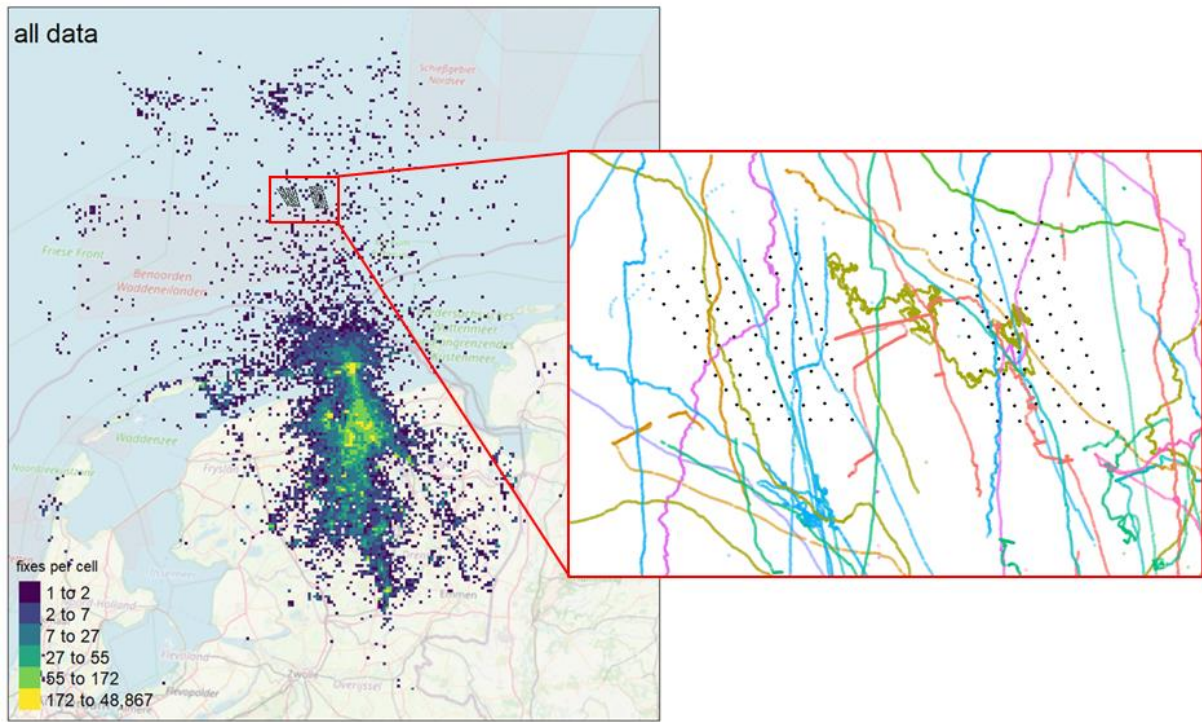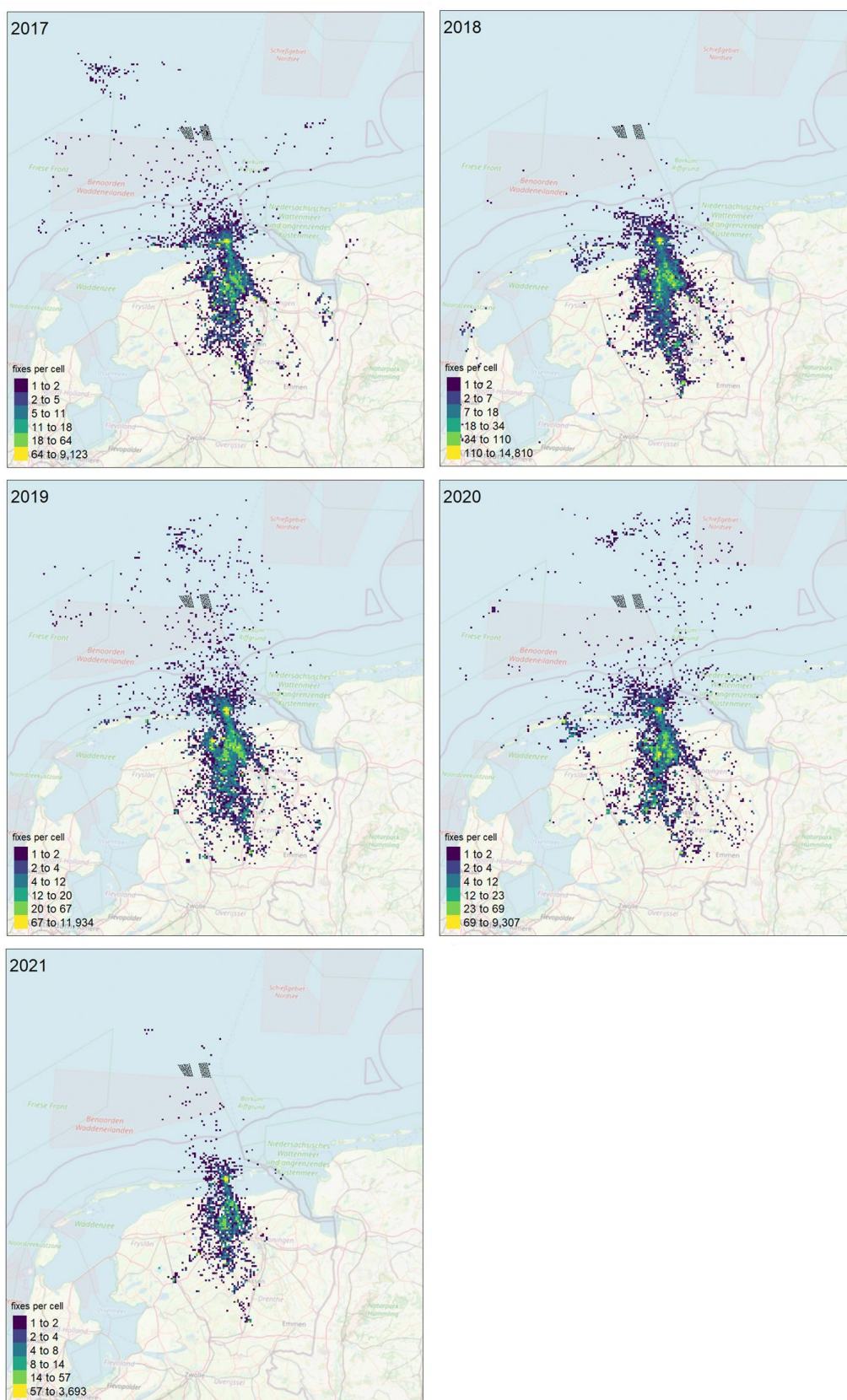
Figure 4: GPS breeding data overview. Map shows two-dimensional spatial raster map of GPS measurements of tracked lesser black-backed gulls from Schiermonnikoog, 2017-2021. Fixes per cell represent 1 hour time intervals based on all data being resampled to the nearest hour for each individual. Inset shows all GPS measured tracks through the Gemini wind farm area 2017-2021. Colours represent different individuals and black dots show turbine locations.
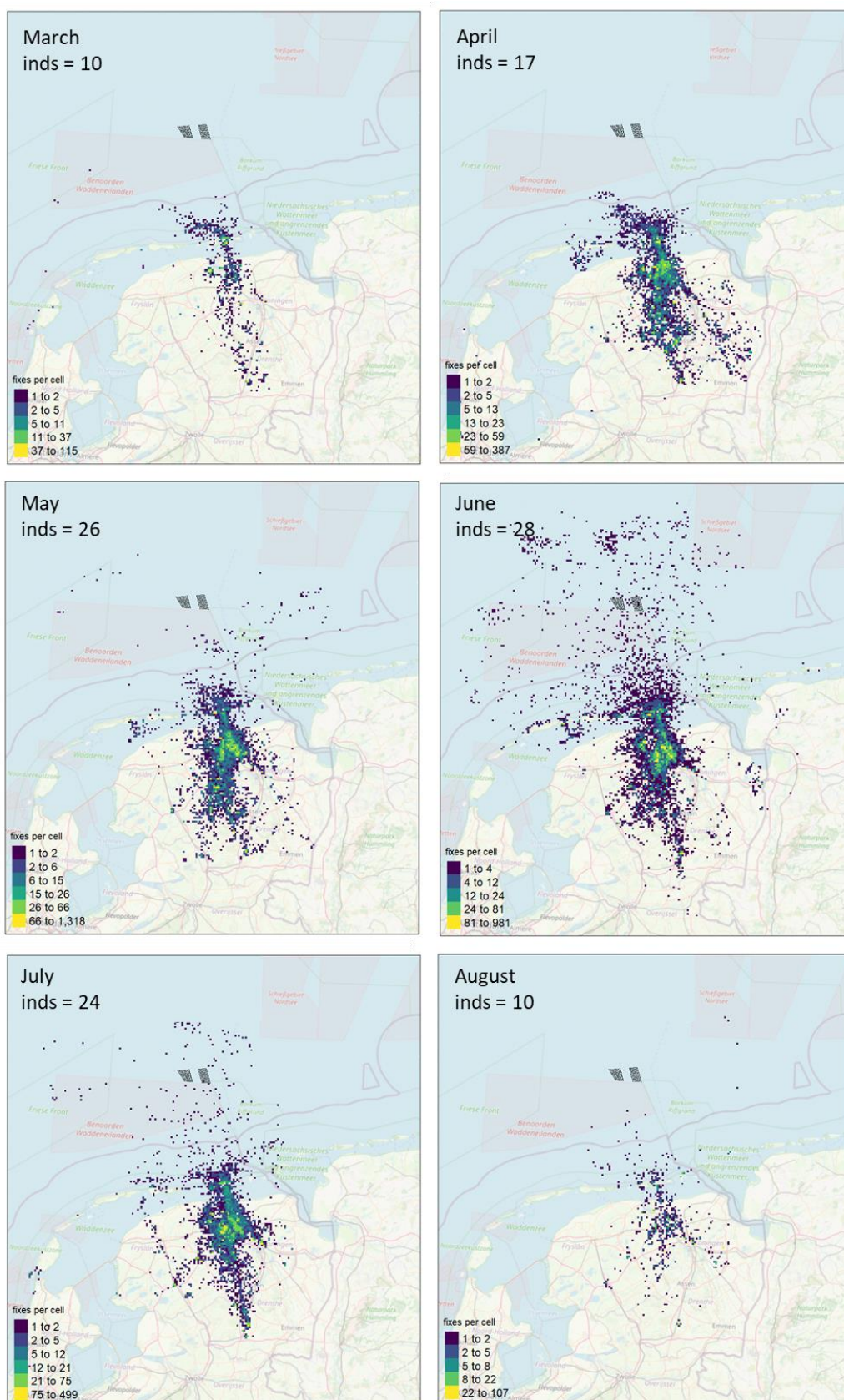
Figure 5: Two-dimensional spatial raster map of GPS measurements of tracked lesser black-backed gulls from Schiermonnikoog, grouped according to year, 2017-2021

Figure 6: Two dimensional spatial raster map of GPS measurements of tracked lesser black-backed gulls from Schiermonnikoog, grouped according to calendar month (March until August), 2017-2021

In Figure 5 the two-dimensional spatial raster maps of GPS data are presented for each year of the study, allowing the consistency of space use between years to be examined. The number of individuals present each year (and therefore the amount of GPS data) varied, generally decreasing each year following the end of tag deployment (see Table 1). Upon visual inspection, there is no distinctive difference in space use between years. Terrestrial space use appears similar, with similar areas of foraging interest. Use of marine areas was lower in 2018 and 2021 (noting that the dataset in 2021 was considerably smaller than in all other years).

Figure 6 presents two-dimensional spatial raster maps of the GPS data for each month of the breeding season (grouping all years together). Temporal variation exists in both the number of individuals present (and therefore the amount of data) as well as the two-dimensional space use each month. Presence of gulls was typically lower in March and August, when many birds have either not yet returned, or have already left the breeding area. Marine space use was highest in June and July.

4.2   Proportion of time spent at sea

Lesser black-backed gulls are a generalist coastal species that make both marine and terrestrial foraging trips. The degree to which birds use different foraging areas is highly variable, including between different breeding colonies (see Sage et al 2022 Chapter 2). Therefore, estimates of marine use, or more specifically estimates of interactions between specific breeding colonies and offshore wind farms, are influenced by the amount of time gulls spend at sea.

We measured the overall proportion of time Schiermonnikoog lesser black-backed gulls spend at sea for different years of the project study, to examine broadly how likely gulls are to be at sea and how this changes between years. Additionally, we measured the proportion of time gulls spend on land, not including inside the colony (defined as 1km radius from colony center), to provide some insight into the contrast between time spent in marine or terrestrial areas, mainly for foraging.

Lesser black-backed gulls tagged on Schiermonnikoog breed on the north coast of the island and largely fly north to marine areas, or south to cross back across the island and Wadden Sea to reach mainland foraging destinations. Therefore, to identify specifically marine flight which did not include intertidal areas such as the Wadden Sea, a latitudinal cut off point was chosen based on the Northernmost tip of Schiermonnikoog island (at latitude = 53.52) and all movements north of this line were counted as marine. An overview of proportion of time spent at sea in comparison to other colonies, which does include the Wadden Sea, is presented in Sage et al Chapter 2. Proportion of time at sea or land is calculated as the sum of all GPS timesteps fitting the definition of at sea or at land respectively (not including points in the colony) divided by the sum of all timesteps (again not including points in the colony). We also calculated the weighted average proportion of time spent at sea and on land across all months and years (weighted by the summed timesteps of the data per month) to give an overall average amount of time spent at sea and land.

Table 6: Summary of proportion of time spent in marine or terrestrial areas per year

Year	Proportion of time at sea	Proportion of time on land
2017	0.035	0.84
2018	0.016	0.85
2019	0.041	0.81
2020	0.045	0.81
2021	0.021	0.86
Weighted average over all years	0.032	0.83

Table 7: Summary of proportion of time spent in marine or terrestrial areas per month

Year	Proportion of time at sea	Proportion of time on land
March	0.065	0.71
April	0.030	0.81
May	0.019	0.88
June	0.042	0.81
July	0.027	0.84
August	0.056	0.79
Weighted average over all months	0.032	0.83

Overall Schiermonnikoog lesser black-backed gulls spend a small proportion of their time in fully marine areas (Table 6), in this case the North Sea. Overall, only 3.2% of time was spent here. The proportion of time spent on land was far greater, upwards of 80% each year, in agreement with Sage et al 2022 Chapter 2, which reports 83.5%. The remaining time away from the colony is likely commuting over the Wadden Sea on route to terrestrial foraging locations. This is supported by the estimate of 16.5% of time spent at sea in Sage et al 2022 Chapter 2, which includes the Wadden Sea. The proportion of time spent at sea also varies between years, with a minimum of 0.16 (2018) and maximum of 0.045 (2021) and throughout the season, with peaks in March and August, and to a lesser extent June (Table 7). Early and late marine movements may relate to exploratory marine trips, whilst marine trips in June could be exploratory failed breeders or marine trips associated with chick rearing. This pattern to marine movement also aligns somewhat with the observed pattern in longer movement distances (Sage et al 2022, Figure 2.A.2) and overall Schiermonnikoog gulls tend to travel further at sea than at land (Sage et al 2022, Table 2.A.4). However, since terrestrial trips are far more common, long trips to land still appear with greater frequency compared to sea. Note that the average over all months yields a higher proportion of time spent at sea than the average over all years; this is

likely due to the high proportion of time spent at sea in March and August, when less birds are present, resulting in an overrepresentation of smaller datasets from these months in the average value.

4.3   Flight metrics

More precise knowledge of the flight attributes of lesser black-backed gulls, such as flight altitude and speed may give insight into the potential for lesser black-backed gulls to interact with offshore wind farms, particularly regarding their likelihood of collision. We measured both flight altitude and point to point velocity (the speed measured between successive GPS measurements by dividing distance between points by time interval) for flight at sea (as defined in section 3.2). All points were first resampled to hourly data measurements (based on nearest whole hour) to reduce the effect of spatiotemporal autocorrelation. Flight was then defined as all points where point to point velocity exceeded 2 ms^{-1}. Flight altitude and point to point velocity were then presented as histograms (Figure 7) showing the distribution of metrics encountered in the data. Additionally, the proportion of flight occurring within the RSZ was calculated by summing up the time intervals of all flight points that occurred at altitudes within the RSZ (> 23.5 m and < 153.5 m) and dividing by the total sum of time intervals for all marine flight.
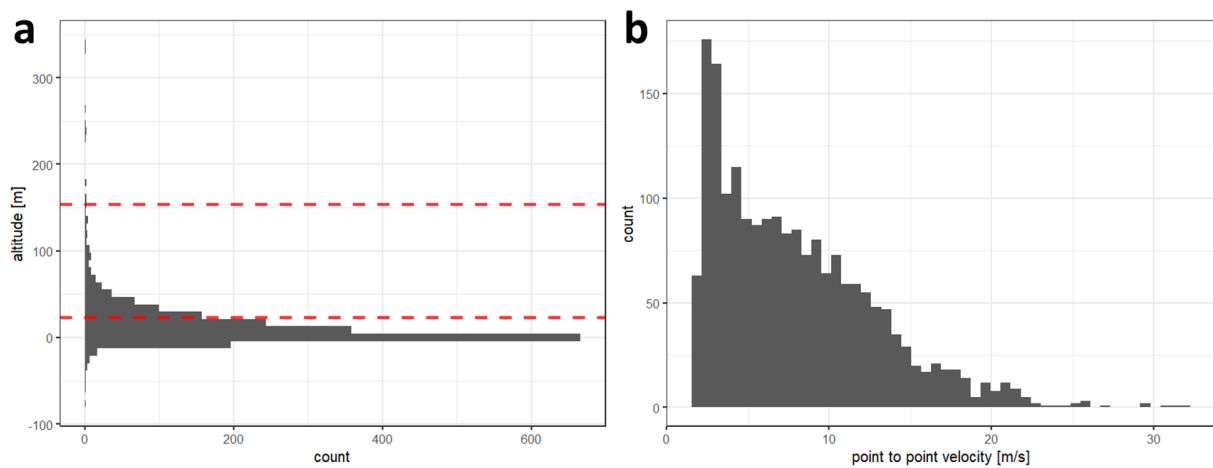

Figure 7: Histograms displaying distributions of a) altitude and b) two-dimensional velocity measured by GPS tracked lesser black-backed gulls between 2017-2021, resampled to hourly time intervals. Red dashed line represents upper and lower boundary of the rotor swept zone (RSZ) of a Gemini wind turbine.

The median point to point velocity for marine flight was 7.02 (interquartile range 3.87 – 11.01) ms^{-1}.

The median altitude of marine flight was 5.36 (interquartile range: 1.64 – 19.36) m and 17% of flight occurred within the RSZ. The majority of marine flight occurred below the RSZ whilst very little occurred above. For a more detailed overview of flight altitude at sea and in relation to weather see attached thesis Sage 2022 Chapter 5. Flight behaviour in response to weather over land is described in detail in Sage 2022 Chapters 3 and 4. Overall flight heights are comparable to previous studies (Corman & Garthe 2014; Ross-Smith *et al.* 2016; Thaxter *et al.* 2017a) and demonstrate that lesser black-backed gulls from Schiermonnikoog do fly within the RSZ relatively regularly.

5. Reassessing the impact of Gemini on breeding Schiermonnikoog lesser black-backed gulls

The tracking of individual lesser black-backed gulls from the breeding population on Schiermonnikoog provides specific insight into the degree of movement occurring through Gemini wind farm. This information can be used to draw comparisons with some of the estimates about gull passages through the wind farm which were made in the Appropriate Assessment of Gemini (Gemini AA, 2012) and discuss where some of the estimates made in the Appropriate Assessment could be improved. The Appropriate Assessment makes an estimate of the total number of passages through the wind farm per breeding season for the entirety of the Schiermonnikoog population (estimated at 5133 breeding pairs). This figure was then used as an input to collision risk models. Our aim was therefore to re-estimate the total number of passages through the wind farm per breeding season for the entire population based on extrapolating from the number of measured GPS tracks through the wind farm area.

The Appropriate Assessment defines a region of impact (deemed AA area) through which bird passages are counted, defined by an area drawn from the nearest edges of Gemini wind farm to a 100km radius delineating the edge of the lesser black-backed gull range (see Figure 1). The logic behind this is likely based on the fact that in order to reach regions beyond the wind farm, gulls are likely to pass through the wind farm, and therefore the wind farm may impact movements beyond. We specifically counted GPS passages through wind farm area (Figure 8) and through the AA area (Figure 9). A passage was visually counted based on an individual track entering the region of impact, or entering within the turbine boundary of the wind farm (not including tracks that only passed between the east and west section of the wind farm, although these were counted as part of the AA area). Note in Figures 8 and 9, the measurement interval on GPS trackers usually switched from high resolution to lower resolution above latitudes of 54.2, but tracks were considered as passages whether they were low or high resolution.

For each year of the study, we counted the total number of wind farm passages and total number of AA area passages, as well as the number of different individuals passing through (Table 8). In general, the number of wind farm passages and number of AA area passages were very similar (indicating that in general gulls who travel to areas beyond the wind farm often also travel through the wind farm). Overall number of passages were low, with far more passages being observed in 2019 than in all other years.

We then estimated the population wide number of passages for the wind farm and AA area per year, based on the GPS counts. A constant population estimate of 5133 breeding pairs was assumed, the same as was used for the Appropriate Assessment. For each year the number of individuals in the entire GPS sample was counted and used to measure the proportion of the Schiermonnikoog population that was presented (number of individuals/(number of breeding pairs × 2)). The number of passages for that year and area was then divided by the proportion of the Schiermonnikoog population represented to extrapolate the estimates of population wide passages.

The Appropriate Assessment estimates a total number of breeding season passages of 67186, or 20156 when a correction factor of 0.3 was applied to account for the lower number of gull sightings above latitudes of 53.6 (Camphuysen & Leopold, 1994). This uncorrected estimate was found to be a very large overestimate in all years when compared to the GPS based estimates. The corrected estimate was also found to be an overestimation, although the degree to which it was an overestimation varied considerably between years. In 2017 this estimate was an order of magnitude higher than the GPS based estimate, whereas in 2019 the GPS based estimate was around half the AA

based estimate. The small individual sample size and high individual variability is likely to be a large driver of uncertainty around the GPS based estimate between years, but changes in food availability and presence are likely to also play a role in the areas which birds use at sea. The proportion of time spent at sea also varied between years (Table 6), but there is not a clear link between the proportion of time spent at sea and the number of passages through the wind farm. Whilst in 2019 use of sea areas was relatively high compared to other years, 2020 showed a higher proportion of time spent at sea, so an increase in time spent at sea alone does not explain the unusually high number of wind farm passages in 2019. Other factors such as individual variability and upwellings in certain food resources in different sea areas are likely to play a role here.

5.1   Recommendations for future effect studies

From this study we can make conclusions about the effectiveness of the Appropriate Assessment approach and identify areas where these kinds of assessments could be improved. Firstly, accounting for reductions in gull density with distance from colony makes an important difference. The uncorrected Appropriate Assessment estimate of passages was a much larger overestimation than the corrected estimate. However, more detailed examinations of the proportion of time gulls spend at increasing distances from the colony (Sage 2022, Chapter 2) show that lesser black-backed gulls from Schiermonnikoog spend 95% of their time within 69 km of the breeding colony and 90% of their time within 40km, so the amount of passages occurring in the AA area or wind farm will be less than the 0.3 correction factor currently accounts for. This is due to a rapid decrease in time spent at increasing distances which was observed across all LBBG colonies studied in Sage 2022, Chapter 2, where we additionally advise that future apportioning assessments model gull occurrence as a continuous time distance function. Moreover, this approach is likely also applicable to other colonial breeding seabirds. Secondly, the Appropriate Area assumes gulls are just as likely to be moving over sea as over land, which we also see from the GPS data of Schiermonnikoog is not the case: the proportion of time spent at sea was only 0.032. The degree of land or sea utilisation by LBBG is driven by many factors, such as food availability and quality, intraspecific competition. We therefore advise against estimating time spent on land or sea by any LBBG colonies based on available area of each alone and where possible effort should be made to determine the areas most utilised by colonies specifically. Thirdly, variation between years and throughout the breeding season is large, as shown here for Schiermonnikoog but also for many other LBBG breeding colonies (Sage 2022 Chapter 2), so visual counts used as the basis for any kind of assessment estimates should be taken comprehensively across multiple years and periods in an attempt to capture some of this variation. It remains difficult to quantify the minimum number of years needed to capture a significant amount of interannual variation, although sampling size studies have been conducted for specific purposes, such as characterising area used by tracked seabirds (Thaxter *et al* 2017b).   Finally, it is important to note that the GPS based estimates are extrapolations from a small number of individuals, and are therefore also liable to large amounts of variation, which have influence over all the above conclusions. Movement estimates based on much larger datasets (see Sage et al 2022, Chapter 2) are able to provide far more robust estimates of lesser black-backed gull behaviour in a more generalised way.
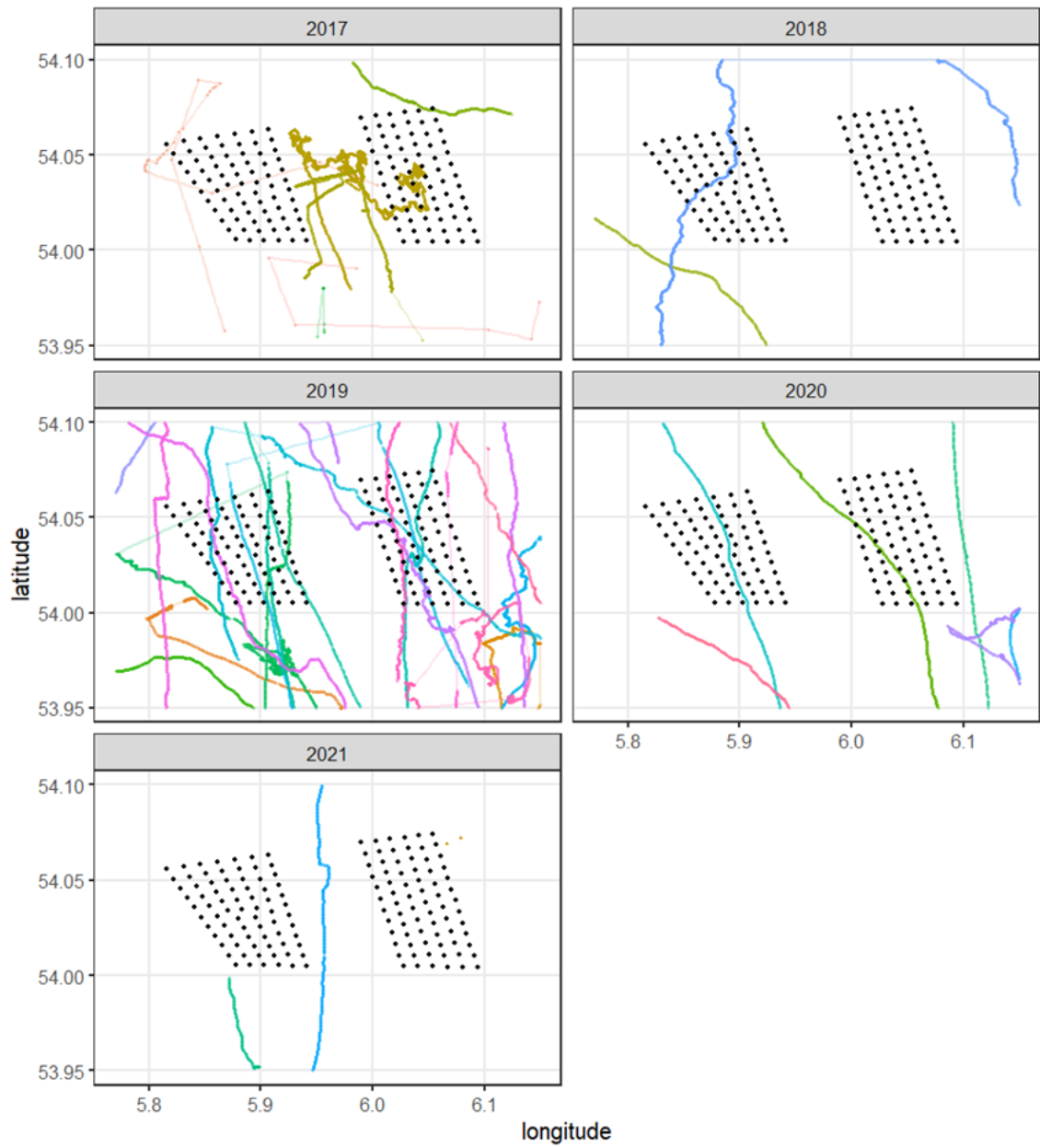
Figure 8: Maps of GPS measured passages through Gemini wind farm for the years 2017-2021. The colour of each within a yearly plot is unique to an individual per day of the year.
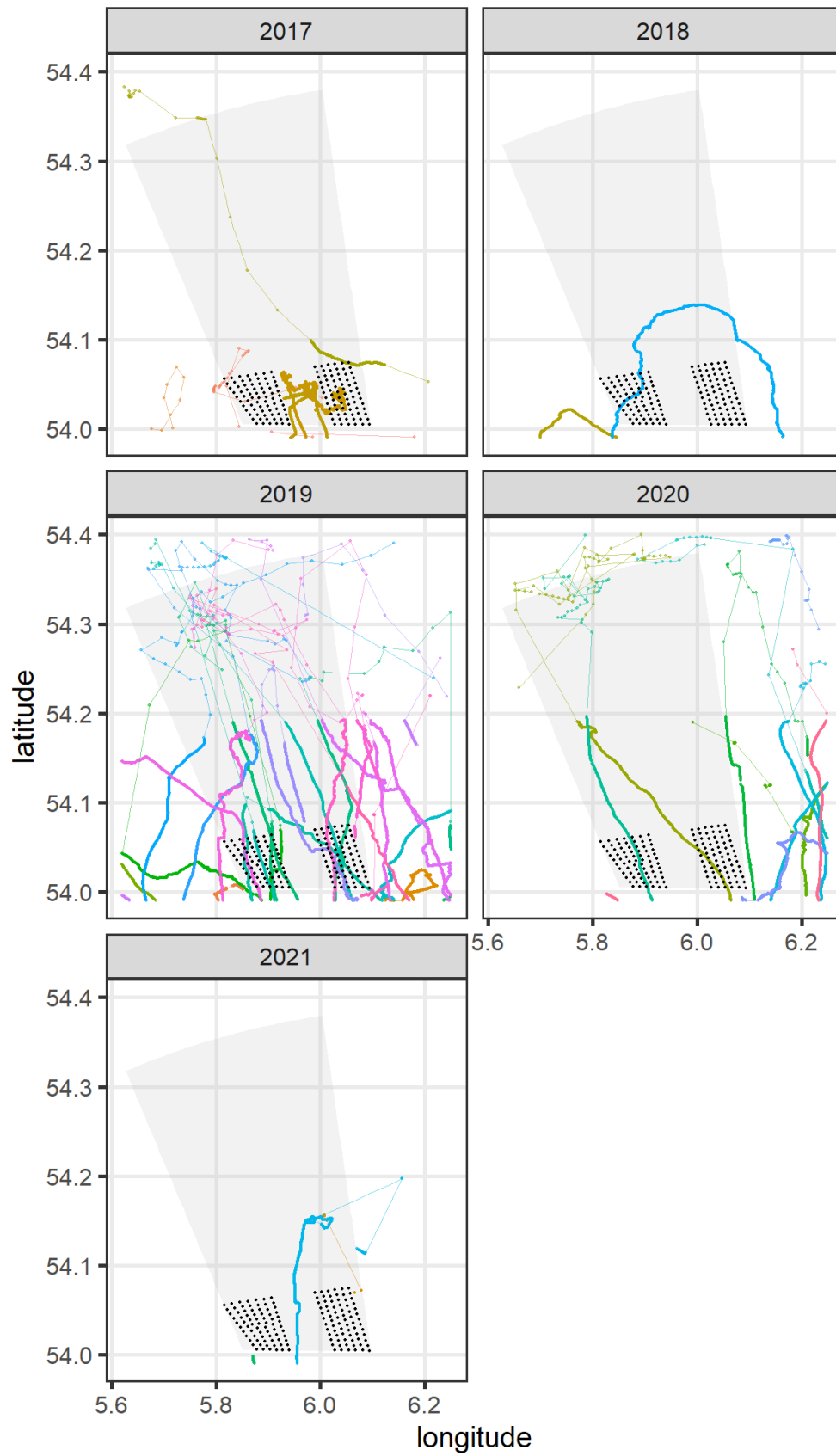
Figure 9: Maps of GPS measured passages through the AA region for the years 2017-2021. The colour of each within a yearly plot is unique to an individual per day of the year.

Table 8: Counts of wind farm and Appropriate Assessment (AA) region passages per year of study, and estimate of population wide passages based on GPS measured passages per year.
* assuming a constant population size of 5133 breeding pairs, as was used in the Appropriate Assessment.

year	number of individuals	Proportion of Schiermonnikoog represented*	Wind farm passages	Individuals passing	AA area passages	Individuals passing	Population estimated passages per year (WF)	Population estimated passages per year (AA)
2017	20	0.00195	3	4	4	4	1540	2053
2018	23	0.0024	1	1	1	1	466	466
2019	13	0.00127	11	5	16	5	8687	12635
2020	11	0.00107	2	1	4	2	1867	3733
2021	6	0.00058	0	0	2	1	0	3422

6. Three-dimensional movement within Gemini wind farm

The overall number of tracked lesser black-backed gulls forming passages through Gemini wind farm throughout the study period was low, particularly in comparison to other locations, such as terrestrial areas, where gulls regularly forage. Visually there is little evidence that gulls avoid the wind farm area, but rather that they rarely travel so far out to sea. As such the potential for quantitative investigation into flight metrics and behaviour which focus only upon movements in the wind farm is limited. We therefore focus more closely on understanding spatial distribution and movement behaviour (Chapters 2 and 3) and on understanding the response of gulls to their aerial environment (thesis Sage 2022). However, by exploring ways of visualising the movement behaviour of lesser black-backed gulls through Gemini wind farm, it is possible to qualitatively examine the types of behaviour occurring, such as foraging or commuting, or possible to visually identify unusual behaviours that could be connected with avoidance. Therefore, in this chapter we present spatial overviews of lesser black-backed gulls movements through the wind farm in relation to important behavioural metrics: velocity and flight altitude, as well as in relation to important collision related metrics: flight altitudes in the RSZ and horizontal distance to a turbine.

For all maps movement tracks within and immediately surrounding the windfarm area were extracted from the rest of the data. Tracks were then visualised, coloured according to continuous changes in altitude (Figure 10) continuous changes in point-to-point velocity (Figure 11), a discrete measure of whether or not the measurement altitude fell within the RSZ (Figure 12), using the same definition presented in section 3.3, and a discrete measure of whether or not the measurement fell within 75 m (the turbine blade length of 65 m plus 10 m accounting for positional accuracy) of a turbine centroid. For this final measure only tracks that occurred within the wind farm itself were considered, as all other tracks were known to be outside of the 75 m range.

Interactive versions of these maps, where specific values, individuals and time stamps for every measurement can be explored, are provided as supplementary files S2.
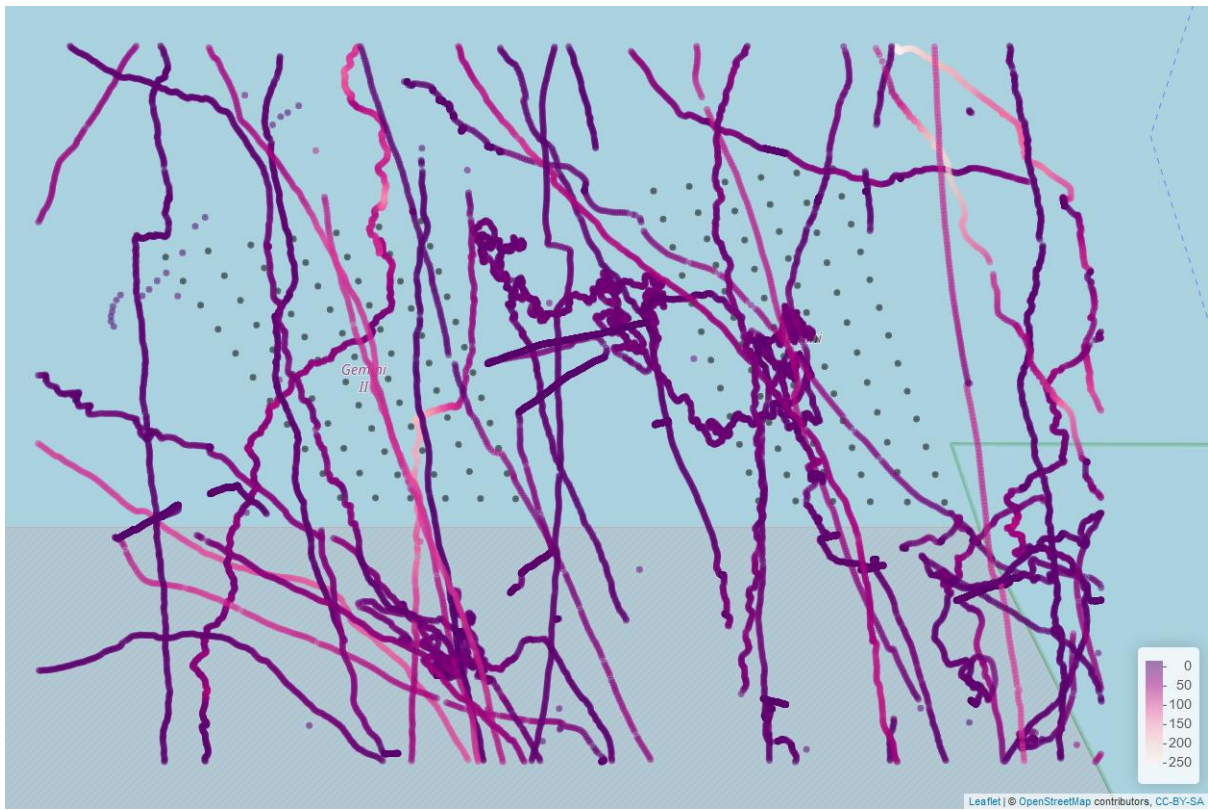
Figure 10: Overview of movement in Gemini wind park showing altitude (m above mean sea level) per position.
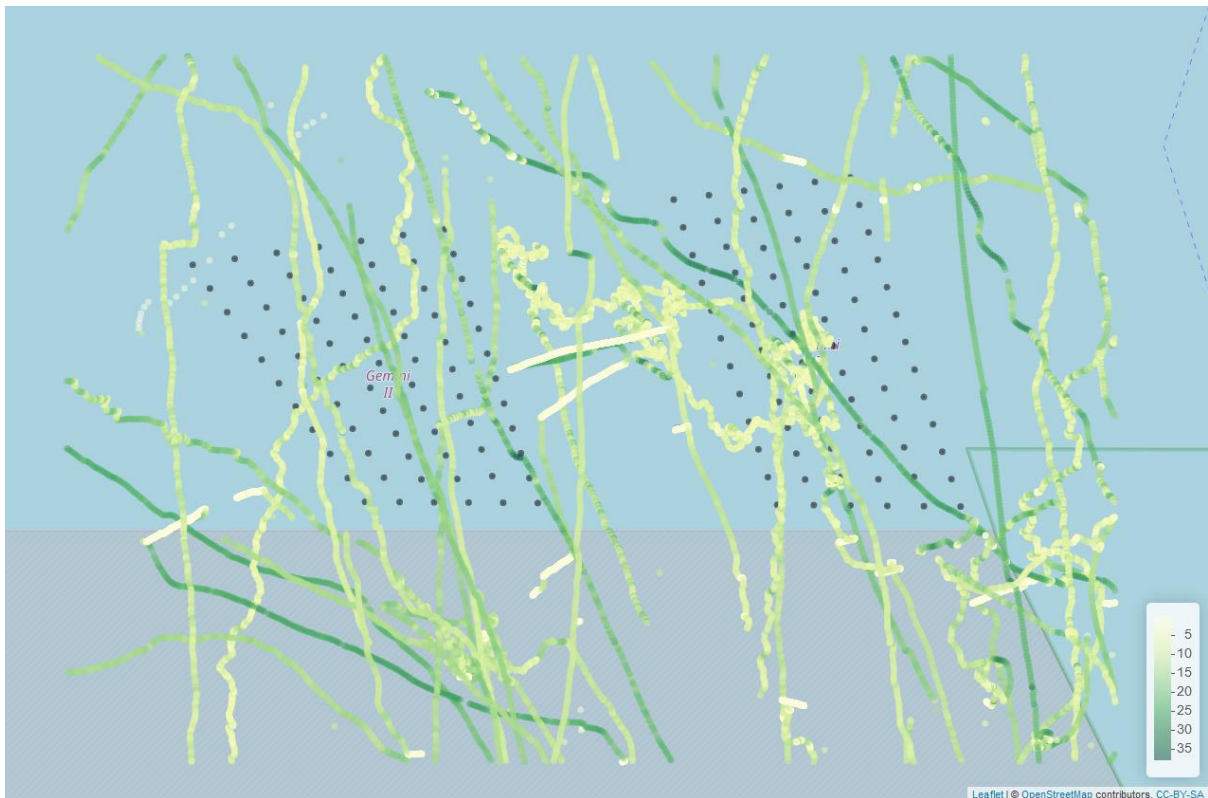

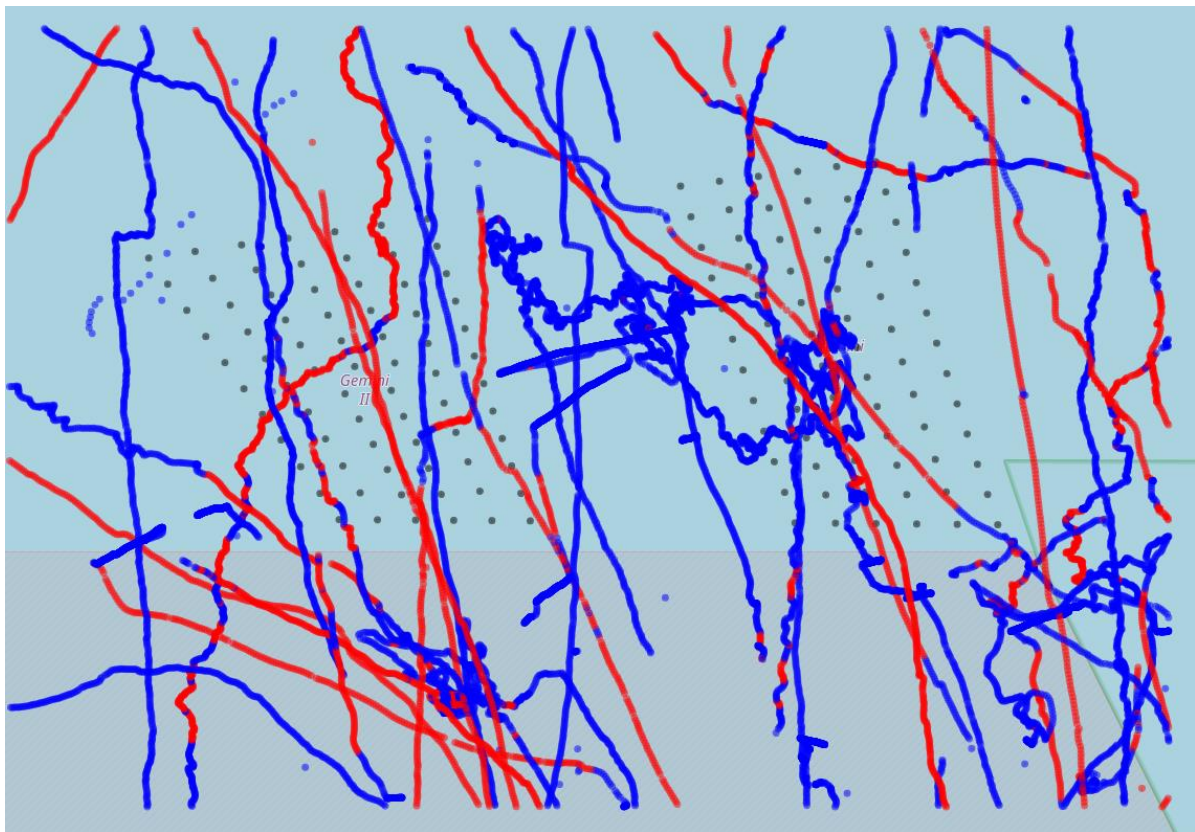*Figure 11: Overview of movements in Gemini wind park showing ground speed (m s^{-1}) per position.*

Figure 12: Overview of tracked lesser black-backed gulls in Gemini showing where measurements occurred at altitudes outside of the RSZ (in blue) and inside the RSZ (red).
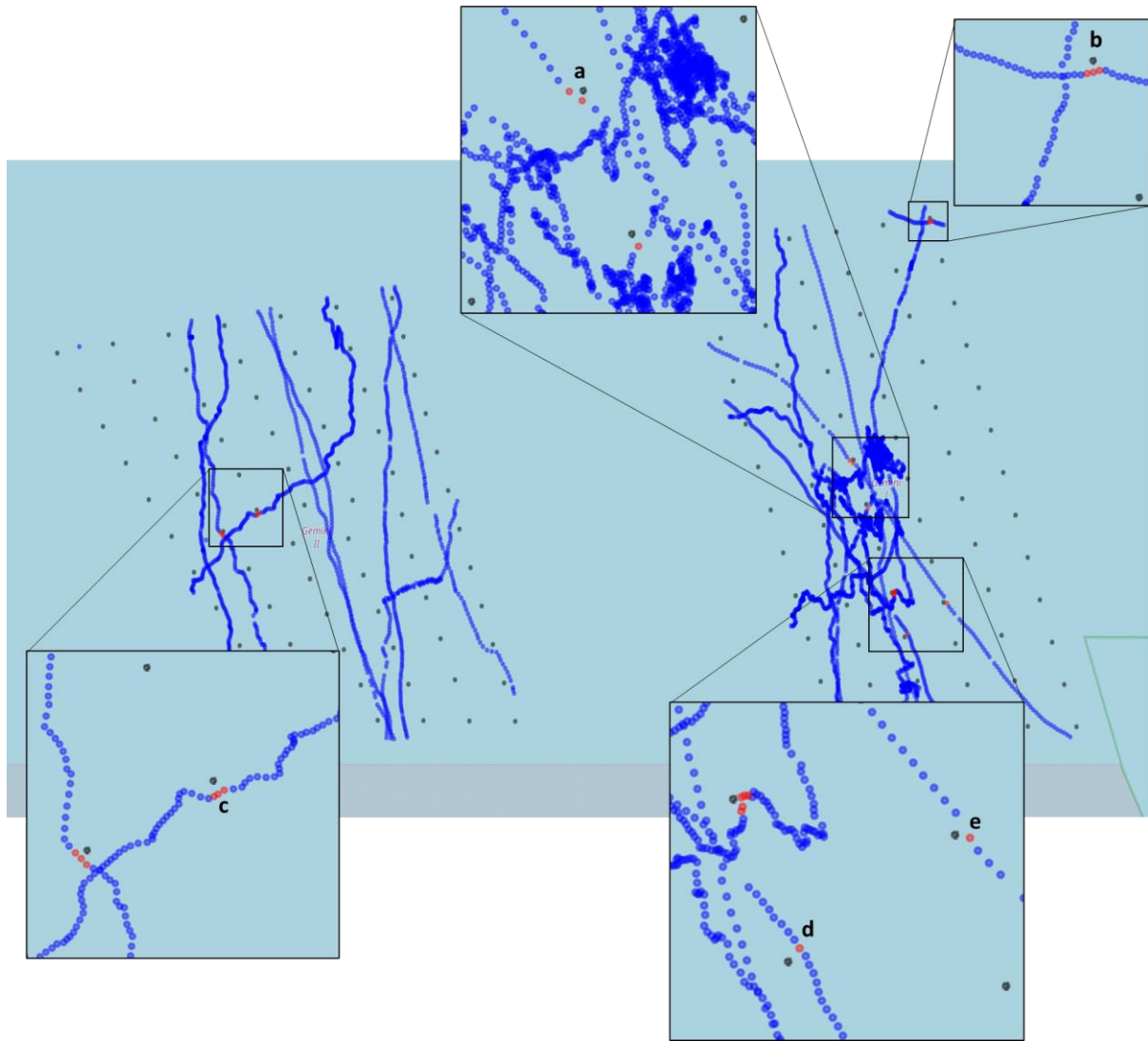
Figured 13: Overview of tracked lesser black-backed gulls in Gemini (between turbines) showing where measurements occurred within 75m of a turbine (red), measured in 2D. Four highlighted boxes show close-up views of all these instances. Letter labels refer to each instance where flight occurred within 75 m of a turbine and at altitudes within the RSZ.

6.1   Behaviours observed within Gemini wind farm

Visual inspection of the tracked lesser black-backed gulls passing through Gemini wind farm reveals a range of different behavioural patterns. Most tracks were long, straight and directional. These movements are indicative of commuting flights, whereby gulls take directional flights to specific (usually foraging) areas. At Schiermonnikoog, several hotspots of foraging activity occur in the very north of the marine foraging range (see Figure 4) and commuting passages through Gemini often end up in these areas, particularly in 2019 (also see Figure 9). More tortuous passages also occur, which are suggestive of more searching behaviour. These could be indicative of active searching and foraging, or a combination of searching, foraging and commuting; in many cases bird still pass through the area with relatively little deviation to their movements. Very occasionally we observe very active foraging behaviour centred on the wind farm area. The main example of this occurs in 2017 (Figure 8) where an individual undertakes highly tortuous movement in the eastern wind farm regions and in between the east and west wind farm region, at low altitudes with no clear directional passage

through the wind farm area. Birds occasionally sit on the water, either for brief periods of time, often during foraging, or for longer periods of time usually associated with rest. These second examples are most identifiable in visual maps, as birds move with the current (Shamoun-Baranes *et al.* 2011) and GPS tracks leave straight lines moving at very slow speeds (Figure 11). These were not observed between the wind farm turbines, but did occur in the immediate wind farm surrounds and between the two wind farm regions. Specific flight behaviours such as thermal soaring can also be observed within the wind farm, which are characterised by tightly tortuous flight in one direction, often not in the overall direction of travel, associated with an increase in altitude during tortuous flight. A clear example is seen in 2019 in the western wind farm region, where a bird uses thermal soaring directly between turbines to reach altitudes over 100 m as part of a south bound commute (Figure 10). For more details on thermal soaring flight at sea and its implications for offshore wind farm interactions see thesis Sage 2022 Chapter 6.

6.2   Flight altitude inside Gemini windfarm

Flight altitude inside the wind farm was generally relatively low, with some rarer moments of flight at higher altitudes. Flight altitudes above 100 m were mostly observed in relation to ephemeral behaviours like thermal soaring, whilst commuting and foraging flights were usually below 50 m. Flight within the RSZ is common (Figure 12), usually below hub height, and is most associated with commuting flight.

6.3   Horizontal proximity of birds to turbines

In general flight within close horizontal proximity to turbines was rare, far rarer than flight at altitudes within the RSZ, such that the occasions can be summarised in a few number of instances. This is partially understandable as birds are unlikely to come within close horizontal proximity to a turbine more than once or twice within a passage through the wind farm (unless there is some level of attraction to turbines) whilst flight within the RSZ can occur throughout a wind farm passage. Some wind farm passages occurred in north-south alignment with the north-south turbine alignment, whilst other passages saw birds crossing between turbines during more diagonal passages or more tortuous movements.

Eight separate instances of a flight path coming within 75 m of a turbine were observed. Five different individuals came into close distance (with two individuals coming into close distance 2 and 3 times respectively) and instances were identified in all years except 2021. Of the eight instances, five instances that brought tracks within 65 m of a turbine were also within the RSZ (Figure 13). Therefore, these instances can be interpreted as the moments with the highest collision risks. All of these five instances occurred during commuting type passages through the wind farm, where the majority of the passage was within the RSZ. Two instances occurred within one passage by individual 4524 on the 25-06-2019. One of the instances occurred when an individual briefly passed within the most north easterly wind turbine, otherwise not passing through the wind farm at all.

6.4   Turbine avoidance

Occasionally movements were observed that could be interpreted as some kind of micro-avoidance behaviour, where a gull changes direction near to a turbine, sometimes with associated changes in altitude and direction. The clearest example of this is on 24-06-2019, when individual 5554 is passing north bound through the easternmost edge of the west Gemini region. Movement direction is aligned with a turbine and therefore potential collision, but at around 138 m from the turbine the bird turns sharply west, its altitude sharply increases from around 30 m to around 60m, and its speed briefly

decreases then increases, before resuming its commuting path in a similar style along the next row of turbines.

6.5   Measuring lesser black-backed gull movement in a wind farm: potential and limitations

One of the key aims with tracking individual lesser black-backed gulls from Schiermonnikoog in this project was to obtain high resolution three dimensional flight tracks of gulls inside of Gemini wind farm in order to gain more understanding of offshore flight behaviour and ultimately explore the possibility of measuring collision risk. From this project we have been able to measure individual gull movements at very high resolution within Gemini and the quality of the information gained is very high. We are able to distinguish types of behaviour on a fine scale, from foraging to commuting to thermal soaring. We are able to clearly measure parameters that are important for quantifying avoidance behaviours and collision risk; flight altitude, distance to turbines, changes in flight velocity and altitude. There are opportunities to incorporate other important factors, such as wind direction or turbine orientation and operation status. Ultimately, high resolution GPS tracks of gulls provide the necessary information that could be used to model avoidance. However, whilst the quality of the tracks are high, the overall quantity of tracks is too low to perform the analysis that would be needed to model collision risk in a statistically robust way. Only 17 passages were identified across all five years of data collection (Table 7) and Schiermonnikoog gulls rarely travel as far out to sea from the colony as Gemini is located. Whilst we can identify moments within tracks that are indicative of certain behaviours, such as avoidance, it is not possible to measure the statistical significance of impacts of these behaviours.

Overall, the high-resolution GPS tracks measured in Gemini provide a vital insight into gull behaviour within wind farms and provides an initial input of knowledge that can be used to conceptualise methodological approaches for more quantitative studies of collision risk, should more data be gathered in the future. One such approach might to be to utilise individual based modelling to create a null model, which can be compared to true wind farm passages according to metrics of avoidance (e.g., altitude and speed) to identify potential avoidance behaviours.

7. Conclusions

The overall aim of this project was to gain insight into the behaviour of lesser black-backed gulls from the Schiermonnikoog breeding population and their potential interactions with offshore wind, particularly collision risk. This aim was investigated mainly though quantifying movements of individuals from Schiermonnikoog using GPS tracking integrated with environmental data. The main output of this project is presented in the PhD thesis Sage 2022 which had the overall aim to gain deeper insight into how atmospheric conditions influence the movement behaviour of lesser black-backed gulls, particularly in human engineered landscapes and in the context of wind farm development. This report provides additional overviews and knowledge regarding the space use, movement behaviour and wind farm interactions of Schiermonnikoog lesser black-backed gulls.

Below we summarise the key pieces of information and findings presented in this report.

1. By creating an overview of collected GPS data we are able to identify fundamental information on arrival and departure dates at the colony area, both across years and individuals, allowing for more precise understanding of breeding season timings (**Chapter 2**).
2. The detailed breeding monitoring carried out through fieldwork at the Schiermonnikoog colony, presented in **Chapter 2**, gives further insight into breeding season timings as well as breeding success, which can be directly compared with other long term monitoring projects.
3. In **Chapter 3** we provide an overview of the main output of this project, the PhD thesis entitled 'Wind energy for all! The dynamic flight of gulls in human engineered landscapes'.
4. In **Chapter 4,** by examining the spatial distribution of lesser black-backed gulls breeding on Schiermonnikoog we gain new insights into their foraging behaviour and identify important commuting zones and foraging areas both on land and at sea.
5. By quantifying the amount of time lesser black-backed gulls spend in offshore or onshore areas (**Chapter 4**) we determine that the vast majority of foraging is carried out on land rather than at sea.
6. By explicitly measuring flight altitude (**Chapter 4**) we gain a more three-dimensional understanding of lesser black-backed gull behaviour, and identify that whilst the majority of flight occurs below the RSZ, flight at altitudes within the RSZ occurs regularly (17% of flight time).
7. In **Chapter 5** we reassess the impact of Gemini on lesser black-backed gulls using the framework of the original Appropriate Assessment with newly acquired knowledge based on GPS tracking, and identify that large estimates of foraging range which do not fully account for reduced bird density with increased distance from colony may contribute to overestimations of impact. We also note that gull behaviour is highly variable, between years and between individuals, so long term studies of many individuals play an important role in measuring gull behaviour and wind farm impacts.
8. Visualising lesser black-backed gull movements on a fine scale through Gemini wind farm (**Chapter 6**) allows us to identify different types of movement behaviour and connect them to certain collision risk factors such as altitude or turbine proximity in order to gain insight into when gulls may be most at risk. We are also able to identify movements that have the characteristics of micro-avoidance behaviour.

Collision risk for gulls passing through an offshore wind farm area depends on flight altitude, speed, types of avoidance behaviours and flux of bird passages through the area, all of which have been examined in this project. Whilst this project does not make the steps to estimate collision risk, the research presented here provides new insight into behaviour associated with collision risk and

information here can potentially be used as input for future studies or models that explicitly estimate collision risk.

7.1 General recommendations for future study and conservation practice

Based on the research presented in this report and the accompanying PhD thesis that forms the main output of this project, we can make some general recommendations for future effect studies of planned wind farms, some of which also have broader applicability in spatial conservation. Here we present a concise summary of these recommendations in a way that can be directly applied in conservation settings. More background and detail on some of these recommendations can be found in Sage 2022, particularly Chapter 6.

1. We recommend that pre-construction surveys are carried out throughout different times of the year over several years so as to account for the different levels of variability we see in LBBG occurrence (Figure 4 and 5). Surveys should have an aim to discover where birds occur with greater or lesser consistency. For example, LBBG presence between years can be very consistent in some areas and variable in others, in Schiermonnikoog this appears as greater consistency at land and more variability at sea (Figure 5).

2. Using distance between a wind farm site and the surrounding breeding colonies remains the standard for apportioning the potential effects of wind farms on breeding birds. However, we identify the value in refining the ways that distance measurements are applied. Logarithmic functions measuring the decreasing time spent by gulls at increasing distances from the colony provide a better measure of the potential overlap of breeding colonies with wind farm sites and can be applied based on species wide averages or with site specific data where possible (Sage 2022 Chapter 2).

3. Early visual surveys at the Gemini wind farm site suggested that a lot of the observed lesser black-backed gulls were loafing or non-breeding birds. This was somewhat confirmed throughout this research project as very few GPS tracked lesser black-backed gulls from Schiermonnikoog entered Gemini wind farm. Attributing potential negative effects using non breeding birds remains difficult as the origin of these birds are unknown, and whilst the potential for negative effects on non-breeding birds to influence broader populations should not be ignored, there is the potential to over attribute effects to nearby colonies. Whilst more research is needed into non-breeding LBBG behaviour and interactions with wind farms, time distance functions presented in Sage 2022 Chapter 2 can be used to model the expected density of birds from surrounding colonies in a wind farm area. These estimates can be compared to visual counts and may indicate what proportion of visually observed birds are not accounted for, and may therefore be non-breeders or non-local birds. However, further work needs to be done to decide how non-breeding birds should be handled in apportioning estimates.

4. The time LBBGs spend at sea can vary considerably, not necessarily in relation to the areas of available land and sea surrounding a breeding colony. Where possible we recommend that effect studies seek to determine how much time different colonies spend at land and sea and apply the results to any effect models or apportioning estimates.

5. Effect studies should seek to identify not just the presence of gulls in a wind farm area but also their different behaviours, and relate these behaviours to relevant metrics such as flight speed and altitude in order to gain insight into potential risks, such as collision. For example, we identify that commuting flight through Gemini wind farm by Schiermonnikoog gulls is often undertaken at flight altitudes within the rotor swept zone (Chapter 6) and we identify that specific fight behaviours such as thermal soaring increase the likelihood of flying within the rotor swept zone (Sage 2022 Chapter 5).

6. We recommend that more long-term effect studies consider gather high resolution tracking data of gulls within wind farms over long time periods. High resolution data has the potential to provide valuable insight into collision risk in lesser black-backed gulls, but in this project the quantity of data limited our capacity to model collision risk or avoidance behaviour quantitatively. Studies which collect large amounts of high-resolution tracking data within wind farms, or collate data from different wind farm locations, may be able to address this issue.

8. Research offshoots

This project was carried out in collaboration with other individuals and organisations with the principles of sharing data and knowledge. As a result, several other projects have arisen which use data gathered as part of this project. A brief overview of these projects is provided below

1. Migration research: whilst this project focused on local breeding season movements of lesser black-backed gulls, GPS loggers provided year-round data collection that facilitated the study of migration. Migration data from Schiermonnikoog lesser black-backed gulls was used in several research projects forming part of a PhD thesis (Brown 2022), and the published research paper (Brown *et al.* 2021).
2. Dietary analysis: Diet samples collected from the breeding colony at Schiermonnikoog have been used in research regarding microplastics in seabird diets in the North Sea.
3. Bachelors theses: Throughout this project, bachelors students were involved in research, particularly during field work. Two bachelors thesis studies were produced out of this project, focusing on temporal diet patterns in lesser black-backed gulls and spatial nest distributions respectively.

Acknowledgements

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