Are offshore wind farms in the Netherlands a potential threat for coastal populations of noctule?

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Abstract: Offshore wind farms likely cause mortality amongst migratory bats. Yet it remains unknown whether resident coastal bat populations may be affected by offshore wind developments. We performed an analysis to assess the potential risk of offshore wind farms in the Dutch North Sea for local coastal populations of noctule (*Nyctalus noctula*). First, we assessed the potential overlap between their foraging range and areas with operational and planned offshore wind farms. Subsequently, we tracked 14 noctules from a coastal population during late summer and autumn and analysed their movements. In general, it seems unlikely that offshore wind farms in the Netherlands will significantly affect coastal populations of noctule since offshore wind developments take place beyond their regular foraging range. In some cases however, noctules do perform distant flights ('swarm flights'), possibly in response to migrating insects. We recorded six distant foraging trips both over land and over sea with a maximum distance of 18.5 km from their roost and 12.7 km from shore. Acoustic records confirm that noctules are occasionally present in offshore wind farms at distances of 15-25 km from shore. During such an event, noctules face the risk of a collision as virtually all their flight activity occurs at heights within the rotor swept area of offshore wind turbines.

Keywords: bat mortality, energy transition, collision, barotrauma.

Introduction

The development of the offshore wind sector plays an important role in the Dutch energy transition. In 2022 a capacity of 2.5 GWH has been realized, consisting of 260 turbines in six different offshore wind farms. The installed capacity should increase to 11 GWh in 2030, which equals to 8.5% of the total energy consumption in the Netherlands and 40% of the current electricity use (Offshore Wind Energy Roadmap 2030). Offshore wind farms will therefore enable a considerable reduction in greenhouse gas emissions in the Netherlands.

Despite this environmental gain, there are biodiversity concerns at the same time: onshore wind turbines are known to cause mortality amongst bats due to collisions (Johnson et al. 2003, Bach & Rahmel 2004, Kunz et al. 2007, Arnett et al. 2008, Rydell et al. 2010, Cryan et al. 2014, Thaxter et al. 2017) and possibly barotrauma (Grodsky et al. 2011, Rollins et al. 2012, Lawson et al. 2020). Significant numbers of fatalities have been reported on land (Hayes 2013, Voigt et al. 2015, O'Shea et al. 2018), which may cause declines in local as well as migratory populations (Lehnert et al. 2014). In temperate regions most fatalities concern migratory species and occur during late summer and autumn (Rydell et al. 2010, Voigt et al. 2015, Frick et al. 2017, Rodrigues 2018). In order to reduce fatalities curtailment measures have been implemented in many wind farms on land which limit the production time during periods when bats are most active (Arnett et al. 2011, Peste et al. 2015, Adams et al. 2021).

Yet, there is no information on bat mortality in offshore wind farms (OWFs). As bats forage in a similar way around offshore wind turbines as they do around onshore wind turbines (Ahlén et al. 2009), it seems likely that fatalities also occur at sea. Based on the precautionary principle mitigation measures have been issued for the Dutch offshore wind farms in the Borssele area (Zeeland) to protect Nathusius' pipistrelles during their autumn migration over sea (Staatscourant 2016).

A total of 21 noctules from a coastal population near Sint Maartensvlotbrug (Noord-Holland) was tagged in October 2018 and August-September 2019. The obtained GPS data revealed that some of the nocturnal feeding trips took place over sea. This was the first evidence that at least some local noctules in the Netherlands venture out offshore during nightly foraging trips onto the North Sea.

As foraging distances up to 26 km from the roost have been reported (Kronwitter 1988), local populations of noctules along the Dutch coast may be affected by offshore wind developments. This effect may be significant when: (1) their foraging range overlaps with offshore wind farms, (2) a large proportion of the population forages offshore, and (3) they fly at heights overlapping the rotor swept area (RSA), thereby running a high risk of collision and/or barotrauma.

In this paper, we assess the potential risk of offshore wind developments in the Netherlands on local coastal populations of noctules, based on:

1. The location of maternity colonies of noctules along the Dutch coast, and the potential overlap of their foraging range with operational and planned offshore wind farms.
2. The activity pattern of noctules from a coastal colony at Sint Maartensvlotbrug (Noord-Holland), based on their foraging distance from the roost, their time budget spent over land and over sea, and their flight height.

Material & methods

Overlap of potential foraging range and offshore wind farms

First, we assessed the geographical locations of the maternity colonies in the Dutch coastal provinces, excluding the areas with Pleistocene sandy soils in the eastern and southern parts of these provinces, using a subset of the data obtained between 2010 and 2021 by Mostert (in prep.) during a national survey on the occurrence of noctules in the Netherlands. During this survey roosts were found during pre-dawn visits to forests and estates, using acoustic detectors to detect swarming individuals. Subsequently, the number of individuals leaving the roost at dusk was counted. In some cases, additional roosts were found during evening visits, as noctules are often very vocal and audible before sunset. For more details on bat inventories see Helmer et al. (1987).

Next, we assessed the geographical locations of operational OWFs and those in the preconstruction phase (National Georegister: Licensed Wind Farms). Areas in which offshore wind developments will take place in the future were also identified (National Georegister: Designated wind energy areas).

Finally, we assessed the overlap between the geographical locations of the operational and planned OWFs and the presumed maximum foraging range of noctules of 26 km from the roosts (cf Kronwitter 1988).

Activity pattern of noctules from a coastal population at Wildrijk

Wildrijk is a small forest reserve of 18 ha which is located at N 52.791 E 4.704 near Sint

Figure 1. Wildrijk (dark green) and surroundings.

Maartensvlotbrug in Noord-Holland. The area surrounding the forest is characterized by flower bulb cultivation, some small scattered villages, the nature reserve Zwanenwater and the coastline. The distance to shore is 2.2 km (Figure 1). The ground level of Wildrijk and its surroundings typically lies within 1 m below to 1 m above sea level. Zwanenwater is somewhat higher, with elevations between 5-8 m in most of the area, whilst the outer dunes reach a maximum of 20 m a.s.l. (https://ahn.arcgisonline.nl/ahnviewer/).

Tagging bats and tag retrieval

Bats were caught by hand from 'Swegler 2Fn bat boxes' during daylight hours, as well as with mist nets after dark. Before being tagged, each individual bat was measured, weighed, sexed, aged and its reproductive status was assessed using the criteria described by Haarsma (2008). All work has been executed under the Nature legislation permit 2018-057682 (Wageningen Marine Research) and the Animal Welfare protocol AVD248002016459 / VZZ-18-005 (Dutch Mammal Society).

The initial aim of this study was to obtain a dataset to validate the location estimation algorithm for the Dutch Motus network (Lagerveld et al. in prep.). Bats were therefore equipped with multiple tags:

1. A GPS tag (Pathtrack nanoFix® GEO – MINI (0.90 g) to obtain accurate location fixes, which are stored on the device.
2. A coded VHF tag (LOTEK NTQB2-1; 0.32 g) to get simultaneous detections at one or more Motus receiver stations (www.motus.org), and,
3. A VHF beeper tag (Telemetrie Service Dessau V5; 0.28 g) to ensure relocation of the tagged animal, or to find the fallen-off tag-pack in the field.

The coded VHF tag and the VHF beeper tag were glued onto the GPS tag using Superglue (Bison, Goes, the Netherlands) and the GPS tag was glued to the area between the shoulder blades using SAUER Hautkleber original (Manfred-Sauer-Stiftung, Lobbach Germany). This glue dissolves in a few weeks and in case tags cannot be retrieved, they will fall off automatically. Bats caught in bat boxes were placed back after being tagged, and bats caught in mist nets were released in the immediate vicinity. The total weight of the tags was never more than 5% of the weight of the animal. Because tagging disrupts normal nighttime activities (and thus potentially influences behaviour; e.g. Aldridge & Brigham 1988, Kenward 2000), the GPS tags of the animals that were caught after dark were programmed to start data collection the night after the animal had been tagged. Data collection of the animals that were tagged during the day (and placed back in their roost) started at dusk on the same day.

The capacity of the GPS battery enabled data collection during 1-4 consecutive nights, depending on the settings of the tags (Table 2). Note that GPS tags need an unobstructed view of the sky to make a location fix. While bats reside in their roost, the GPS tag produces null-fixes. Therefore, when a location fix is made, in principle the animal is in flight. However, when GPS tags fall off at a location with satellite coverage (e.g. in the open field, or in an area with limited tree cover) before the data collection has ended, they are still able to make location fixes. When this happens, long series of location fixes are made which are typically less than 20 metres apart. Therefore, this situation is easily identifiable in the data. During this study, two GPS tags fell off before the data collection ended: ID 12 from 3 September 2019 19:00 UTC onwards and ID 14 from 27 August 2019 21:30 UTC onwards, consisting of 69 location fixes in total. These location fixes were removed from the data set (9.9% of the data).

Analysis

The analysis of the activity pattern was done in R 4.0.2 (R Core Team 2022). We created a map of the flight paths using the package ggplot2 (Wickham 2016). Of each GPS fix the distance to the centre of Wildrijk as well as the distance to shore was assessed, using the package rgeos (Bivand & Rundel 2020). The time budget over land and over sea of each individual was calculated based on the number of GPS fixes in each habitat divided by the total number of GPS fixes. Subsequently, the time budget was assessed in relation to the distance from Wildrijk. We did not assess the home range given the limited amount of monitoring hours/days of each individual. Finally, we assessed the flight heights over sea and over land. As GPS altitude data refers to the altitude above mean sea level, the recorded altitude data over sea corresponds with the flight height. To assess the flight heights over land we subtracted the ground level (https://ahn.arcgisonline.nl/ahnviewer/) from the GPS altitude. Subsequently, we compared the flight heights over land and over sea, using a two-sample *t*-test. Our GPS data contained two negative altitude values (-11.3 m and -4.5 m, both recorded at Wildrijk), which we removed from the analysis.

Results

Overlap of OWFs and potential foraging range

Offshore Wind Farm Egmond aan Zee (OWEZ) was the first OWF in the Netherlands and was commissioned in 2006, followed by Princess Amalia Wind Farm (PAWP) in 2008, Luchterduinen (LUD) in 2015 and Gemini (Buitengaats and Zee-energie) in 2017. The OWFs in the Borssele area (lot 1, 2, 3, 4 and 5) became operational throughout 2020–2021. Characteristics of the operational OWFs are shown in Table 1. Currently several OWFs are under development in the areas Holland Coast South and Holland Coast North. Further west and north several areas for future OWFs have been designated (Offshore Wind Energy Roadmap 2030).

Table 1. dimensions and number of wind turbines of operational OWFs. In OWFs relative close to the coast (OWEZ, PAWP and LUD) the RSA varies between 20–153 m above sea level.

Operational OWF	Nacelle heigth (m)	Rotor diameter (m)	RSA heigth (m)	Number of wind turbines
OWEZ (Offshore Wind Farm Egmond aan Zee)	70	90	35 - 125	36
PAWP (Princess Amalia Wind Farm)	60	80	20 - 100	60
LUD (Luchterduinen)	81	112	25 -153	43
Gemini (Buitengaats & Zee-energie)	89	130	34 - 164	150
Borssele 1 & 2	117	167	33 - 200	94
Borssele 3 & 4	?	164	?	97
Borssele 5	?	164	?	2

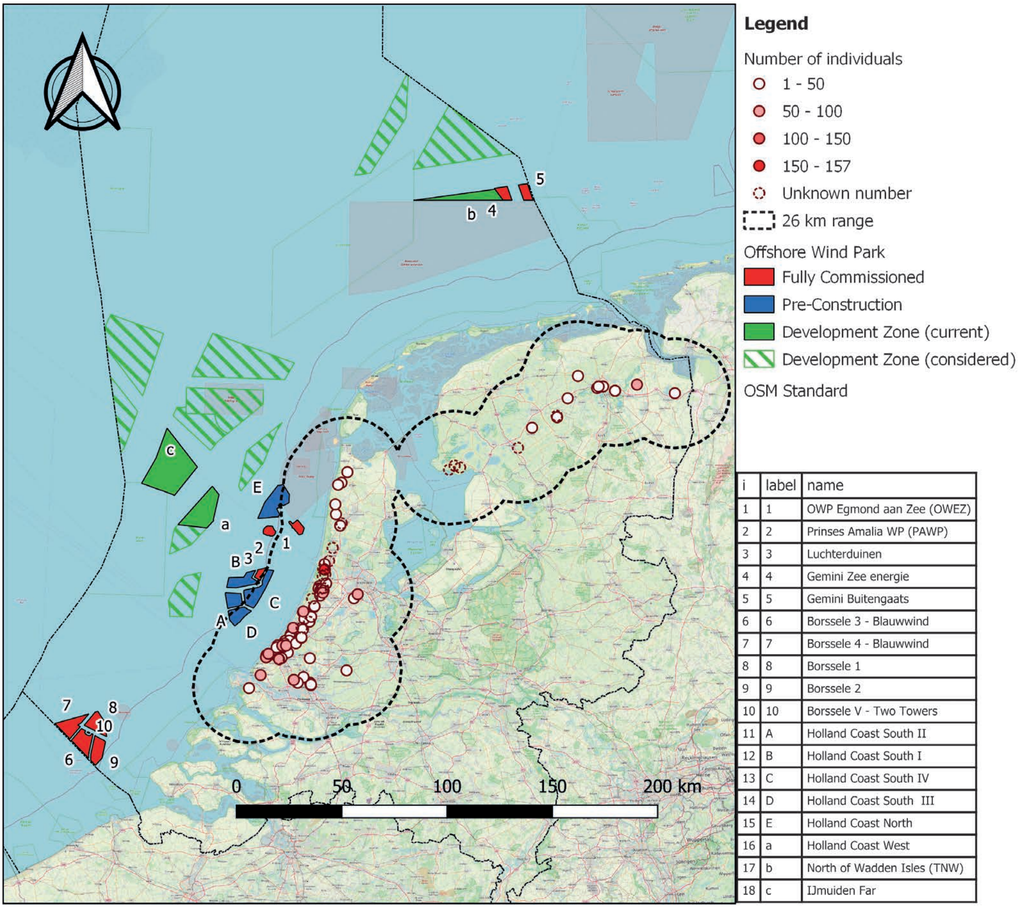

Figure 2. Location of the maternity colonies in the coastal provinces (excluding Pleistocene areas), their presumed maximum foraging range of 26 km (Kronwitter 1988), operational OWFs as well as OWFs under construction and designated areas for wind farm development.

Table 2. Overview of tagged animals and settings of the tags.

ID	Sex	Age	Tagged			GPS			
			Latitude	Longitude	Data/Time [UTC]	Tag number	Time-on [UTC]	Time-off [UTC]	Interval [min]
1	Male	Adult	52.791	4.704	03-10-2018 17:15	20461	17:00	22:00	3
2	Male	Adult	52.791	4.704	03-10-2018 17:17	20462	17:00	22:00	3
3	Female	Adult	52.794	4.707	09-10-2018 09:00	20468	17:00	22:00	3
4	Female	Adult	52.794	4.707	09-10-2018 09:10	20469	17:00	22:00	3
5	Female	Adult	52.794	4.707	09-10-2018 09:20	20466	17:00	22:00	3
6	Male	Adult	52.789	4.703	09-10-2018 20:00	20464	17:00	22:00	3
7	Female	First year	52.789	4.701	19-10-2018 15:00	20464	15:00	20:00	3
8	Female	Adult	52.789	4.701	19-10-2018 15:10	20466	15:00	20:00	3
9	Male	Adult	52.794	4.707	19-10-2018 16:00	20462	15:00	20:00	3
10	Male	Adult	52.791	4.705	27-08-2019 09:20	21233	19:00	22:00	1
11	Male	Adult	52.794	4.708	27-08-2019 09:50	21287	19:00	22:00	1
12	Male	Adult	52.790	4.705	27-08-2019 10:30	21305	19:00	22:00	2
13	Male	Adult	52.791	4.704	27-08-2019 09:00	21490	19:00	22:00	2
14	Male	Adult	52.790	4.705	27-08-2019 10:45	21312	19:00	22:00	2
15	Male	Adult	52.791	4.704	27-08-2019 09:30	21349	19:00	22:00	1
16	Male	Adult	52.794	4.707	02-09-2019 15:00	21279/21313	19:00	22:00	2
17	Male	Adult	52.794	4.708	03-09-2019 09:00	21468	19:00	22:00	2
18	Male	Adult	52.794	4.707	20-09-2019 09:00	56321	18:00	20:00	2
19	Male	Adult	52.794	4.707	20-09-2019 09:15	21506	18:00	20:00	2
20	Male	Adult	52.794	4.707	20-09-2019 09:30	21341	18:00	20:00	1
21	Male	Adult	52.794	4.707	20-09-2019 09:45	21509	18:00	20:00	1

During the national survey on the occurrence of noctule in the Netherlands (2010-2021) a total of 97 maternity colonies was found in the Dutch coastal provinces, excluding the areas with Pleistocene sandy soils in the eastern and southern parts of these provinces. In the area concerned 56 colonies were found in Zuid-Holland, 25 in Noord-Holland, 8 in Friesland and 8 in Groningen. No colonies could be found in Zeeland. From 79 colonies, the number of individuals was assessed, resulting in an average of 31 individuals per colony (range 10–157).

Figure 2 shows the overlap between OWF areas and the potential foraging range, using a maximum distance of 26 km from the roosts (cf Kronwitter 1988). Currently one operational OWF (OWEZ) lies within the area of overlap, while PAWP and Luchterduinen are located just outside the presumed maximum foraging range. The area of overlap includes also the eastern part of the development zones Holland Coast South and Holland Coast North.

The operational OWFs in Borssele and Gemini, as well as all designated areas for future wind energy developments are located beyond the potential foraging range of coastal noctules.

Activity pattern of noctules from a coastal population at Wildrijk

A total of nine individuals was tagged in 2018 (between 3 and 19 October) and twelve individuals in 2019 (between 27 August and 20 September), including 16 adult males, one first year and four adult females. The GPS tags collected data during 2-5 hours per day and

Table 3. Retrieved tags and monitoring data.

ID	Sex	Age	Tag retrieved			GPS data		
			Latitude	Longitude	Data/Time [UTC]	Number of days	Number of location fixes	Time budget over sea
1	Male	Adult			-			
2	Male	Adult	52.793	4.707	17-10-2018 18:00	3	48	0%
3	Female	Adult			-			
4	Female	Adult			-			
5	Female	Adult	52.797	4.723	17-10-2018 18:00	3	37	3%
6	Male	Adult	52.789	4.702	17-10-2018 16:00	2	30	10%
7	Female	First year	52.790	4.703	19-10-2018 15:00	1	6	0%
8	Female	Adult	52.789	4.701	19-10-2018 15:10	1	16	0%
9	Male	Adult			-			
10	Male	Adult	52.790	4.703	10-09-2019 16:00	2	15	0%
11	Male	Adult	52.783	4.712	30-08-2019 18:00	1	83	0%
12	Male	Adult	52.790	4.705	03-09-2019 09:00	1	58	78%
13	Male	Adult	52.799	4.725	29-08-2019 16:00	1	41	20%
14	Male	Adult	52.799	4.724	29-08-2019 17:00	1	53	0%
15	Male	Adult	52.793	4.705	28-08-2019 16:00	1	58	0%
16	Male	Adult	52.794	4.707	05-09-2019 09:00	2	37	0%
17	Male	Adult			-			
18	Male	Adult	52.800	4.726	26-09-2019 16:00	4	68	7%
19	Male	Adult	52.799	4.725	26-09-2019 16:00	4	79	0%
20	Male	Adult			-			
21	Male	Adult			-			

used time intervals of 1-3 minutes between the fixes (Table 2).

We obtained data from 14 out of 21 tagged individuals (Table 3). Six GPS-tags were not retrieved and the data of one could not be extracted from the GPS due to technical problems. The dataset included eleven males (all adults) and three females (one first year and two adults).

The number of monitored nights per individual was on average two nights (range 1-4) and depended on the settings of the GPS tag (Table 3). On average 45 location fixes were obtained per individual (range 6–83 location fixes). Nine individuals were detected exclusively over land, whereas five individuals were detected both over land and over sea. On average 8% of the time budget of the animals included in this study was spent over sea. One individual (ID 12) spent most of its time (78%) over sea.

Figure 3 shows the flight tracks of all individuals combined. Note that tracks are frequently incomplete as the GPS tags were programmed to collect during a few hours per day (Table 2).

Most flight activity occurs relatively close to the roost (Figure 4). In total, we recorded 629 location fixes. Of these, 58% were made up to 3 km from the centre of Wildrijk; 72% up to 5 km and 89% up to 7 km. Within this 7 km flight range, 3% of the location fixes occurred over sea. In some cases (11% of the data) more distant flights were performed during which 71% of the location fixes occurred over sea. For example, ID 12 reached a maximum distance of 18.5 km from Wildrijk and 12.7 km from shore at 27 August 2019 20:04 UTC and ID 6 which was detected 3.3 km from shore at 10 October 2018 17:03 UTC when it flew back to the coast at a distance of 10.5 km from Wil-

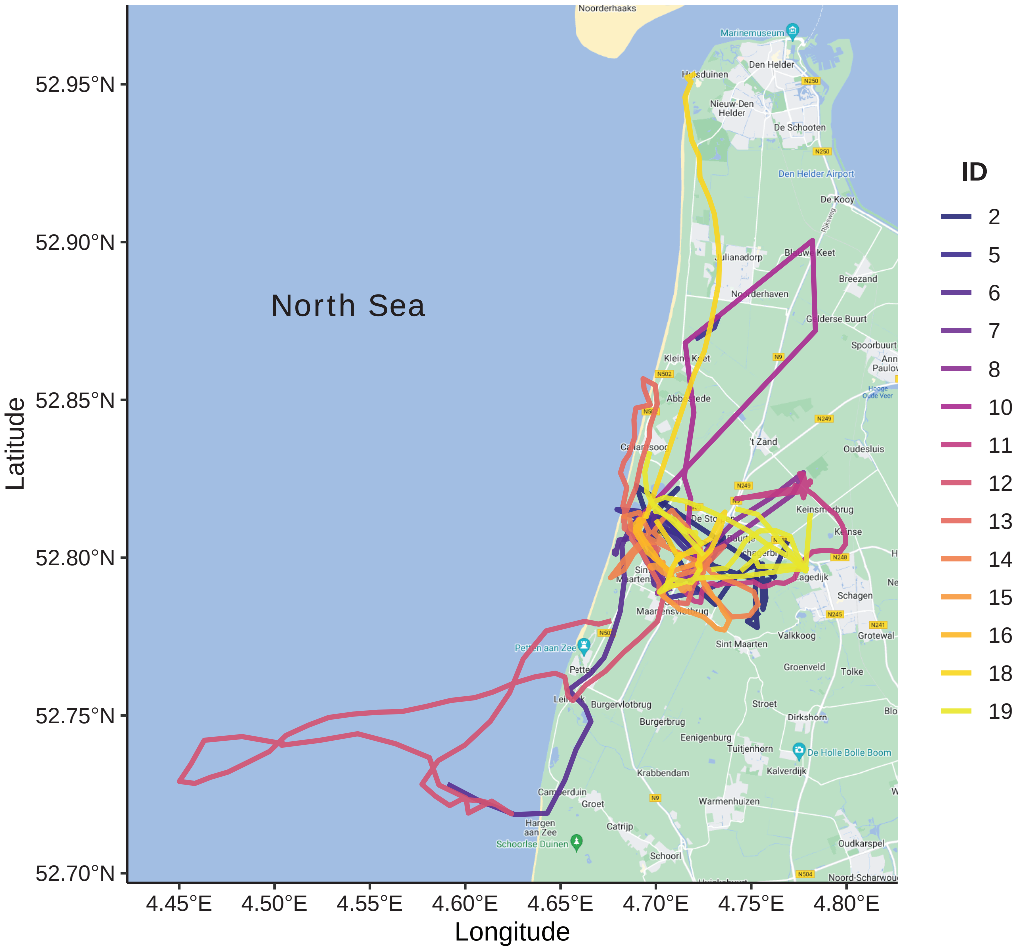

Figure 3. Flight tracks of all individuals.

Table 4. Flights over 7 km and weather conditions at de Kooij (retrieved from https://www.knmi.nl/).

ID	Date	Time (UTC)	Max distance Wildrijk (km)	Habitat	Wind direction (degrees)	Wind speed (m/s)	Temperature (°C)	Precipitation (mm/h)	Atmospheric Pressure (Hpa)
6	10-10-2018	17:03	10.5	Land & Sea	70	5	16.2	0	1013.8
5	11-10-2018	17:01	9.7	Land & Sea	130	4	18.9	0	1010.2
13	27-8-2019	19:36	7.3	Land & Sea	70	3	25.4	0	1013.3
12		20:04	18.5	Land & Sea					
10		20:37	13.2	Land					
18	22-9-2019	18:00	18.5	Land & Sea	130	3	20.7	0	1005.8

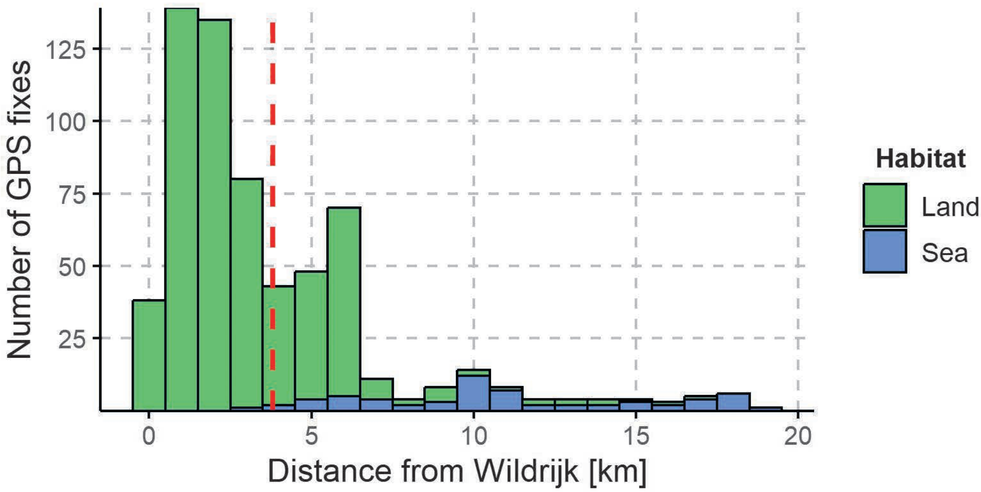

Figure 4. Histogram of the distance between the GPS location fix and Wildrijk. The vertical dashed line indicates the mean distance (3.8 km).

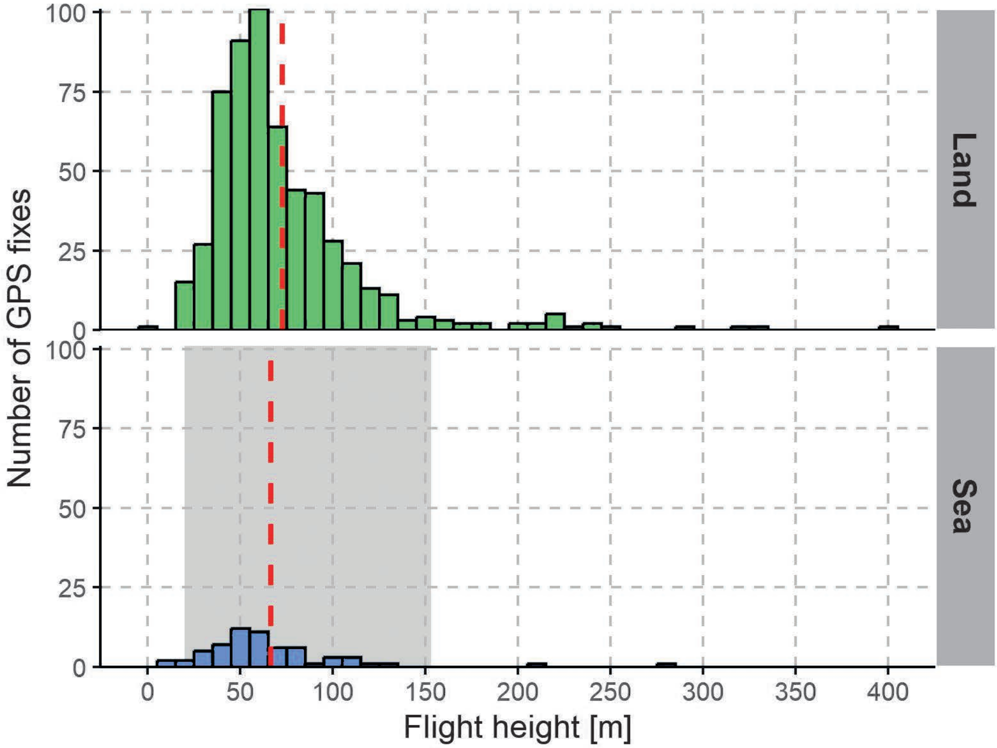

Figure 5. Histogram of the recorded flight heights over land and over sea. The dashed vertical lines indicate the mean flight heights. The shaded area represents the RSA of offshore wind turbines at OWEZ, PAWP and LUD.

drijk (Figure 3). All other individuals detected over sea (ID 5, 13 and 18) flew at distances within 0.4 km from shore.

Table 4 summarizes the flights over 7 km and corresponding weather conditions at de Kooij/Airport den Helder (retrieved from https://www.knmi.nl/). Distant flights coincided with low easterly winds, no precipitation, relatively high temperatures and relatively high atmospheric pressure. One trip occurred exclusively over terrestrial habitats while the remaining five occurred both over land and over sea.

Figure 5 shows the flight heights over land and over sea. The average flight height over land was 72.6 m (SD 42.9, range 6–400) and over sea 66.4 m (SD 42.1, range 8-280). This difference proved to be not significant (t=1.0848, df=625, P-value = 0.2784). On land 94.4% and at sea 93.5% of the flight activity occurred at heights between 20–153 m.

Discussion

We found the highest density of coastal maternity colonies in the western part of the Netherlands, in a relatively narrow strip along the inner dunes between The Hague and IJmuiden, where many estates and old forests are present. A few scattered colonies occur further north in Noord-Holland. Agricultural areas east of the dunes in Zuid-Holland and Noord-Holland are largely unsuitable for noctules, with the exception of some older forests around Amsterdam and Rotterdam. We found no colonies in Zeeland and the Wadden Islands, even though some suitable habitat is locally present. The Wadden Sea coast of Friesland and Groningen consists of an open agricultural landscape which does not harbour colonies. In southern parts of Friesland and Groningen there are some small estates and forests with a few colonies of noctule. Since males generally roost individually or in small groups in the vicinity of a maternity colony (Sluiter & van Heerdt 1966, Limpens at al. 1997), we consider the observed distribution of the maternity colonies representative for the species' range of local populations along the Dutch coast.

Our study shows that most flight activity occurs within a few km from Wildrijk; 58% of the data was recorded within a range of 3 km and 89% within 7 km. The observed main flight range corresponds well with foraging distances between 3-6 km in other areas in the Netherlands (Limpens et al. 1997), distances between 2.4-5.2 km in Germany (Kronwitter 1988, Roeleke et al. 2020) and 4.2 km in the UK (Mackie & Racey 2007). Furthermore, our study shows that the time budget spent over sea within 7 km from Wildrijk was low (3%), despite its proximity to the coast (2.2 km).

We recorded six foraging trips over 7 km with a maximum distance of 18.5 km from Wildrijk and 12.7 km from shore (Figure 2). During flights over 7 km the average time budget spent over sea was relatively high (71%). Distant flights up to 26 km are also known from Kronwitter (1988), who considers this 'swarm flights', as they are not confined to specific foraging areas and last longer in comparison to regular foraging trips. Swarm flights seem to be confined to the period between mid-August and mid-September. When they occur, the regular foraging areas are virtually abandoned (Kronwitter 1988). The distant flights we recorded occurred between late August and mid-October during nights with low easterly winds, no precipitation, relative high temperatures and relatively high atmospheric pressure. It seems plausible that foraging opportunities may trigger extensive foraging trips and thus the presence of noctules over sea. High temperatures trigger insect activity and easterly winds may drift these insects offshore. In particular during late summer/early autumn, when large numbers of migrating insects can be expected (Drake & Gatehouse 1995, Chapman et al. 2004, Drake et al. 2012), there can be increased availability of insects over sea. Offshore foraging noctules pursuing insect swarms have also been reported from the Baltic Sea (Ahlén et al. 2009).

Assuming a 26 km maximum range of 'swarm flights' (cf Kronwitter 1988), OWEZ as well as areas along the eastern edge of the wind farm development zones Holland Coast South and Holland Coast North are within reach of coastal colonies. PAWP and Luchterduinen are located just outside the presumed maximum range. The occurrence of noctules in this area is confirmed by acoustic records from OWEZ (3 and 8 September 2012 and 4 September 2014, 15 km from shore), PAWP (4 September 2014, 9 and 12 September 2016, 25 km from shore) and LUD (23 August 2016, 23 km from shore) (Lagerveld et al. 2014, 2015 and 2017). However, the number of noctules occurring in this area is likely to be underestimated due to limitations of acoustic monitoring in general (Barataud 2020, Voigt et al. 2021) and the presence of only one acoustic detector in each OWF. In addition, only 15% of the recorded 'Nyctaloids' (including *Nyctalus*, *Vespertilio* and *Eptesicus* species) were identified to species level. To date, there are no acoustic records (with certainty) from monitoring locations in the Dutch North Sea further south, west and north (Lagerveld et al. 2014, 2015, 2017 and 2019). The only two offshore records well beyond the presumed 26 km maximum foraging range include two grounded individuals at gas production platforms at 5 September 1994 and 10 September 1996, respectively 5 km north off Ameland and 15 km north off Texel (Boshamer & Bekker 2008).

Given the timing of the occurrence, from late August until mid-September, it seems plausible that the acoustic records and visual observations at the Dutch North Sea refer to resident noctules. Seasonal migrants are likely to occur later in the season, as the main migration period in the Netherlands appears to run from late September until mid-November (https://www.trektellen.nl/species/graph/1/0/1090/0?jaar=0).

Aerial hawking bats like noctules are vulnerable to wind turbine induced mortality as their flight activity overlaps with the RSA (Rodrigues et al. 2015, Roeleke et al. 2016, Roemer et al. 2017). The operational OWF within the presumed maximum foraging range (OWEZ) as well as the ones just outside this range (PAWP and LUD) consist of wind turbines with RSAs between 20–153 m. a.s.l. Our data shows that 93.5% of the flight activity at sea occurs between 20–153 m, indicating that virtually all flight activity occurs at heights within the RSA. The observed average flight height over sea was lower in comparison to land (respectively 66.4 m and 72.3 m), but this difference proved to be not significant. A study in eastern Germany showed that 95% of noctule flight activity in open habitats occurs at heights between 0 and 144 m above ground level (Roeleke et al. 2016). This matches our observations very well, as we recorded 95.2% of the location fixes within this altitudinal range.

When interpretating the results of tracking studies one should always take the accuracy of the measurements into account (Hulbert & French 2001, Frair et al. 2010, Péron et al. 2020). The horizontal position accuracy of GPS wildlife tracking equipment ranges from less than 5 m in open habitats (Hulbert & French 2001) to 30 m at locations with high canopy cover (Frair et al. 2010). In our study we observed horizontal position errors up to 20 m. Given the extent of the movements we recorded, we can safely conclude that these errors cannot affect the observed spatial use. The vertical GPS error is generally larger than the horizontal position error, and even in good conditions vertical errors up to 20 m can be expected (Péron et al. 2020). Obvious erroneous GPS altitude data in our study included two GPS locations fixes (0.3% of the data) with negative heights of respectively -4.5 and –11.3 m, and we cannot exclude the possibility of other GPS location fixes containing vertical errors too. However, we think it is unlikely that our dataset contains many erroneous GPS altitude data as we recorded an identical altitudinal flight activity pattern as Roeleke et al. (2016). In the unlikely event our dataset is biased and the actual average flight height is for example 20 m lower or

20 m higher, virtually all flight activity will be still be at heights within the RSA of offshore wind turbines (see Figure 5).

Conclusions

In general, it seems unlikely that offshore wind farms in the Netherlands will significantly affect coastal populations of noctule since offshore wind developments take place beyond their regular foraging range. In some cases however, noctules do perform distant flights ('swarm flights'), possibly in response to migrating insects. We recorded six distant foraging trips both over land and over sea with a maximum distance of 18.5 km from Wildrijk and 12.7 km from shore. Acoustic records confirm that noctules are occasionally present in offshore wind farms at distances of 15–25 km from shore. During such an event, noctules face the risk of a collision as virtually all their flight activity occurs at heights within the rotor swept area of offshore wind turbines.

Note however, that this study cannot be considered 100% representative for all colonies along the coast and at all times of the year, as it is based on a limited number of individuals from one local population during autumn (and adult male biased). To gain more certainty about the potential risk, it is therefore recommended to conduct additional research into the habitat use of coastal noctules from different colonies, during their entire active period and for different sex and age classes, hereby specifically focusing on the extent and orientation of swarm flights, as well as the conditions in which these occur.

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Samenvatting

Zijn offshore windparken in Nederland een potentiële bedreiging voor de populaties van rosse vleermuizen langs de kust?

Offshore windparken veroorzaken waarschijnlijk sterfte onder migrerende vleermuizen tijdens hun trek over zee. Het is echter nog niet bekend of de ontwikkeling van de offshore windsector een effect kan hebben op lokale populaties vleermuizen langs de kust. We voerden een analyse uit om het potentiële risico te bepalen van offshore windparken in de Nederlandse Noordzee op populaties van rosse vleermuizen (*Nyctalus noctula*) langs de kust. We bepaalden eerst de overlap tussen hun potentiële foerageergebied en de operationele en geplande offshore windparken. Vervolgens analyseerden we de vliegbewegingen van 14 gezenderde rosse vleermuizen aan het einde van de zomer en in de herfst. In zijn algemeenheid lijkt het onwaarschijnlijk dat offshore windparken in Nederland significant negatieve effecten hebben op lokale populaties rosse vleermuizen, omdat de ontwikkeling van de offshore windsector buiten hun reguliere foerageergebied plaatsvindt. Echter, in sommige gevallen maken rosse vleermuizen langdurige en verre foerageervluchten ('zwermvluchten'), die mogelijk samenhangen met migrerende insecten. Gedurende deze studie stelden we zes verre foerageervluchten vast, zowel over land als over zee, met een maximale afstand van 18,5 km van hun verblijfplaats en 12,7 km uit de kust. Akoestische monitoring in offshore windparken op 15-25 km uit de kust bevestigt dat rosse vleermuizen hier soms aanwezig zijn. Op die momenten lopen rosse vleermuizen risico op een aanvaring, omdat vrijwel al hun vliegactiviteit plaatsvindt op rotorniveau.

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