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Interactions between seals and offshore wind farms

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1 Summary

1. Harbour seal (*Phoca vitulina*) and grey seal (*Halichoerus grypus*) movement data were collected using telemetry tags from animals hauled out at Rødsand in southern Denmark. These data were combined with similar, but lower temporal resolution, historic data collected in 2009. Rødsand and the neighbouring Vitten-Skrollen are within 10 km of two large wind farms: Nysted and Rødsand II. The aim of this study was to investigate possible interactions between the seals and the wind farms.

2. A total of 1603 GPS/GSM tagged seals-days of data were obtained from the ten seals (five harbour seals and five grey seals). These produced a total of 69,355 GPS location fixes (an average of 43.3 locations per day). The mean GPS/GSM tag duration was 160 days.

3. Generally the adult harbour seals remained within 50 km of Rødsand or Vitten-Skrollen haulout sites. In contrast the two juvenile harbour seals (Pv-60265-09 and Pv-02-10) travelled over 200 km to distant haulout sites; north through the Langelands Belt, the Great Belt (Storebælt) and beyond. The grey seals travelled to even more distant haulout sites, up to 500 km away from Rødsand, and eastwards into the Baltic Sea. Both species frequently transited from the two haulout sites through the two nearby wind farms. Visually, there is no obvious interruption of travel at the wind farms' boundaries.

4. Interaction was assessed using three analyses: 1. residence times within wind farm zones, 2. a comparison of path speed and tortuosity inside and outside the wind farms and 3. the proximity of individual locations to individual wind farm towers.

5. All three analyses indicated no significant effect of the wind farms on seal behaviour. This is in accord with another local study of haulout counts that concluded that the wind farms had no long term effect on the local seal population trends.

6. Caution should be exercised in generalising the findings of this study to other potential sites of interaction. The type of wind farm foundation influences both the construction noise and also any subsequent reef effect. At other seals colonies the different availability of alternative haulout sites and foraging areas may affect their reaction to an altered seascape.

2 Introduction

Globally, the maritime generation of energy from the wind is rapidly increasing (Iniyan *et al.* 2007). At the same time there is both public and legislative concern about potential detrimental effects to marine wildlife (Gill 2005; Inger *et al.* 2009). Our current *uncertainty* in being able to predict any such effects hinders appropriate and efficient management decisions.

In Europe, many offshore wind farms are in the vicinity of locations used by harbour seals (*Phoca vitulina*) and grey seals (*Halichoerus grypus*) for breeding, hauling out or foraging. There is thus potential for a deleterious effect on seal populations due to noise and disturbance - caused primarily by construction, but also possibly by operation (Madsen *et al.* 2006). On the other hand, wind farms may increase available prey by acting as artificial reefs and restricting local fisheries (Linley *et al.* 2007). Or there may be no effect on seals. However, while there has been a lot of speculation, there is little hard evidence documenting seal interactions with *operational* wind farms.

Two large Danish wind farms, Nysted and Rødsand II (Fig 1), offer an opportunity to collect the required evidence. They are within 10 km of two nationally important harbour and grey seal haulouts. The seals in this region have been studied for many years (Dietz *et al.* 2003; Teilmann *et al.* 2005; Edren *et al.* 2010). More recently, high resolution track and dive behaviour data for both species have been obtained as part of an environmental assessment for the construction of a fixed link Danish-German crossing of the adjacent Femern Belt[1].

We tackle three questions about the animals' interaction with these wind farms:

1. **Wind farm zone residence**: do seals avoid, or target, wind farms?
2. **Track tortuosity and speed:** are seals' movement patterns (tortuosity and speed of travel) different within wind farms than in neighbouring areas?
3. **Proximity to the turbines**: does the distribution of seals within the wind farms suggest avoidance of, or attraction to, the turbine towers?

This study comprises two parts. First, the collection of further, higher resolution seal track data. Second, the development of a robust statistical framework with which to answer these three questions.

[1] http://www.femern.com/

3 Method

3.1 Study area

3.1.1 Seals

The study area is centred on two seal haulout sites in the Danish part of the western Baltic Sea (Fig 1). Rødsand haulout is at the tip of a 6 km sand spit that stretches from Gedser in the east. It has been a seal sanctuary since 1978 and up to a hundred seals (both species combined) can haul out on land there. 18 km to the west is the second, smaller haulout, Vitten-Skrollen, which comprises a series of emergent glacial boulders in shallow (< 5 m) water. Together these form the most important grey and harbour haulout sites in the region.

3.1.2 Wind farms

Two major wind farms are within 5 km of both Vitten-Skrollen and Rødsand haulout sites (Fig 1). Both sets of turbines use gravity foundations because of the high local incidence of boulders and the load bearing properties of the sea bed. Each foundation weighs approximately 1,500 tonnes. They sit in water 6-10 m deep.

Nysted[2] (also known as Rødsand I) wind farm lies to the south of the island of Lolland, Denmark, and is owned jointly by DONG Energy and PensionDanmark. It has 72 2.3 MW Siemens turbines which have a total capacity of 166 MW. The turbines are arranged in eight rows (850 m apart) of nine turbines each (480 m apart). The farm was commissioned in 2004.

Rødsand II[3] wind farm is immediately to the west of Nysted and is owed by E.ON. It has 90 2.3 MW Siemens turbines which have a total capacity of 207 MW. The turbines are arranged in five curved rows consisting of 18 turbines each. Construction began in the last quarter of 2008. Foundation installation took place between May 2009 and early March 2010. The farm was commissioned in October 2010.

3.2 Telemetry system

The movements and behaviour of local seals were monitored using telemetry tags.

Two types of telemetry tag were deployed: the Sea Mammal Research Unit's GPS/GSM tags[4] and the smaller Wildlife Computers Argos Spot tags[5]. The GPS/GSM tag is essentially a data logger that attempts to record the location of a seal at regular intervals using a hybrid GPS system. Stored location and behavioural data are opportunistically relayed ashore by means of an embedded mobile phone (GSM) modem when the tag comes within mobile phone coverage. Data are recorded continuously, whether or not the tag is within GSM coverage. The advantage of this type of tag is

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[2] Data from http://www.power-technology.com/projects/rodsand/

[3] Data from http://www.power-technology.com/projects/rodsand/

[4] http://www.smru.st-and.ac.uk/instrumentation

[5] http://www.wildlifecomputers.com

the frequency and accuracy of the GPS locations and the large amount of behavioural data that can be relayed over the high bandwidth mobile phone data channel (Cronin & McConnell 2008).

The interval between attempts to obtain GPS location fixes was set to 10 mins in the previous, 2009, study and 3 mins in this, 2010, study.

The Spot tag is a smaller and simpler device that provides approximate locations. It uses the Argos satellite system (Argos 2008) to compute locations and to relay this information ashore. However there can be large errors (> 5 km; Vincent *et al.* 2002) in these locations so fine scale movement patterns are difficult to detect. The Spot tag does not record dive activity. However it is considerably smaller than the GPS/GSM tag and thus can be used on smaller animals to provide coarse information on their movements.

3.3 Capture and tagging

All attempts to capture seals were concentrated on the animals hauling out around the low-laying sand spit at Rødsand. Two capture methods were used. First, up to 1 km of monofilament tangle net was laid in the general area of the haulout site. Second, a specifically developed 200 m pop-up net was set about 50 m from the haulout. This was laid on the sea bed as a rolled up 'rope'. The net was triggered by a radio signal which let compressed air inflate the float line. This caused the net to suddenly set itself in front of the seals in the hope that they would become entangled. To minimise disturbance a remote camera was used to observe the Rødsand haulout site. This relayed pictures through the GSM (mobile phone) network.

Once captured the seals were anesthetised with Zoletil®. The tags were attached to the fur at the back of the neck using rapid setting epoxy resin. Morphometric records and biological samples were taken.

3.4 Additional data

The historical 2009 seal data were provided by Femern A/S and used with their permission. The location of wind farms and individual towers, and cable routes, in the Baltic were obtained from 4C Offshore Lowestoft (UK). Bathymetry data were obtained from Seifert *et al.* (2001).

3.5 Analysis

All the analyses were carried out in the R Statistical Package (R Development Core Team 2009).

3.5.1 Data preparation

The GPS locations were filtered to remove the few, erroneous locations where the residual value was greater than 25 and the number of satellites was less than five. 95% of these filtered locations are within 50 m of the true location (D. Russell, *pers. comm.*).

The tracks were divided into foraging trips. Such trips are defined as when an animal is further than 1 km from the haulout site for a period of more than an hour. A simpler definition of 'not hauled out' would include the time when a seal was at sea in the local vicinity of a haulout. Note that we have no direct evidence that these trips were for foraging. Nor do we make any attempt in this study to infer where and when in each trip foraging occurred (c.f. travelling). For each trip the duration and maximum distance from the origin haulout were calculated.

3.5.2 Buffer Zones

The distribution of seals at sea is influenced by a complex interaction of factors that include individual variability, season, prey availability and haulout site availability. Our analytical approach is guided by the fact that we consider that we do not have sufficient data to predict, *at a useful spatial resolution, and with sufficiently small (= useful) confidence limits,* the influence of wind farms on synoptic usage maps (Matthiopoulos *et al.* 2004).

In our approach we considered usage *conditional on a tagged seal being in the vicinity of one of the two wind farms*. Central to this approach is a useful and defensible definition of 'in the vicinity' – which we term here a Buffer Zone (BZ). We set the buffer zones so that:

1. If a line drawn between BZ entry and exit passed through the wind farm zone (WFZ) - the actual track would have to take a significant detour to avoid also passing through the WFZ. Most of the straight lines projected inwards from any point on the outer boundary of the BZ will intersect the WFZ.

2. There will usually be at least one GPS fix within the BZ either side of any series of fixes within the WFZ.

3. The perception of cues generated by the wind farm that may cause a change in behaviour (attraction or repulsion) should be significantly reduced at the outer BZ perimeter. For example, any repulsive cue (e.g. sound) generated within the wind farm itself should not significantly alter behaviour at the perimeter of the BZ.

4. Any environmental gradients are minimised. For example, the buffer zone should not include land.

This approach is critiqued in the Discussion section. A practical compromise resulted in the BZ perimeter being set 2.5 km from the outer perimeter of each wind farm perimeter.

The primary unit of data examined in the first two analyses was the *passage*; this was defined as the time from an animal entering a buffer zone to the time at which it passed back across the outer boundary of the buffer zone. During most, but not all, of these passages the animals also entered the actual wind farm zone. This unit was chosen to balance the risks of pseudo-replication (from dividing the data spuriously finely and treating a single decision as several data points) and under-representing the variability in the data. Essentially it assumes that the animals can be considered to have a single predominant behavioural pattern during each passage, but this pattern can vary between passages.

3.5.3 Wind farm zone residence

In this analysis we first descratised, using linear interpolation, the irregular (in time) track into 2 minute intervals.

The basic data for this analysis was the *ratio* (BZ ratio) of the time the animal was *observed* to be in the BZ, rather than the actual wind farm, over the *predicted* time that it would have been in the BZ if it had travelled at a constant speed along the straight line connecting the points at which it entered and left the buffer (Fig 2):

BZ ratio = observed time in BZ/(passage duration*proportion of straight line path within BZ)

This formulation was used because the observed and straight line times within the wind farm itself could be zero, and therefore using either of those as the denominator in the ratio would produce infinities. The BZ ratio takes values less than 1 when animals spend more than the expected proportion of time within the wind farm itself, so large values of the BZ ratio indicate avoidance of the wind farm.

A weighted mean of the BZ ratio was calculated for each animal. Each passage was weighted by its total duration, so that the overall result represented the effect on the proportion of time that the animal spent in the BZ. The uncertainty around the mean for each animal was estimated by bootstrapping. The width of the resulting confidence intervals depends on the independence of the data points, so the significance of the lag 1 autocorrelation in the BZ ratio was estimated for each animal.

An overall *population* effect was calculated as the mean of the individual effects. This was done for the two species separately, and also for all the animals together. To represent both the uncertainty in the individual estimates and that resulting from the limited number of animals from which data were available (5 of each species), a bootstrap confidence interval was calculated by combining the sets of bootstrap estimates for the individuals into a single distribution and repeatedly drawing sets of 10 (or 5) values from this. The mean of each set of values then provided a single bootstrap estimate of the overall population effect.

This process was carried out separately for each wind farm and for both wind farms together. It was also done for the data from Rødsand II during the period when construction work was being carried out there (May 2009 to March 2010). Similar calculations were also carried out for a 'virtual' wind farm, a translocation of Nysted eastwards to a broadly similar area of the sea (Fig 3), that was used as an approximate 'control'. The significance of the difference between the effects within the actual wind farms and the control was investigated.

3.5.4 Track tortuosity and speed

Path tortuosity (turning angle) and travel speed have become established as useful metrics to discriminate feeding from travelling behaviour (Patterson *et al.* 2008). We restricted our analysis to locations obtained during passages of the BZ that entered the WFZ and for which the time from the preceding location to the subsequent one was less than or equal to 30 minutes. This, slightly arbitrary, cut-off was necessary to balance the less accurate estimates provided by long intervals between points and the limit imposed by the minimum interval between attempts to obtain GPS fixes (3 or 10 minutes). There were 1,786 locations on 117 paths that were available for the analysis. Relaxing restrictions to paths for which locations were available from within both the buffer zone and the actual wind farm could greatly increase the amount of data available but might introduce bias into the comparison by requiring an additional assumption that the main difference between the animals' behaviour during the passages for which different amounts of data were available was due to the effects of the wind farm.

Turning angles (the change in heading between the direction of approach from the previous location and the direction of travel towards the subsequent location) and speeds (based on the mean of the previous and subsequent path segments weighted by their durations) were estimated for each location. Each turning angle was between 0 and 180, and we treated left- and right-hand turns as equivalent. Two mean turning angles were calculated for each passage: one for the time in the BZ and another for that in the WFZ. Two mean speeds were also calculated for the locations in each passage. These averages were not time-weighted because, while that could be considered to better represent the average behaviour, there is a loss in precision, and generally bias downwards, in the estimates based on the longer triplets. The mean tortuosity of the section of each passage that was within the BZ was subtracted from that for the part within the WFZ to give a mean difference in tortuosity for each passage. The mean difference in speed was calculated similarly. Overall differences were calculated for each animal as the mean of the values for its passages, weighted by the passage durations. Confidence intervals were generated around each of these by bootstrapping with the passage as the unit of resampling for the animals from which sufficient suitable data had been obtained. Population means and confidence intervals were generated in a similar way as for the BZ ratio, though the test of significance in this case was differences from zero rather than from one, and as there was only data from 10 passages through the Rødsand II wind farm, no estimates were produced for that site.

3.5.5 Interaction with towers

In order to explore fine scale interaction with individual towers we considered the relationship of individual WFZ GPS location fixes with the positions of the individual towers. For each WFZ location we calculated the distance to the nearest tower. In order to test for attraction to, or repulsion from, the turbine towers we compared the frequency distribution of these *real* distances with the frequency distribution derived from the same number of points - but randomly distributed within the WFZ.

4 Results

4.1 Capture and tag deployment

The details of the 2010 capture and tag deployment are shown in Table 1. We also include details of seals caught during the previous 2009 expedition at Rødsand.

Over a period of eight days of effort during 2010 a total of six seals were captured. They comprised five grey and one harbour seal. Our initial target was harbour seals since they were deemed more likely to remain in the region (McConnell *et al.* 1999; Cunningham *et al.* 2008; Sharples, Mackenzie & Hammond 2009). But as time progressed and we were only catching grey seals we decided to tag the grey seals that we caught. To maintain our tag supply in the hope of catching harbour seals in the remainder of the trip, we also deployed Argos Spot satellite tags which were made available by the Danish National Environmental Research Institute (now National Centre for Environment and Energy, Aarhus University) to some of the initial grey seals. Argos tags provide inferior and less frequent locations, but would provide a safety net of gross movement data.

The tracks of all seals are shown. However, in our analysis of fine temporal and spatial scales of interaction, we only include the ten seals (five harbour seals and five grey seals) that were fitted with GPS/GSM tags.

4.2 System performance

Mean GPS/GSM tag duration was 160 days (range 100-220 days; Table 1). A total of 1,603 GPS/GSM tagged seals-days of data were obtained from the ten seals. These produced a total of 69,355 GPS location fixes (an average of 43.3 locations per day). However, this includes time spent hauled out when the tag automatically reduces the rate of GPS fix attempt. Inter-fix intervals when the tracks were *at sea and within a BZ or WFZ* are shown in Table 2. The average median inter-fix intervals for tags programmed to attempt fixes every 3 minutes was 4.94 minutes; the average for those programmed to attempt fixes every 10 minutes was 11.22 minutes.

4.3 Movement patterns

4.3.1 General

The tracks of all seals are shown in Fig 4, grouped by tag type and species. These Figures present the tracks at two scales: at large scale showing the entirety of the tracks (right hand map) and at small scale in the vicinity of the Nysted and Rødsand II wind farms (left hand map).

Generally the adult harbour seals remained within 50 km of Rødsand or Vitten-Skrollen haulout sites. In contrast the two juvenile harbour seals (Pv-60265-09 and Pv-02-10) travelled over 200 km to distant haulout sites; north through the Langelands Belt, the Great Belt (Storebælt) and beyond.

The grey seals travelled to even more distant haulout sites, up to 500 km away from Rødsand, and eastwards into the Baltic Sea.

This contrast in movement patterns between the two species is in accord with other studies elsewhere (McConnell *et al.* 1999; Cunningham *et al.* 2008; Sharples, Mackenzie & Hammond 2009) and with previous studies in this region using Argos tagged seals (Dietz *et al.* 2003).

4.3.2 Rødsand or Vitten-Skrollen trips

Whilst the tracks of some of the more widely ranging seals (primarily grey seals) do approach distant wind farms, we restricted our analysis to interactions with Nysted and Rødsand II wind farms.

Visually it is apparent that both seal species tagged in this study frequently transited from the two haulout sites through the two nearby wind farms (Figs 3 and 4.2). The most frequent destination for the harbour seals was to an area up to 10 km to the south and south-east of the wind farms, including the Darss Ridge, and generally in water shallower than 20 m. The destination of the grey seals was more diverse.

In Figs 3 and 4.2 there is evidence of an east-west gradient of decreasing usage. Within this overall trend there is no obvious interruption of travel at the wind farms sites.

Statistics for the 127 trips that both started and finished at either Rødsand or Vitten-Skrollen haulout sites are shown in Table 3. The average median trip duration for grey seals was 0.76 days, and for harbour seals was 1.78 days. The average median trip maximum extent for grey seals was 14.45 km, and for harbour seals was 18.30 km.

4.4 Wind farm zone residence

581 passages through Rødsand II or Nysted wind farms were recorded. The results for the individual animals were very variable, although almost all the point estimates of mean BZ ratios for the individuals, and all those averaged across animals, were less than 1 (Table 4). This indicates that less time than expected was spent in the buffer zone and, therefore, more time than expected was spent in the actual wind farms. However similar, though generally slightly weaker, effects were also observed for the control area, and the difference between the actual wind farms and the control was not significant (Table 4). This would seem to suggest that a large part of the observed effect may be due to some environmental feature shared by the wind farm sites and the control area, rather than being the result of the physical presence of the wind turbines. The apparent attractive effect appears strongest within the Rødsand II wind farm while it was being constructed. This is a surprising result that merits further investigation. Two possible explanations are that, in the absence of pile driving, the effects of construction are quite localised and either the animals slow down to avoid the vessels or exploit the foraging opportunities provided by the disturbance of the sediment. However, it must be recognised that this result is based on data from only six animals.

4.5 Track tortuosity and speed

The restriction of the analysis to passages that contained locations in both a wind farm and the buffer zone around it dramatically reduced the amount of data. A summary of these data is shown in Table 5 along with the resulting confidence intervals around the estimates of the mean difference in turn angles. Very few of these differences are significantly different from zero, and all the point estimates are an order of magnitude less than the average angle of turning (~26^0 in both the WF and BZ) of the paths when approximated by straight lines between the GPS fixes.

The average speeds of the animals, estimated along the straight lines connecting GPS fixes, were almost exactly 1m/s. The estimates of the differences between the speeds in the wind farms and the buffer zones were generally around 0.1m/s (Table 6), and were not statistically significant.

4.6 Proximity to the turbines

1,793 GPS location fixes occurred within either Rødsand II or Nysted wind farms zones (WFZ). The results are shown in Fig 5. The mean nearest neighbour distance to a turbine tower for the observed locations was 260.38 m (SE 2.55) and for the randomly distributed locations was 265.29 m (SE 2.60). The difference between these two means is 4.91 m and not statistically significant (p~0.07). This result suggests that the animals were probably attracted towards the devices but the effect was weak, with the overall change having a 95% chance of lying somewhere between +11 and -2 m.

5 Discussion

5.1 Capture and tag deployment

A total of 13 seals (seven grey and six harbour seals) were captured and tagged in this study in 2010 and in the previous study in 2009. Capture at both Vitten-Skrollen and Rødsand was difficult. At both sites the seals were aware of the approach of capture teams up to 1 km away. The eventual captures involved a mix of drift nets and the deployment of a bespoke radio controlled pop-up net.

At total of 32 field days (160 person days) were required to catch the 13 seals over four catching trips.

5.2 System performance

The use of GPS/GSM tag technology was central to the success of this study. It provided data of the necessary spatial and temporal resolution to investigate small-scale interactions. It provides data far superior to those provided by Argos tags in a previous study in 2003 (Dietz *et al.* 2003). However, it is clear that for the investigation of small-scale effects in localised areas such as these, it is important that the tags are set up to frequently attempt to obtain GPS fixes. The previously reported (Lonergan, Fedak & McConnell 2009) effects of interpolation error on GPS track estimation impose serious limitations on this kind of study. It would have been useful to reduce even the 3 minute intervals used here, though there is a trade-off against the reduction in battery life that would result.

5.3 Interactions with wind farms

We used three sets of metrics to explore possible interaction with the wind farms at different scales. None of the three showed strong evidence of a substantial effect of the wind farms on the animals' behaviour.

While it appears that the animals spent a significantly higher than expected proportion of their time in the wind farm zones than in the surrounding buffer zones, a similar and indistinguishable effect was apparent for the control site (which did not contain any turbines). This could be interpreted as suggesting that the three 'wind farm' sites have a common pattern of differences from their buffer zones, and these differences are sufficient to limit their use as controls for investigating the effects of wind farms. The BZ ratio was lower for the wind farms than for the control for most individuals and the overall 'population' estimates suggest that there is less than a (1) 20% chance of a stronger attraction to the control than to the wind farms and (2) 5% chance that such an attraction would increase the proportion of time the animals are in the buffer zone by more than 4% (which implies a much smaller effect on usage of the, much larger, wind farm zones).

Even having taken a very restrictive view of the data, in order to avoid introducing bias into the comparisons, the results seem very clear cut. It appears very unlikely that there could be as much as a 10% difference in the speed or tortuosity of the paths in the wind farm and buffer zones, and the true value is probably much less. A less rigorous approach to the problem might have allowed the wind farms to be investigated separately, but could have produced spurious results.

The difference between the means of the real and random nearest tower distances was 4.91 m. This difference was not statistically significant, despite the large number of locations (1,793). The plausible size of the overall effect is also too small to be regarded as biologically significant. We thus conclude that there is effectively no detectable attraction to, or repulsion from, the individual turbine towers.

Edren *et al.* (2010) analysed the number of seals hauled out at Rødsand and Vitten-Skrollen over the period 1990-2005, covering the period of the construction and operation of Nysted wind farm. Although there was a temporary reduction in the number of seals hauled out during ancillary pile driving operations, they showed that there was no long term effect on haulout behaviour trends.

Their observation at the population level (using haulout counts as a proxy for population) is in accord with our findings that any effect of the installations on movements and behaviour at sea is small.

5.4 Method critique

5.4.1 Wind farm zone residence

It is clear from these results that the buffer zones are imperfect control areas. They also suffer from the difficulty that, particularly for sites close to the shore, it is difficult to make them broad enough to obtain an adequate number of GPS locations within them. Identifying other control sites will also generally be problematic, since wind farms and other marine developments are carefully sited to exploit particular features of the marine environment. An alternative form of control would be a baseline study (at the necessary spatial resolution) carried out before construction began, though the utility of this depends on there having been no other substantial environmental changes affecting the area. Another difficulty with this comes from the wide variation in the behaviour of individual seals. In previous work, at other sites, we have found that the most powerful comparisons are those examining the behaviour of individuals for changes. That approach works well for investigating the effects of intermittently operating devices, but is less applicable when assessing the impact of fixed structures. The particular difficulty of capturing animals around this site would make it unrealistic to rely on re-catching the same animals in different years. There are welfare issues, as well as practical limitations on battery technology, that complicate the development of longer lasting tags able to provide the required quality of information over multiple years.

The linear interpolation of locations into 2 minute interval locations introduces the possibility of bias when there is a large gap between locations. When a seal hauls out the tag enters an energy saving mode and GPS locations are less frequent. When the seal ends this mode a GPS location is attempted immediately. If, as happens occasionally, this immediate attempt is unsuccessful, there is the risk that the stationary interval from the last location within the haulout to the end of the haulout is incorporated into the two minute interpolation to the next location – making that segment appear to be slower than it actually was. This, in turn, could occasionally advance the apparent time of entry into the buffer zone and thus overestimate the time in the BZ. These problems could be reduced by increasing the frequency of the tags attempting to obtain GPS fixes, though there is a limit to this that results from the animals spending most of their time below the surface of the water. The only way beyond that limit is to move to other technologies, such as accelerometry or dead reckoning, to interpolate between GPS fixes, but these add complexity and increase the power consumption of the devices.

5.4.2 Track tortuosity and speed

It is not obvious that relaxing the requirement that only passages where locations are available in both the wind farm and the surrounding buffer zone would actually improve the precision of the results. While it would increase the sample size, it could also introduce additional uncertainty associated with the variability of the behaviour of even individual seals. An alternative way of increasing the sample size would be to increase the width of the buffer zone, though that would further reduce the comparability of the buffer and wind farm zones. If the estimates of speed and turn angles were all equally reliable it might make sense to weight the individual locations according to the time period each one represents, however the complex shape of the paths makes this likely to bias all estimates downwards, with the extent of the bias depending on the exact patterns of movement. Attempting to improve the precision of the results by using individual locations as resampling units would risk pseudo-replication.

Probably the most important uncertainty in this part of the study comes from the uncertainty around which characteristics of a path indicate foraging. While it seems reasonable that tortuous paths should be associated with searching for food, it is not clear what the effect that behaviour will have on animals' speeds or how any changes in underwater behaviour will affect the movement patterns visible at the surface.

5.4.3 Proximity to the turbines

In the analysis, any error in the track locations would reduce the power of the observations to detect attraction to or repulsion from the towers. However, since 95% of the GPS locations have less than 50 m error, we regard the reduction in power as small.

Two aspects of this analysis are simplistic: taking a uniform distribution as the null model may miss some features of the animals' usage of the area that derive from the topography or other environmental features within the area, and the use of the set of GPS fixes as representative of the animals' use of the area. Weighting the locations by their temporal spacing would ease the second issue, though there would remain a more awkward issue about the appropriate way to treat uncertainty: considering each location as an independent data point may risk pseudo-replication. That, in turn, could result in the precision of the results being overstated and larger overall effects being concealed. However, more important than this is the problem that any artificial reef effect will primarily alter underwater behaviour: the turbines are close enough for the seals to spend the majority of their time underwater foraging close to the devices and surface anywhere in the area between them.

5.5 Generality of findings: wind farm

Construction noise due to foundation pile driving is regarded as a major potential threat. However, Nysted and Rødsand II wind farms used gravity foundations (Leonhard & Birklund 2006). This foundation design does away with the need for extended pile driving operations (though not entirely in the case of Nysted; Carstensen, Henriksen & Teilmann 2006). However, gravity foundations do entail significant sediment dredging (approximately 2,000 tonnes of dredged sediment per foundation) and replacement with coarser material and concrete blocks. Gravity foundations are suitable for use in shallow (< 10 m) water where the sea bed is capable of bearing the vertical load. Thus the impact of construction noise would have been less at Nysted and Rødsand II compared with the more common pile-driven tower wind farms.

The type of tower and its foundation also influence the rate of bio-fouling and the generation of any artificial reef effect (Leonhard & Birklund 2006; Linley *et al.* 2007). In the case of both gravity and pile driven towers, the type and extent of scour protection will influence biological colonisation (Reubens, Degraer & Vincx 2011). Also, the biomass and maturity of reef fauna will increase through time and any attraction to seals may not be evident in the first few years of operation. Klaustrup (2006) showed that there had been no significant increase in fish abundance at the Nysted wind farm by 2006, but cautions that his study was only three years after the construction of the wind farm and so any reef effect inducing an increase in fish biomass could occur later. His study also emphasised the many, apparently subtle, differences in wind farm construction and marine habitat could potentially influence changes in the local marine biota.

5.6 Generality of findings: seals and study area

The seals in the area of the Rødsand Seal Sanctuary have been, and continue to be, regularly exposed to human activities. Edren *et al.* (2010) stated:

"Passenger ferries pass the area every few hours at a distance of 7 km and the waters 13 km south of the sanctuary comprise one of the world's busiest shipping routes. From September to March, when the seal sanctuary is open for access, the sand bank is used for hunting birds, and small boats are regularly seen in the area. Moreover, a few hunting permits are issued every year allowing local fishermen to shoot harbour seals near their fishing gear outside the sanctuary."

It is thus possible that local seals were habituated to disturbance well before the construction and operation of the wind farms. Thus seals from areas of lower chronic anthropogenic disturbance may be more vulnerable to wind farm construction and operation.

There is a further possibility that those seals that may have been disturbed subsequently emigrated, leaving behind the more robust individuals. This is more likely for grey seals that have the capacity for long distance (> 500 km) travel. However, the fact that Edren *et al.* (2010) demonstrated no long term effect in the trends of haulout counts suggests that mass emigration is unlikely.

Hall (*pers. comm.)* identified the prey in seal scats collected at Rødsand as including small cod (*Gadus morhua*), herring (*Clupea harengus*) and black gobies (*Gobius niger*). Lundstrom *et al.* (2010) showed that seal diet in the Baltic varied with season, year and region. The relevance to this study is that such variability in diet (and presumably prey availability) confounds a simple prediction of changes in seal behaviour due to variability in local fish abundance.

5.7 Recommendations for future work

While we have demonstrated that there are no significant interactions with the Nysted and Rødsand II wind farms, studies should be carried out at wind farms where the towers are pile driven into the sea bed, and where there is greater acoustic disturbance, before, during construction and after commission.

Other analytical approaches should be explored including individual-based models (Nabe-Nielsen *et al.* 2010).

The dive behaviour collected in this study, and the historic seal telemetry data collected in the region by Dietz *et al.* (2003) should be integrated into a further analysis.

6 Acknowledgements

We gratefully acknowledge the support for the 2010 data extension and data analysis provided by The Crown Estate, UK.

We also gratefully acknowledge the permission to use 2009 seal tracking data by Femern A/S. This study would have been impossible without the tenacity, enthusiasm and skill of the various

members of the catching team from the Danish National Environmental Research Institute (now National Centre for Environment and Energy, Aarhus University).

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8 Tables

seal	species	sex	age	mass (kg)	length (cm)	axial girth (cm)	tag type	tagging date	final date	duration (day)
Hg-01-10	Hg	M	adult	37	113	87	G	08/10/2010	27/03/2011	170
Hg-02-09	Hg	M	juvenile	49	117	94	G	31/10/2009	02/05/2010	183
Hg-04-09	Hg	F	juvenile	48	112	89	G	24/10/2009	19/02/2010	118
Hg-04-10	Hg	M	juvenile	43	119	89	G	06/10/2010	29/03/2011	174
Hg-05-10	Hg	M	juvenile	42	115	89	G	07/10/2010	28/02/2011	144
Hg-37281-10	Hg	M	juvenile	40	122	89	A	08/10/2010	30/03/2011	173
Hg-60266-10	Hg	M	adult	82	146	110	A	07/10/2010	30/03/2011	174
Pv-02-10	Pv	F	juvenile	36	120	82	G	08/10/2010	07/02/2011	122
Pv-05-09	Pv	M	adult	97	149	119	G	27/10/2009	04/02/2010	100
Pv-07-09	Pv	M	adult	113	153	123	G	27/10/2009	04/06/2010	220
Pv-10-09	Pv	M	adult	90	137	117	G	27/10/2009	22/04/2010	177
Pv-12-09	Pv	M	adult	103	156	123	G	27/10/2009	10/05/2010	195
Pv-60265-09	Pv	F	juvenile	32	104	83	A	27/10/2009	28/03/2010	152

Table 1. Deployment details and tracking duration. The shaded data come from a previous study in 2009. Tag type: A = Argos satellite, G = GPS/GSM. Species: Hg = grey seal, Pv = harbour seal.

seal	number of fixes	median inter-fix interval (min)	tag setting for GPS attempt interval (min)
Hg-01-10	86	4.67	3
Hg-02-09	110	10.17	10
Hg-04-09	267	10.20	10
Hg-04-10	27	4.13	3
Hg-05-10	19	4.67	3
Pv-02-10	61	6.27	3
Pv-05-09	227	16.03	10
Pv-07-09	384	10.67	10
Pv-10-09	131	9.93	10
Pv-12-09	455	10.33	10

Table 2. Statistics of the intervals between successive GPS fixes whilst a seal was in Rødsand II or Nysted wind farm (WFZ) or buffer (BZ) zone.

seal	number of trips	median duration (days)	median maximum extent (km)
Hg-01-10	0	.	.
Hg-02-09	6	0.42 (0.14-3.88)	5.95 (1.78-32.36)
Hg-04-09	24	1.58 (0.11-13.76)	34.00 (1.16-62.77)
Hg-04-10	0	.	.
Hg-05-10	2	0.29 (0.09-0.49)	3.40 (2.35-4.44)
Pv-02-10	0	.	.
Pv-05-09	7	2.54 (0.68-5.50)	21.20 (10.03-35.48)
Pv-07-09	44	1.23 (0.04-7.70)	13.10 (1.10-25.71)
Pv-10-09	13	1.75 (0.50-5.85)	21.50 (8.30-31.61)
Pv-12-09	31	1.58 (0.07-17.98)	17.40 (1.30-46.87)

Table 3. Trip metrics for seals either starting or finishing a trip at either Rødsand or Vitten-Skrollen haulout sites. The 95% quantiles (2.5 – 97.5) are shown in parentheses.

seal	species	BZ ratio (median & 95% CI)				
		Control	Both wind farms	Nysted	Rødsand II	
					all	May 09 - March 10
Hg-01-10	Hg	0.98 (0.86-1.10)	0.83 (0.69-0.94)	0.85 (0.75-0.95)	0.78 (0.45-1.10)	-
Hg-02-09	Hg	0.91 (0.77-1.00)	0.81 (0.68-0.94)	0.83 (0.61-1.04)	0.78 (0.68-0.93)	0.78 (0.67-0.93)
Hg-04-09	Hg	0.95 (0.84-1.03)	0.94 (0.82-1.06)	1.02 (0.91-1.12)	0.72 (0.51-1.00)	0.72 (0.51-0.96)
Hg-04-10	Hg	0.88 (0.73-1.00)	0.97 (0.75-0.62)	1.04 (0.65-1.41)	0.84 (0.75-0.93)	-
Hg-05-10	Hg	1.00 (0.88-1.09)	0.91 (0.54-1.00)	0.91 (0.52-1.00)	1	-
Pv-02-10	Pv	1.05 (0.88-1.21)	1.00 (0.79-1.21)	0.87 (0.61-1.05)	1.13 (0.98-1.51)	-
Pv-05-09	Pv	0.89 (0.66-0.99)	0.49 (0.36-0.68)	0.89 (0.60-1.09)	0.41 (0.27-0.62)	0.41 (0.26-0.62)
Pv-07-09	Pv	0.80 (0.73-0.88)	0.91 (0.79-1.05)	0.92 (0.79-1.06)	0.75 (0.58-0.92)	0.92 (0.83-0.67)
Pv-10-09	Pv	0.82 (0.74-0.92)	0.92 (0.78-1.08)	0.95 (0.81-1.12)	0.57 (0.34-1.00)	0.54 (0.29-0.66)
Pv-12-09	Pv	0.88 (0.81-0.94)	0.82 (0.72-0.92)	0.81 (0.72-0.92)	0.82 (0.59-1.10)	0.96 (0.55-1.35)
Aggregated:	Hg	0.95 (0.87-1.01)	0.88 (0.79-0.98)	0.92 (0.80-1.06)	0.84 (0.71-0.95)	0.75 (0.60-0.88)
	Pv	0.88 (0.80-0.99)	0.83 (0.65-0.98)	0.89 (0.79-0.99)	0.75 (0.52-1.00)	0.73 (0.47-0.99)
	Both	0.91 (0.85-0.98)*	0.86 (0.75-0.95)*	0.91 (0.82-0.99)	0.79 (0.65-0.93)	0.74 (0.54-0.91)

* These values are not significantly different from each other (p > 0.1)

Table 4. Differences in the usage of the buffer zones (BZ) and the wind farms. The BZ ratio is the time animals spent in the buffer zone around the wind farm as a proportion of the time they would have been expected to be in the BZ if they had travelled with constant velocity. Values below one indicate that more time than expected was spent in the wind farm itself and suggest attraction towards it. Values above one suggest avoidance.

seal	species	Total numbers of:		Difference in tortuosity between wind farm and buffer (median & 95% CI)	
		passages	**locations**	**Both wind farms**	**Nysted**
Hg-01-10	Hg	7	114	9.9 (-0.2 – 25.2)	12.0 (-0.8 – 31.8)
Hg-02-09	Hg	7	84	-4.9 (-10.5 – 0.6)	-4.7 (-12.1 – 2.1)
Hg-04-09	Hg	19	217	9.8 (-0.7 – 25.1)	5.0 (-2.2 – 14.3)
Hg-04-10	Hg	1	17	3.2	3.2
Hg-05-10	Hg	2	27	4.1	4.1
Pv-02-10	Pv	3	84	23.4	23.4
Pv-05-09	Pv	6	53	11.6 (5.6 – 15.4)	10.9 (2.2 – 16.1)
Pv-07-09	Pv	27	563	-9.6 (-28.8 – 7.3)	-10.0 (-30.2 – 6.9)
Pv-10-09	Pv	11	153	-16.7 (-37.3 – 1.5)	-16.6 (-37.3 – 2.2)
Pv-12-09	Pv	34	474	1.7 (-8.6 – 12.8)	-0.5 (-10.8 – 9.9)
Aggregated:	Hg	36	459	4.4 (-1.6 – 11.5)	3.9 (-1.5 – 11.6)
	Pv	81	1327	1.5 (-13.2 – 17.6)	0.22 (-13.1 – 18.1)
	Both	117	1786	3.2 (-4.2 – 11.6)	2.2 (-6.0 – 11.3)

Table 5. Differences in the animals' paths in the buffer zones (BZ) and the wind farms. The tortuosity columns contain weighted averages (in degrees) of the difference between the angle of turning at locations within the wind farms and locations within the buffer zones. Values greater than zero indicate that the paths were less directed within the wind farms. No confidence intervals are shown where there are insufficient data.

seal	species	Total numbers of:		Difference in speed between wind farm and buffer (median & 95% CI)	
		passages	locations	Both wind farms	Nysted
Hg-01-10	Hg	7	114	-0.20 (-0.43 - 0)	-0.20 (-0.50 – 0.04)
Hg-02-09	Hg	7	84	-0.01 (-0.20 – 0.20)	-0.05 (-0.31 – 0.18)
Hg-04-09	Hg	19	217	-0.10 (-0.26 – 0.04)	-0.06 (-0.07 - -0.05)
Hg-04-10	Hg	1	17	0.05	0.05
Hg-05-10	Hg	2	27	-0.06	-0.06
Pv-02-10	Pv	3	84	-0.01	-0.01
Pv-05-09	Pv	6	53	-0.13 (-0.36 – 0.09)	0.02 (-0.14 – 0.18)
Pv-07-09	Pv	27	563	0.08 (-0.13 – 0.28)	0.08 (-0.14 – 0.28)
Pv-10-09	Pv	11	153	0.07 (-0.15 – 0.28)	0.07 (-0.16 - 0.26)
Pv-12-09	Pv	34	474	-0.04 (-0.17 - 0.10)	-0.04 (-0.18 - 0.09)
Aggregated:	Hg	36	459	-0.06 (-0.17 - 0.03)	-0.06 (-0.17 - 0.03)
	Pv	81	1327	0 (-0.13 - 0.10)	0.02 (-0.07 - 0.12)
	Both	117	1786	0.03 (-0.11 – 0.04)	-0.02 (-0.10 - 0.05)

Table 6. Differences in the animals' paths in the buffer zones (BZ) and the wind farms. The speed columns contain weighted averages (m/s) of the difference between the speed at locations within the wind farms and locations within the buffer zones. Values greater than zero indicate that movement was faster within the wind farms. No confidence intervals are shown where there are insufficient data.

9 Figures

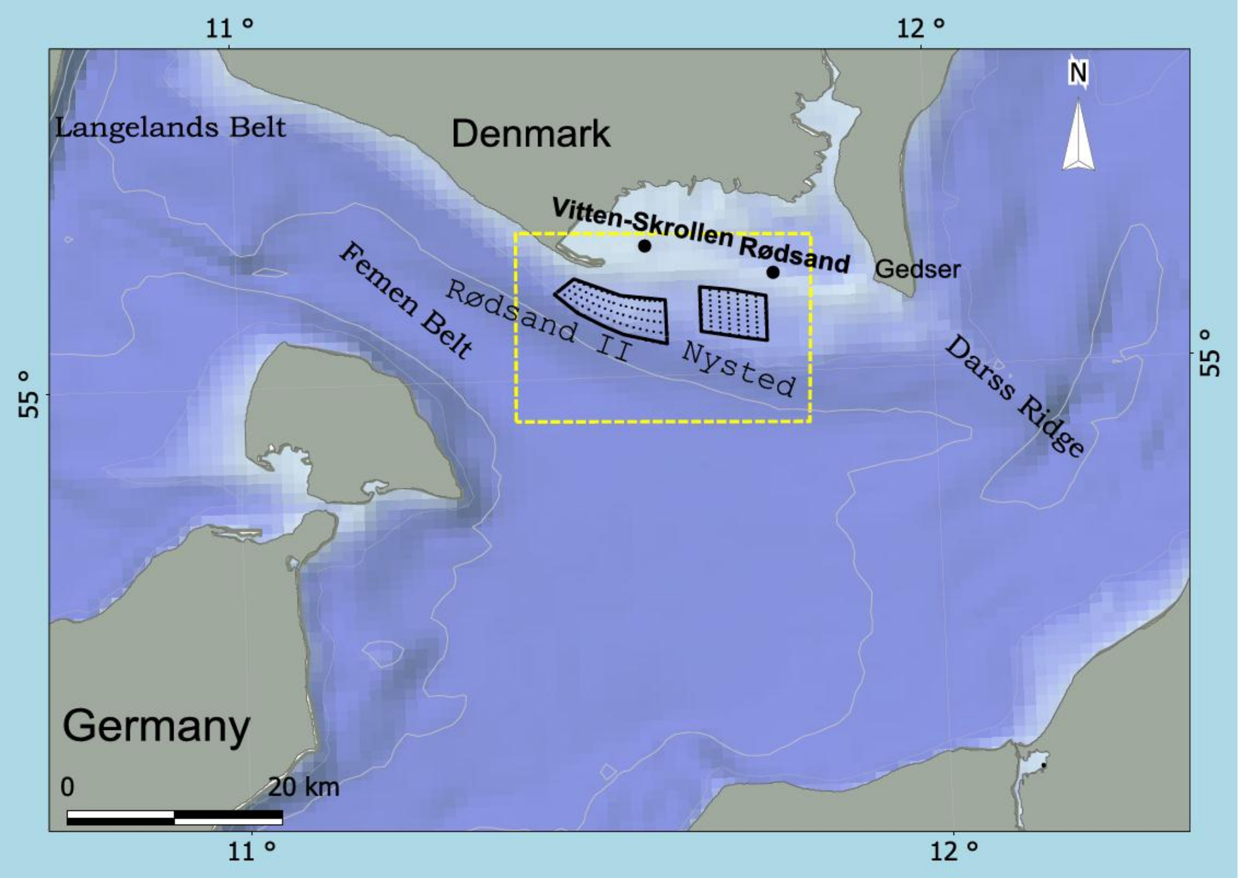

Fig 1. Map showing the study area. The two haulouts of Rødsand and Vitten-Skrollen are shown by black dots. To the south are the two wind farms of Rødsand II and Nysted. The depth contours are at 10 m intervals. The dashed box shows the extent of the smaller maps in Fig 4.

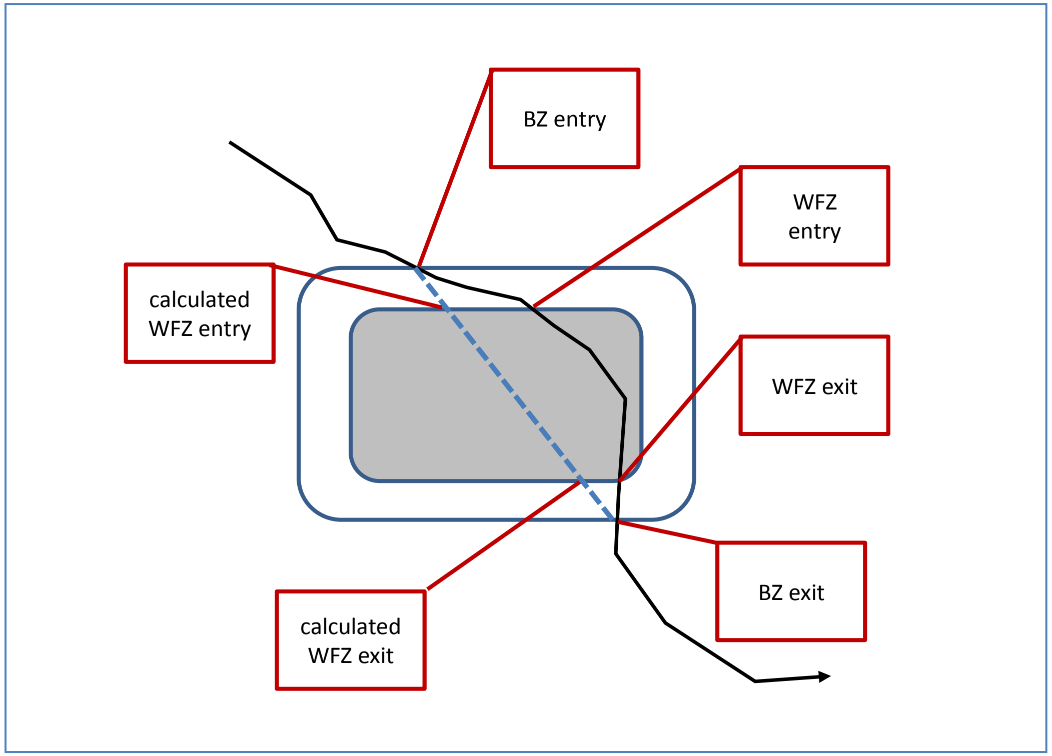

Fig 2. Illustration of wind farm residence BZ ratio calculation. A wind farm zone (WFZ) is shown in grey. It is surrounded by a buffer bone (BZ). The track of a tagged seal is show in black. A simulated straight track from BZ entry to BZ exit is also shown (dashed blue). See Section 4.5.3 for a full description.

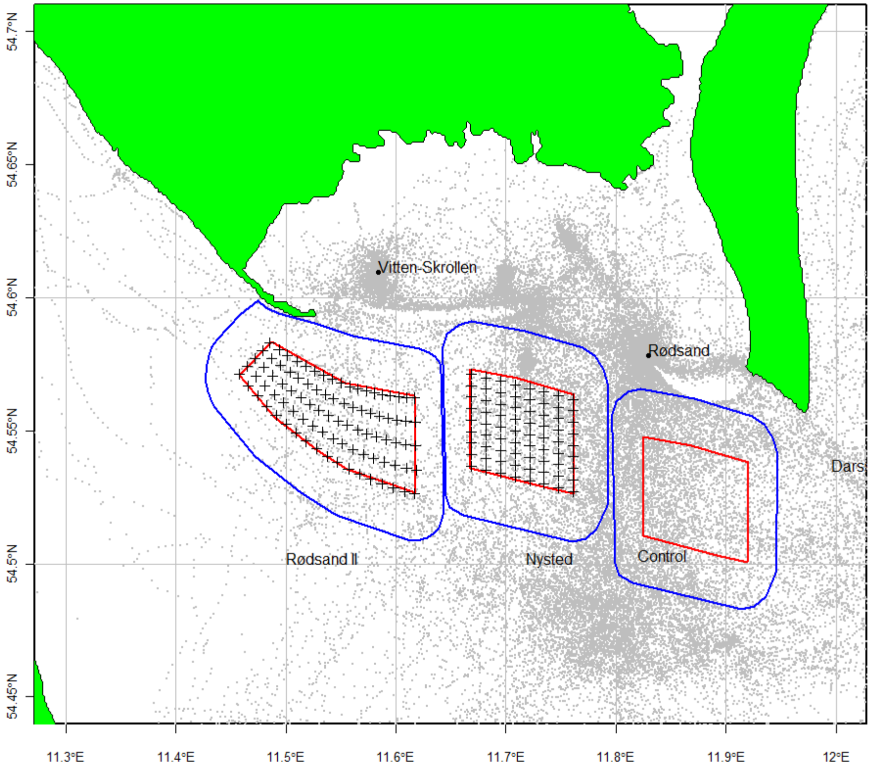

Fig 3. Map showing all seal locations (grey) within the buffer zones (blue) and within the perimeters of Nysted and Rødsand II wind farms (red). The individual towers are shown as crosses. The position of the control wind farm is also shown.

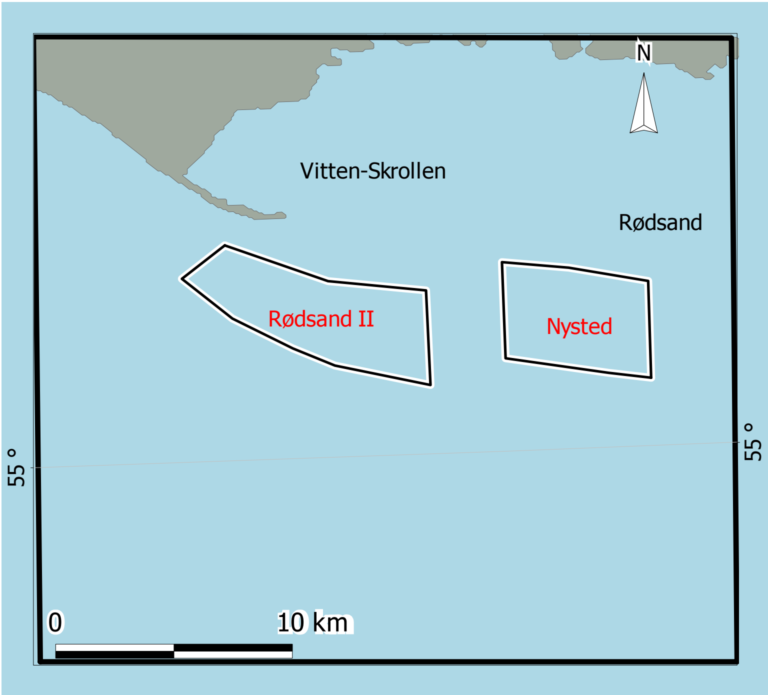

Fig 4.1. Map showing the two haulout sites of Vitten-Skrollen and Rødsand (black text) and wind farm perimeters (black over white lines, names in red text). The rectangle in the lower left of the right hand map shows the geographical extent of the left hand map. This is the template for the rest of Fig 4.

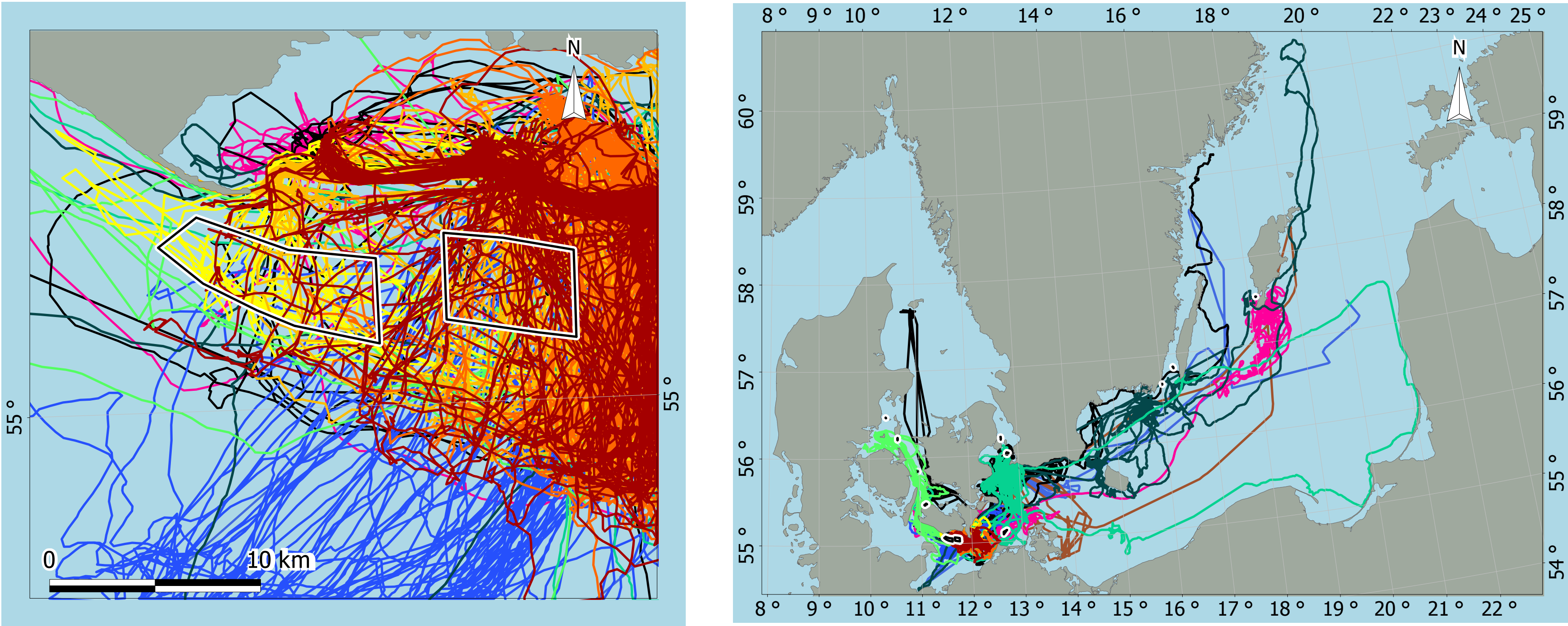

Fig 4.2. Track of all seals (colour-coded by seal). Wind farm perimeters are shown as black over white lines.

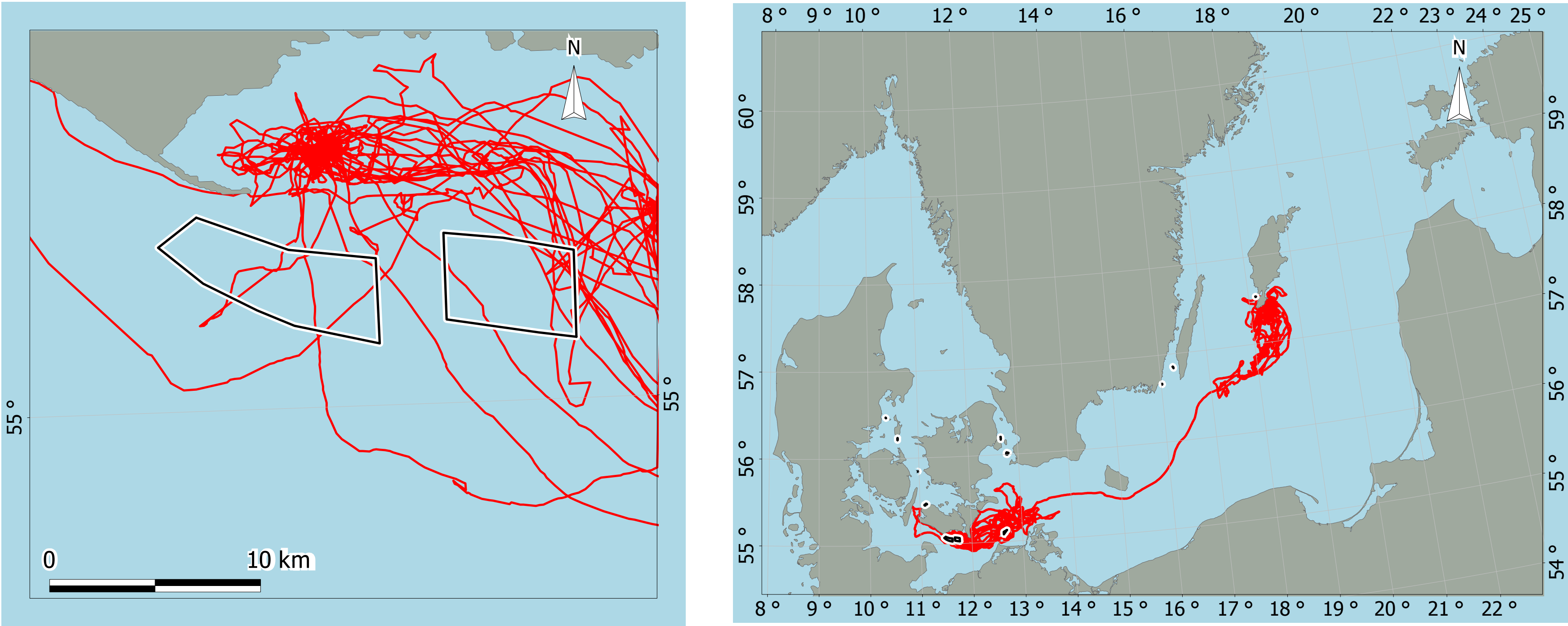

Fig 4.3. GPS track of seal **Hg-01-10**. Wind farm perimeters are shown as black over white lines.

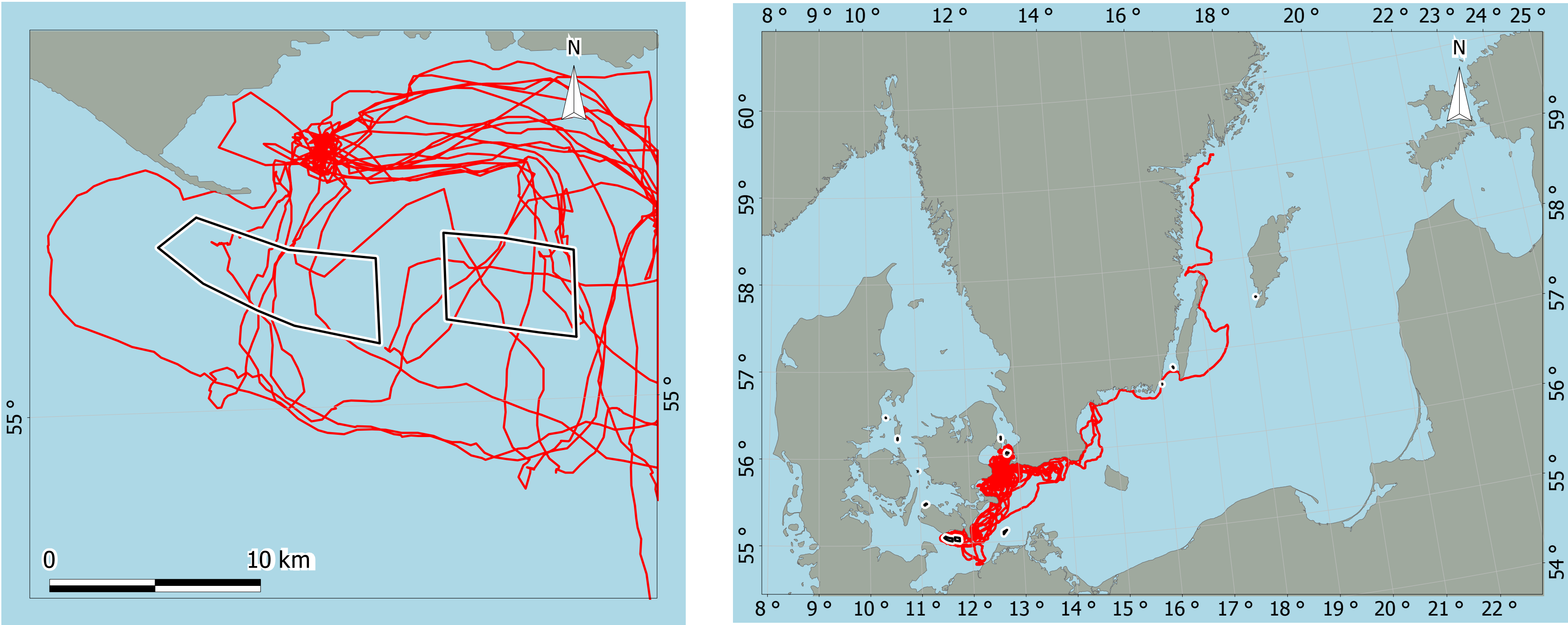

Fig 4.4. GPS track of seal **Hg-02-09**. Wind farm perimeters are shown as black over white lines.

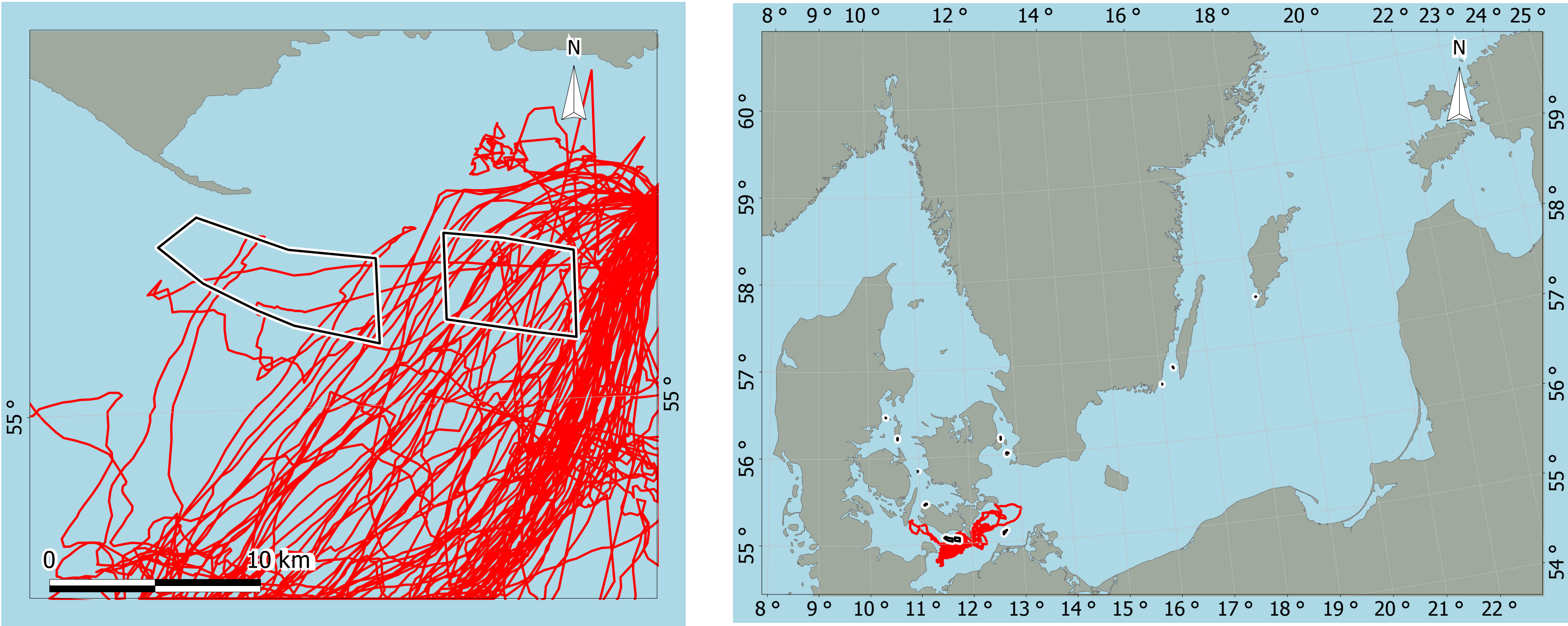

Fig 4.5. GPS track of seal **Hg-04-09**. Wind farm perimeters are shown as black over white lines.

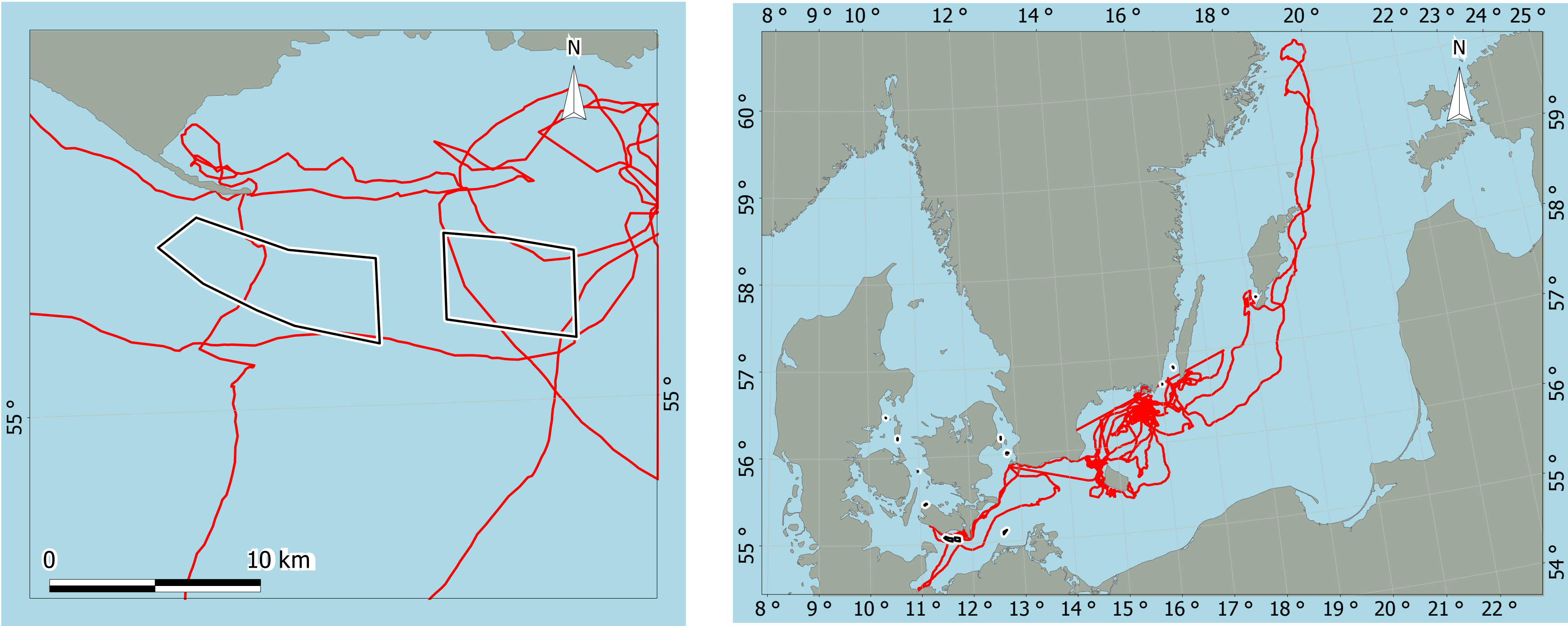

Fig 4.6. GPS track of seal **Hg-04-10**. Wind farm perimeters are shown as black over white lines.

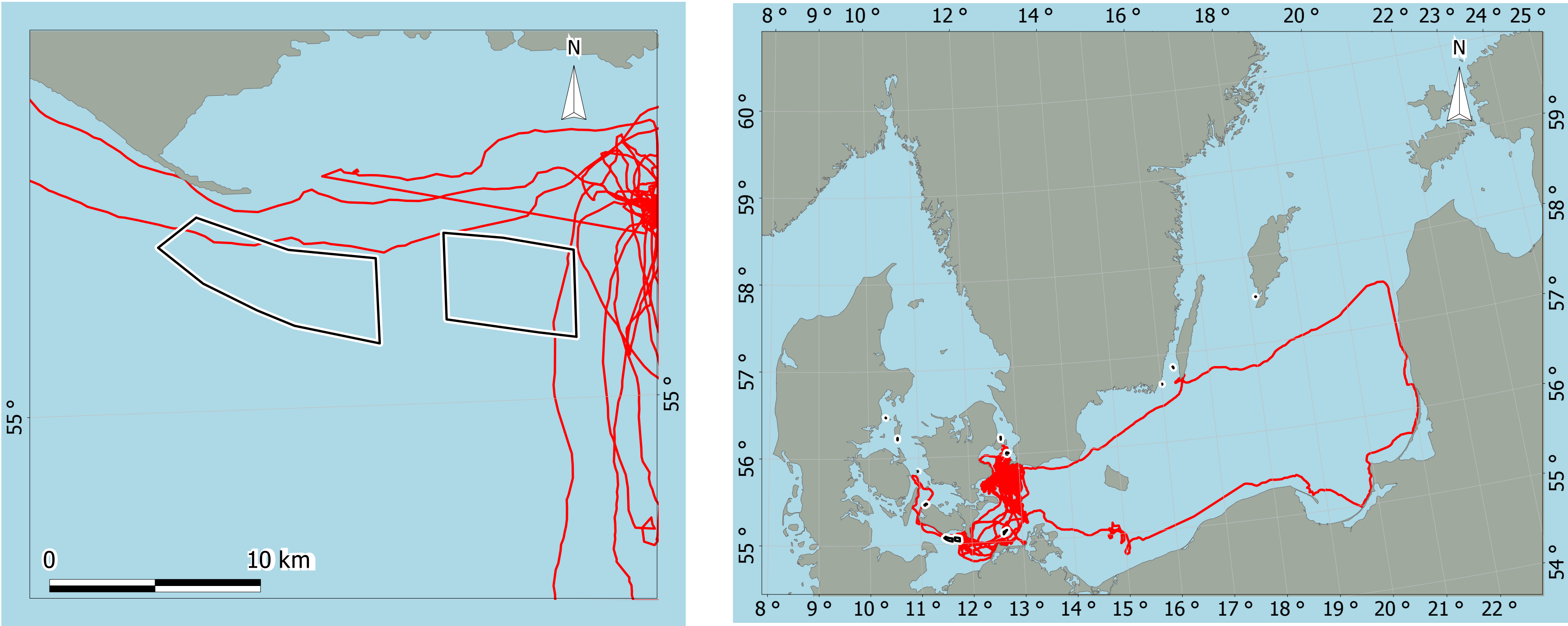

Fig 4.7. GPS track of seal **Hg-05-10**. Wind farm perimeters are shown as black over white lines.

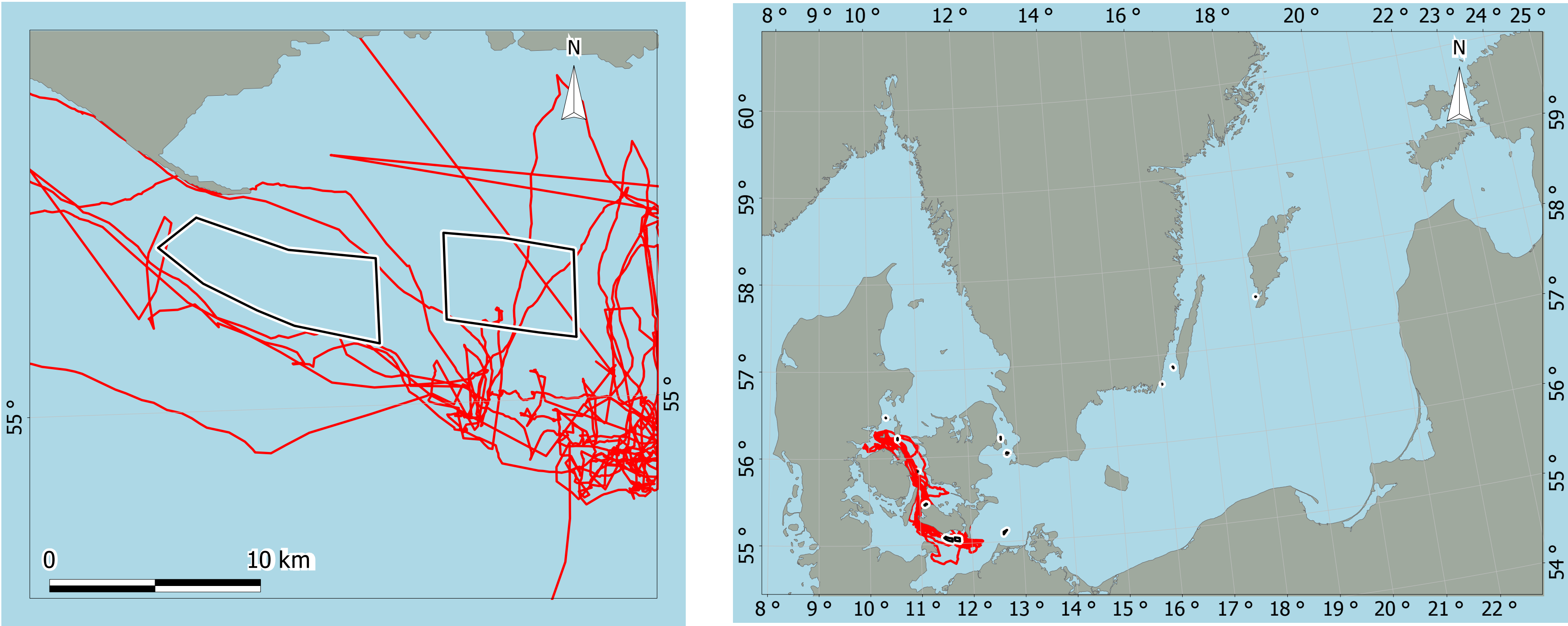

Fig 4.8. GPS track of seal **Pv-02-10**. Wind farm perimeters are shown as black over white lines.

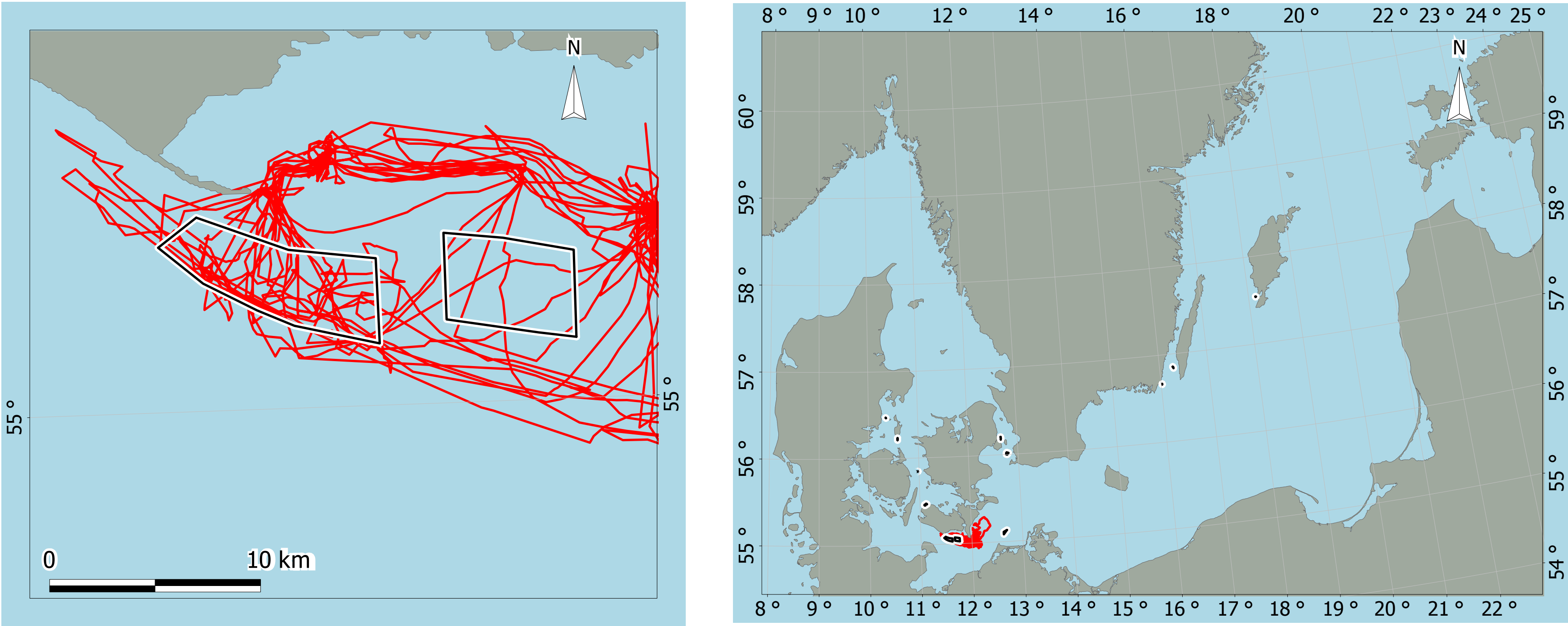

Fig 4.9. GPS track of seal **Pv-05-09**. Wind farm perimeters are shown as black over white lines.

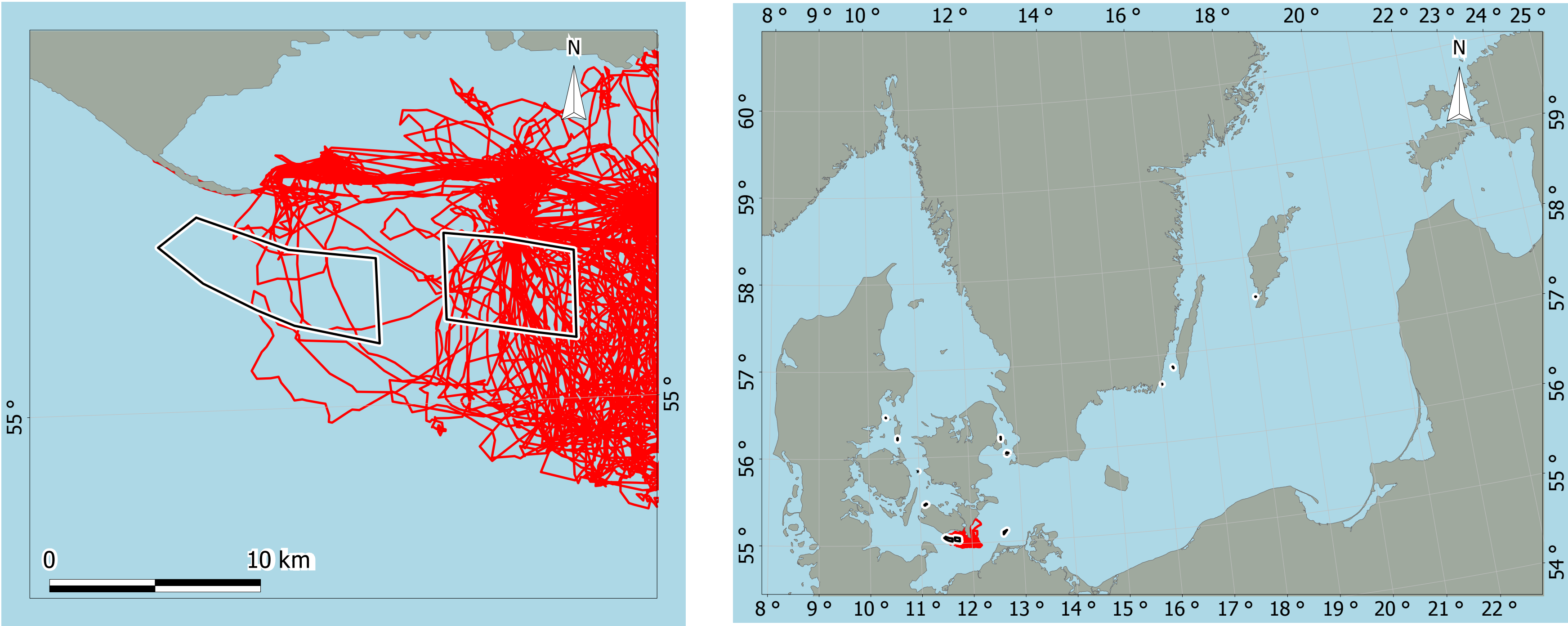

Fig 4.10. GPS track of seal **Pv-07-09**. Wind farm perimeters are shown as black over white lines.

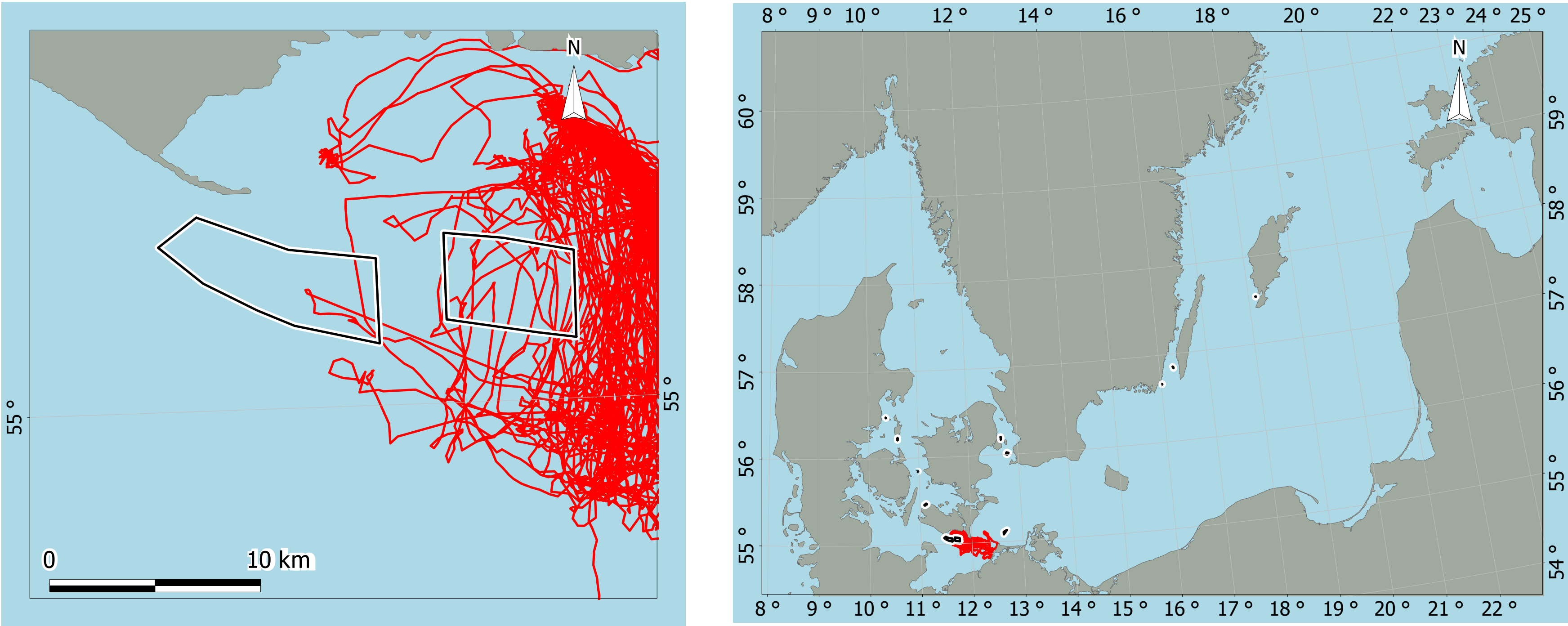

Fig 4.11. GPS track of seal **Pv-10-09**. Wind farm perimeters are shown as black over white lines.

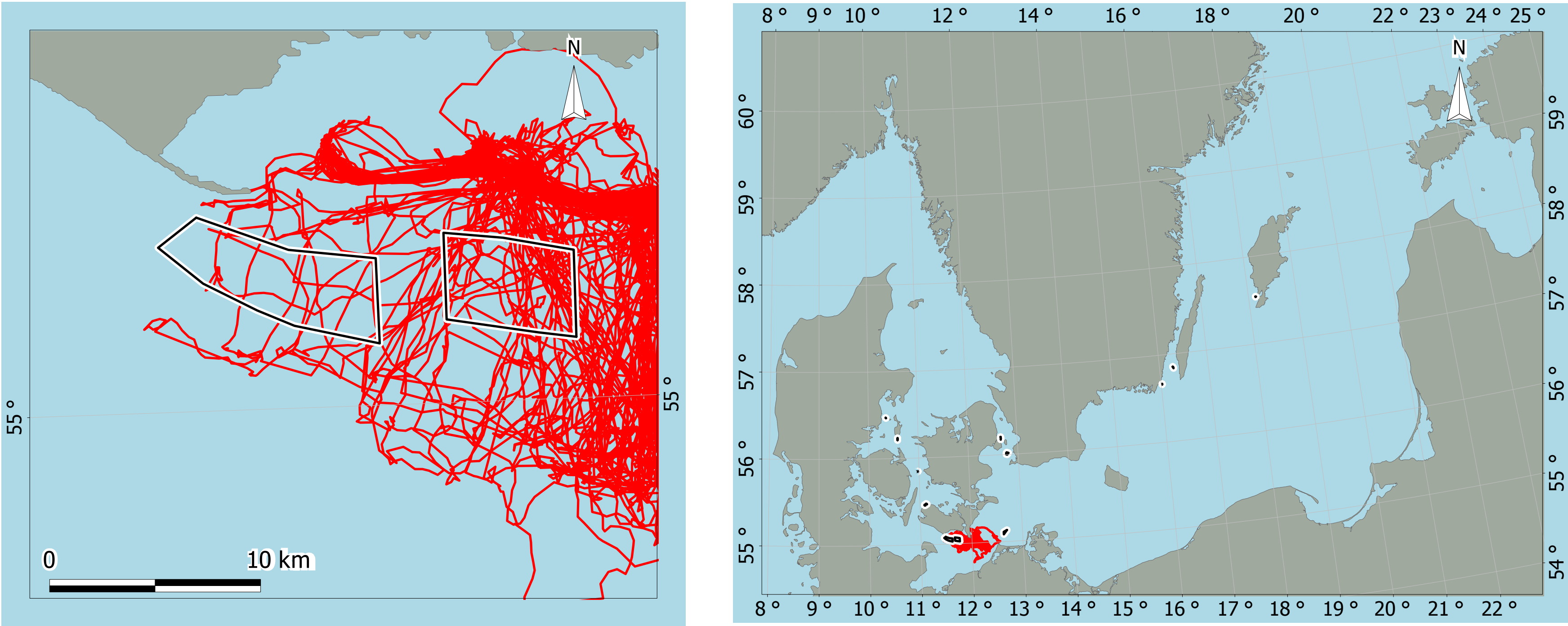

Fig 4.12. GPS track of seal **Pv-12-09**. Wind farm perimeters are shown as black over white lines.

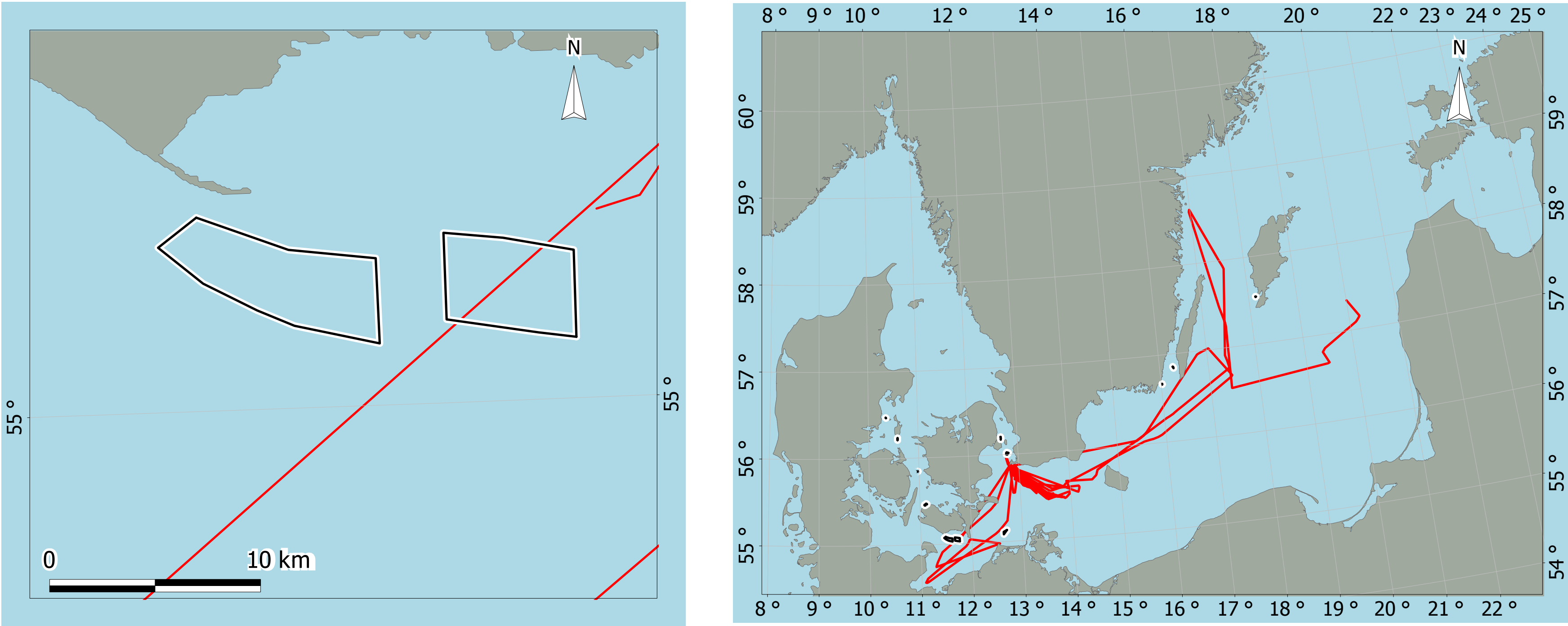

Fig 4.13. Argos track of seal **Hg-37281-10**. Wind farm perimeters are shown as black over white lines.

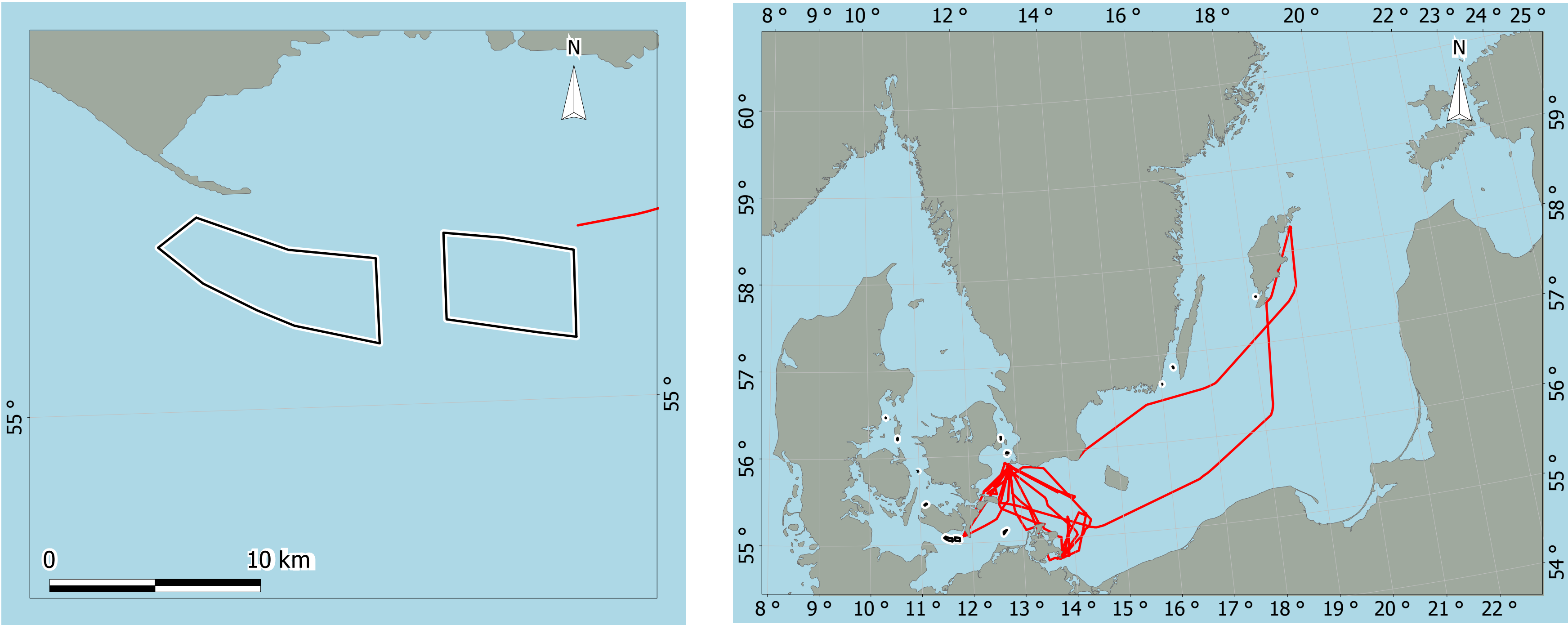

Fig 4.14. Argos track of seal **Hg-60266-10**. Wind farm perimeters are shown as black over white lines.

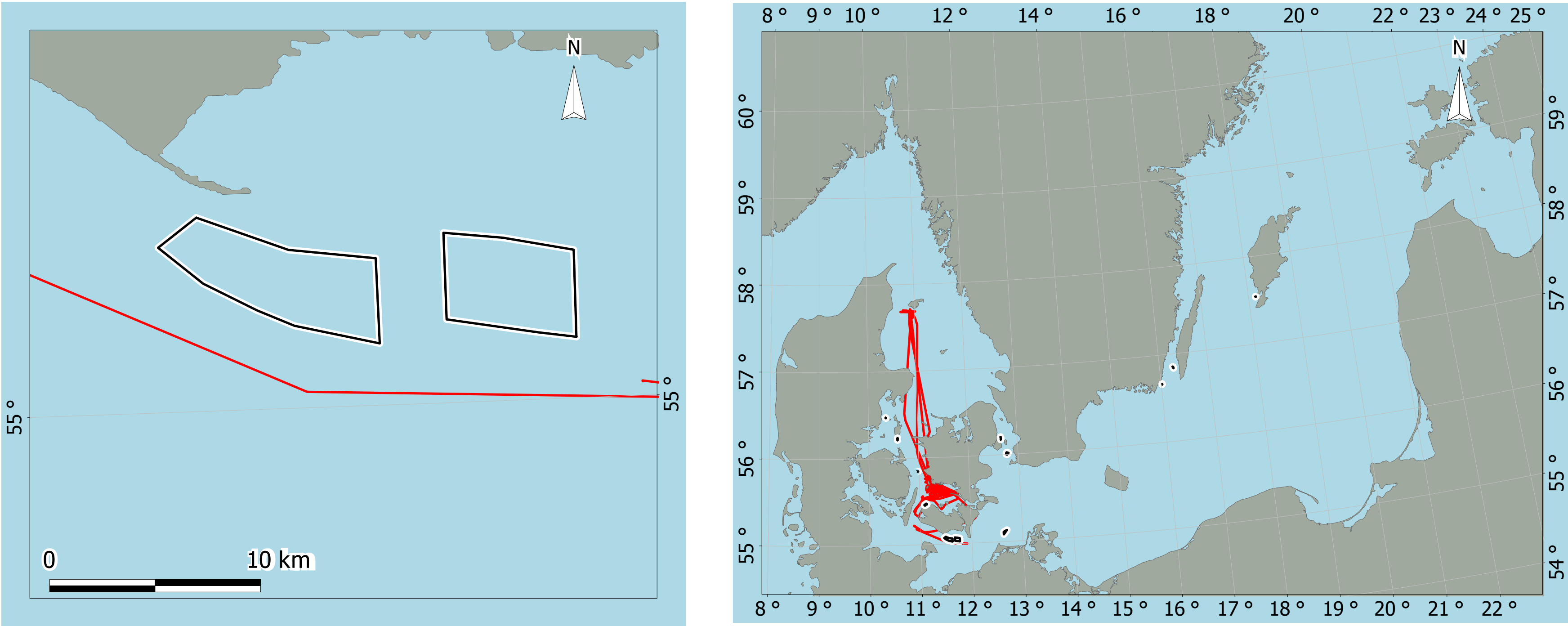

Fig 4.15. Argos track of seal **Pv-60265-09**. Wind farm perimeters are shown as black over white lines.

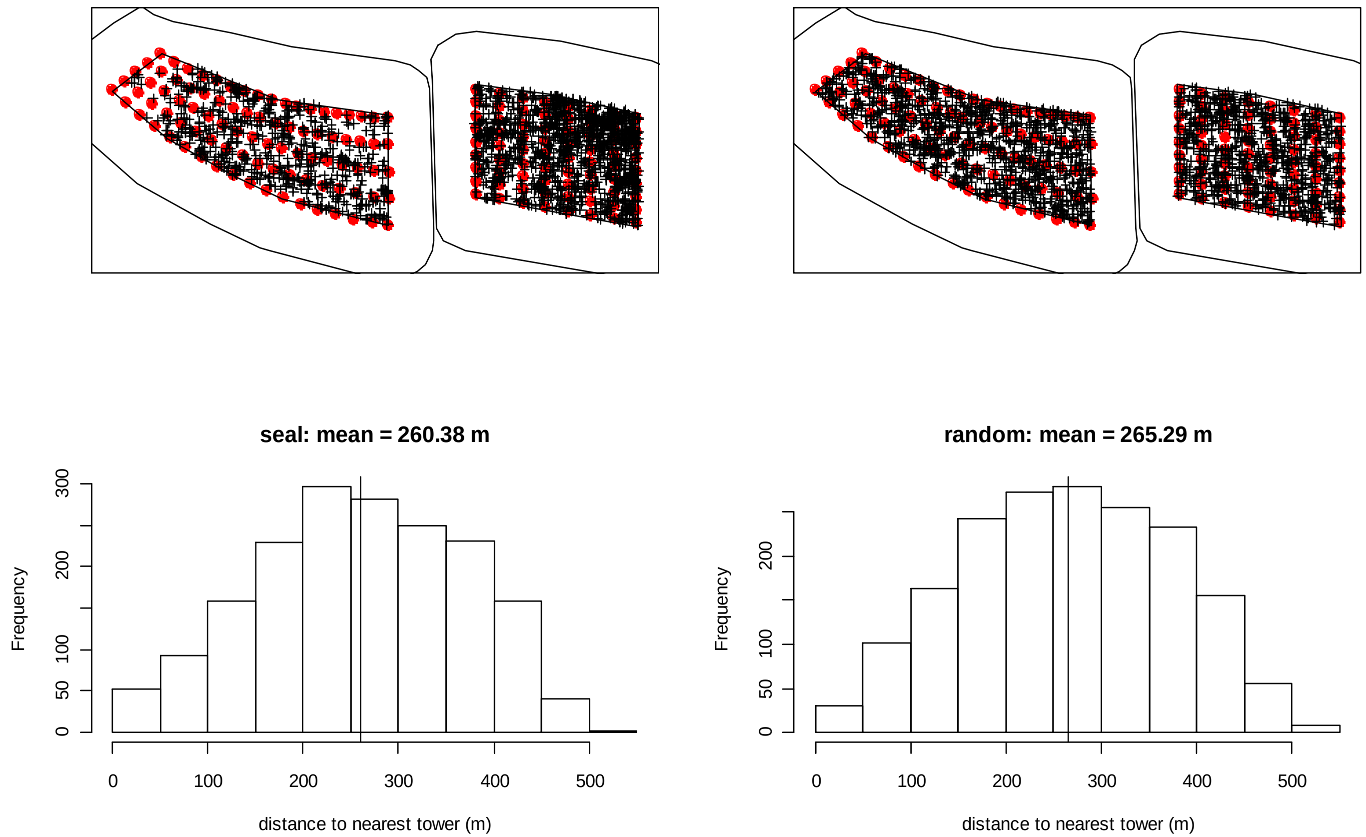

Fig 5. Map of seal GPS locations fixes and individual towers (top left) and the frequency distribution of nearest neighbour distances (bottom left); map of random locations within wind farm perimeter and individual towers (top right) and the frequency distribution of nearest neighbour distances (bottom right). The boundaries of the two buffer zones are also shown.

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