Activity Budgets:
Analysis of seal behaviour at sea

Report to BEIS

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1 Executive summary

The Department for Business, Energy and Industrial Strategy's (BEIS) Offshore Energy Strategic Environmental Assessment programme (SEA), requires robust evidence on which to base the relevant assessments. BEIS previously funded the development of a framework to define grey seal (*Halichoerus grypus*) and harbour seal (*Phoca vitulina*) activities (resting, foraging and travelling) using telemetry data on six-hour resolution. The resting state was assigned when the majority of a six-hour interval was spent non-diving (on land or at surface); the movements of the individuals when diving were used to classify two diving states: foraging and travelling. The state characterised by relatively slow, tortuous movements was assumed to be foraging and the state characterised by faster more directed movements was assumed to be travelling. The resolution at which activities could be classified was determined by the temporal resolution on which the required summarised behavioural data were available from historic telemetry data collected by Argos Satellite Relay Data Loggers (SRDL). On a six-hour resolution, there were issues in estimating separate foraging and travelling states for some tagged harbour seals. Furthermore, activities defined in geographical space may be misleading in areas with high tidal currents.

BEIS recently funded the deployment of high resolution GPS phone tags on 25 harbour seals and 21 grey seals in the southern North Sea. The high-resolution data collected allowed activities to be defined on a two-hour resolution. Activity budgets were defined using (1) movements calculated using geographic locational data (geo-centric movement data) and (2) movements calculated by adjusting geo-centric movements to account for surface tidal currents (hydro-centric movement data). Hydro-centric movements thus reflect the active movement of seals horizontally through the water (in hydro-space), rather than their geographic movements across space (geo-space). There were sufficient data to allow analyses of data from 24 harbour seals and 18 grey seals. Using these data within a Bayesian state-space model, activity budgets were defined in geo- and hydro-space. After running the state-space model, data from three harbour seals and one grey seal were excluded due to issues in defining two diving states in hydro-space, resulting in a sample sizes of 21 and 17 for harbour and grey seals, respectively. Overall activity budgets, defined in geo-space were similar between harbour and grey seals; on average individuals spent approximately 30% of their time in the resting state, 45% of their time foraging and 25% of their time travelling. For both species, significantly more time was spent foraging (at the expense of travelling) in hydro-compared to geo-space, although this varied greatly between individuals. However, almost all intervals classified as foraging in geo-space remained so in hydro-space suggesting that seals rarely move against the current.

The UK coast of the southern North Sea is an area of rapid population increase for both harbour and grey seals, and an area of extensive marine renewable development. In other areas of the UK (e.g. East Coast of Scotland), harbour seal populations have declined rapidly, with a potential cause being competition with grey seals for prey. With the rapidly increasing populations of both species in the southern North Sea competition for resources may soon limit population growth. Habitat preference modelling would allow the activity data generated here to be used to predict important foraging areas. Such predictions would allow quantification of the degree of overlap between grey and harbour seal foraging areas providing a valuable baseline for comparison with their joint distribution in future if and when competition becomes important. Furthermore, in combination with estimates of overall usage, delineating important foraging areas is critical for effective marine spatial planning. The results of this study suggest that important foraging areas predicted using activity data defined in geo-space are robust to the presence of tidal currents. In addition, there are potential inaccuracies in the hydrographic data used and the appropriateness of considering hydro- rather than geo-centric movements may depend on foraging strategy. Thus, activity data defined in geo-space should be used to predict key foraging areas in the southern North Sea.

2 Introduction

A framework for estimating seal activities (resting, foraging and travelling) using telemetry data was developed as part of a study commissioned by BEIS (Russell and McConnell, 2014). Resting and diving intervals were assigned using behavioural data. An interval was assigned to resting if the seal spent the majority of it on the surface of the water (above a tag specific depth threshold) or hauled out on land. Grey (*Halichoerus grypus*) and harbour seals (*Phoca vitulina*) dive when both travelling and foraging; movement data were input into a Bayesian state-space model to assign diving intervals to foraging and travelling (McClintock *et al*., 2013; Russell *et al*., 2015). Relatively slow, tortuous movements are associated with area restricted search, thus the state exhibiting these characteristics was assumed to be foraging and the state characterised by faster more directed movements was assumed to be travelling. Data from two tag types were used in Russell *et al.* (2015): Satellite Relay Data Loggers (SRDL) that use the Argos satellite system for location estimation and data transmission, and GPS phone tags that use the GSM mobile phone network for data transmission. Argos position fixes can encompass large location errors of 50 m to > 2.5 km (Vincent *et al.* 2002), whereas after data cleaning 95% of GPS locations have location errors of < 50 m. The temporal resolution on which states can be defined is limited by the resolution of the summarised behavioural data transmitted by the tag. Such data are available on a six-hour resolution for SRDL tags, and on a two- or four- hour resolution for GPS phone tags. To allow the use of data from all tags, in Russell *et al.* (2015) states were defined on a six-hour resolution. Despite variability in activity budgets between individuals, there were discernible patterns in activity budgets in relation to intrinsic (sex, age) and extrinsic (time of day, time of year and region) covariates (Russell *et al.* 2015).

Within the confines of the state-space model, it is necessary to assume that an interval encompasses only one state, i.e. seals do not switch between foraging and travelling within an interval. This appeared to be problematic for harbour seals when activity budgets were defined on a six-hour resolution; separate foraging and travelling states could not be defined for 25 of 126 individuals (Russell *et al.* 2015). In most regions of the UK, harbour seals forage close to the coast and thus are unlikely to engage in travelling periods that are long enough to result in an interval being assigned to travelling. To investigate whether a two-hour resolution would be more suitable, activity budgets were defined on a two-hour resolution for the individuals in Russell *et al.* (2015) for which appropriate data were available. On a two-hour resolution, foraging and travelling could be distinguished for a higher proportion of individuals (c. 90%) than was possible on a six-hour resolution (c. 80%; Russell, 2015), demonstrating that for harbour seals, a two-hour resolution is more appropriate when assigning activities.

In areas of high currents, activities defined in geographical space may be misleading (Gaspar *et al.*, 2006). For example, if the current is flowing east at a rate of 1 ms^{-1} and a seal is also moving east at a speed of 0.5 ms^{-1}, then geographically the seal is moving at 1.5 ms^{-1} which is a speed which would often be associated with travelling. However, the seal is only moving through the body of water at 0.5 ms^{-1} and thus is more likely to be foraging. In contrast, if the seal is moving west at a speed of 1.5ms^{-1} which is a speed associated with travelling, but the eastward movement of the water means geographically the seal is only moving west at 0.5 ms^{-1}, the interval could be misclassified as foraging. In Russell *et al.* (2015) data from tags deployed in areas with particularly high currents (peak current speeds on a mean spring tide of over 3 ms^{-1}; e.g. Pentland Firth; Figure 1) were excluded from the analyses. However, some other areas where activity budgets were estimated, particularly in the southern North Sea, are exposed to considerable current speeds of over 1 ms^{-1} (Figure 1). Understanding the robustness of activity budget classifications is critical particularly when activity data may be used to predict important foraging areas, that may inform marine spatial planning. Thus, activity budgets defined using movements in geographical space (geo-centric movements) must be compared those defined using hydro-centric movements. Hydro-centric movements reflect the active movement of seals horizontally through the water (in hydro-space), rather than their geographic movements across space (geo-space). Hydro-centric movements can be calculated by adjusting the geographical movement data using data on the speed and direction of tidal currents along the track of a seal. It was not possible to calculate hydro-centric movements using data from Argos SRDL tags due to the coarse temporal resolution and quality of the locational data they transmit.

Previous activity budgets estimations for the southern North Sea were based on data from Argos SRDL tags, and thus were on a six-hour resolution. These data were from ten tags deployed on grey seals at Donna Nook in 2005 and 33 tags deployed on harbour seals between 2003 and 2006 in The Wash and Thames. A more recent and reliable indication of activity budgets of these species is required in this area. Since these deployments there have been extensive wind farm developments with many more planned (Figures 5 and 7). Furthermore, there has been dramatic increases in both the summer foraging (20% p.a. increase) and breeding populations (12% p.a. increase) of grey seals on the UK south-east coast (Duck, Morris & Thompson 2016). Over the same time period, harbour seal populations have recovered from earlier declines and are now at historic high levels (Duck, Morris & Thompson 2016). In other areas of the UK (e.g. East Coast of Scotland), harbour seal populations have declined rapidly (Duck, Morris & Thompson 2016), with a potential cause being competition with grey seals. With the rapidly increasing populations of both species in the southern North Sea competition for resources may soon limit population growth. BIES funded the deployment of GPS phone tags on 25 harbour seal tags in 2012 (Russell *et al.* 2014, 2016; Hastie *et al.* 2015) and 21 grey seals in 2015 (Jones & Russell 2016; Russell 2016). The harbour seals were tagged in The Wash, the largest harbour seal haul out on the UK coast of the southern North Sea, and part of The Wash and North Norfolk Special Areas of Conservation (SAC) for which harbour seals were a primary reason for designation. Eleven of the grey seals were tagged at Donna Nook, the largest grey seal haulout in Europe, which is part of The Humber Estuary SAC for which grey seals are a qualifying feature. Ten grey seals were tagged at Blakeney Point, the second biggest grey seal haulout on the UK coast of the southern North Sea. In this current study, activity budgets were defined in both geo- and hydro-space on a two-hour resolution using the above-mentioned GPS phone tag data. The differences in activity budgets defined in geo and hydro-space will increase understanding as to the robustness of estimates of foraging in geo-space. Furthermore, classifying activities paves the way for a further study predicting key foraging areas for both species. This will allow quantification of the degree of overlap between grey and harbour seal foraging areas providing a valuable baseline for comparison with their joint distribution in future if and when competition becomes important. Furthermore, in combination with estimates of overall usage (Jones & Russell 2016), delineating important foraging areas is critical for marine spatial planning.

3 Methods

3.1 Data used

A total of 25 harbour seals were tagged with GPS phone devices in 2012 in The Wash. Of these, 22 had a duration of over a month and thus were deemed suitable for activity budget analyses. In addition, ten harbour seals were tagged at Thames at a similar time; two of these individuals travelled to the Wash from where they carried out return trips. Thus, data from 24 harbour seals were available for quantifying activity budgets for individuals associated with The Wash.

A total of 21 devices were deployed on grey seals on the UK coast of the southern North Sea in 2015. However, one of these was a solar GPS Argos tag donated by SMRU Instrumentation. Unfortunately, fewer data are transmitted through the Argos system compared to the phone system, and the resulting data were too sparse to be used to define activity budgets on a two-hour resolution. Of the remaining 20 GPS phone tags, 18 had a duration of over a month and thus their resulting data were deemed suitable for activity budget analyses.

3.2 Geo-centric data

All location data were interpolated onto a two-hour resolution which is the resolution on which summarised behavioural data were available. Using these interpolated data, speed and bearings were calculated for each interval.

3.3 Hydro-centric data

Polpred (a software developed at the National Oceanography Centre, UK: Copyright Reserved) provides predicted current direction and speed (water displacement) data on a 1/60° latitude x 1/40° longitude resolution. Surface current speed and direction was predicted at a set of telemetry locations: (1) midpoint between all observed telemetry observations that were less than 15 minutes apart (2) midpoint between regularised 15-minute interpolated locations. It was assumed that the current at the midpoint applied to an entire period (a maximum of 15 minutes) and by deleting the tidal vectors from the geographical vectors, the active (hydro-centric) movement for each period was calculated. If there was no current data available for a period, the non-adjusted geographical movement data were used. This dataset was then interpolated onto a two-hour resolution. Although hydrographic data are available at various depths, surface data were used because the mismatch in the temporal resolution of the locational data (c. 15-minute resolution) and depth data (10 depth points per dive), made reliable interpolation of location and depth data on the same resolution problematic. Furthermore, depth data are not successfully sent for all dives.

3.4 State assignment

The methods used to define activity states are described in brief below. They are described in detail in Russell *et al*. (2015); in that publication activity states were defined in geo-space on a six-hour resolution, in contrast to the two-hour resolution used here.

GPS phone tags transmit both locational and behavioural data. Behavioural data include data on individual dive and haulout events; however, data on all events were not successfully transmitted. Summarised behavioural data are also transmitted which include the proportion of time the tag has been dry (associated with haul out), wet but above the tag-specific depth threshold (at-surface) and diving (below the depth threshold) within a defined period of time. Data from almost all summary periods were successfully transmitted.

The summarised behavioural data were used to define two 'super-states': resting and diving. Resting can occur on land (a haulout event) or on the surface of the sea; resting at sea is likely associated with digestion (Sparling, Fedak & Thompson 2007). An interval was assigned to diving rather than resting if more than 44.4% of a summary period was spent diving. Analysis of the summary data revealed that the maximum percentage of time seals can spend under water is 88.8% of a two-hour period due to having to come up to the surface to replenish oxygen stores between dives. Diving behaviour is thus composed of 11.2% of time on the surface (surface overhead) and the rest underwater. An interval was classified as diving if more than 50% of it was spent engaging in diving behaviour (including the surface overhead). In other words, if over 44.4% of the interval was recorded as diving by the tag ((100-11.2)/2) then the interval was assigned to the diving state. Seals dive when travelling and foraging, thus the locational data were then used to estimate the probability of a diving interval being associated with foraging or travelling. Movement data were input into a Bayesian state-space model (SSM), within which speed (distance/time) over the two-hour interval and bearings were used to estimate the probability that an interval was associated with foraging or travelling. Relatively slow, tortuous movements is associated with area restricted search, thus the state exhibiting these characteristics was assumed to be foraging and the state characterised by faster more directed movements was assumed to be travelling. Intervals were considered non-estimable if no behavioural summary data were available or if there were over six hours between observed locations surrounding the interpolated locations. The state-space model was run twice for each individual, using movements in geo- and hydro-space. Model convergence was judged visually and using the Gelman-Rubin (gbr) statistic.

3.5 Analyses

The same behavioural summary data were used for the geo- and hydro-centric movement data so the proportion of time spent resting was the same in both geo- and hydro- space. Thus, given diving, the proportion of time estimated as foraging vs travelling in geo- and hydro-space was compared. As described above, hydrographic data were not available for every telemetry location and so geo-centric movement data had to be used for some intervals when defining movements in hydro-space. To allow comparison between activity budgets in geo- and hydro-space, the proportion of time diving that was spent foraging was compared for intervals for which there were hydrographic data. This comparison was made within a Generalised Estimating Equation (GEE) framework within the geepack package (Højsgaard, Halekoh & Yan 2006) in R (R Core Team 2014) using a binomial error distribution with a logit link function. The proportion of time diving that was spent foraging was considered as a function of the movement in geo- or hydro-space. The GEE framework allows the non-independence within individuals to be accounted for in the standard errors. For those intervals for which there were hydrographic data, the proportion of intervals that were defined as foraging in geo-space, which remained so in hydro-space was also examined.

4 Results

Convergence of the state-space model was obtained for all grey seals. The model did not converge for one harbour seal; two separate diving states could not be estimated in hydro-space for this individual. The activity data from two further harbour seals and one grey seal were subsequently excluded due to a very small number of intervals being estimated as foraging in hydro-space. These exclusions resulted in activity data being available for 21 harbour seals (Figure 2a) and 17 grey seals (Figure 2b).

The proportion of intervals which were inestimable (due to missing behavioural or locational data), varied between individuals and was lower in harbour seals (0.04; 95% CI: 0.01 - 0.18) than grey seals (0.10; 95% CI: 0.04 - 0.23). The very short time taken, once on the surface of the water, for the data required to obtain a GPS location to be collected, means it is unlikely such missing data were associated with one particular activity. Once such intervals were excluded, the proportion of time spent resting was estimated to be 0.30 (95% CI: 0.21 - 0.36) and 0.28 (95% CI: 0.24 - 0.49) for harbour and grey seals, respectively. For harbour seals, considering geo-centric movements, 0.46 (95% CI: 0.24 - 0.63) and 0.25 (95% CI: 0.06 - 0.48) of time was estimated to be spent foraging and travelling, respectively. Similar results were found for grey seals; the proportion of time spent foraging and travelling was 0.42 (95% CI: 0.26 - 0.64) and 0.26 (95% CI: 0.12 - 0.45), respectively.

There were hydrographic data for 89% (95% CI: 71 - 97%) and 92% (95% CI: 68 - 97%) of diving intervals, for grey and harbour seals respectively. Considering these intervals, there were significantly more diving intervals assigned to foraging compared travelling if hydro-centric rather than geo-centric movements were considered. This difference was particularly apparent for harbour seals (GEEGLM: χ^2=31.24, P < 0.00001; Figure 3a), with the estimated mean proportion of diving intervals assigned to foraging being 0.64 (95% CI: 0.55 - 0.72) in geo-space compared to 0.80 (95% CI: 0.77 - 0.84) in hydro-space. For grey seals, the difference, although significant (GEEGLM: χ^2=9.38, P < 0.01; Figure 3b) was less marked; 0.61 (95% CI: 0.52 - 0.68) and 0.70 (95% CI: 0.64 - 0.74) of intervals were assigned to foraging, in geo- and hydro-space respectively. The track of a grey seal for which the differences in activity budgets defined in geo- and hydro-space were particularly pronounced is shown as an example (Figure 4).

For harbour seals, 99% of intervals which were defined as foraging in geo-space were also defined as foraging in hydro-space (95% CI: 60 - 100%). A similar percentage was found for grey seals (96%, 95% CI: 58 - 100%). The predicted foraging locations defined in geo- and hydro-space are shown for both harbour (Figures 5 and 6) and grey (Figure 7 and 8) seals.

5 Discussion

In this study, a framework developed to classify seal activities (resting, foraging and travelling) along telemetry tracks (Russell *et al.* 2015) was applied to data from GPS phone tags deployed on harbour and grey seals in the southern North Sea. Three activity states were defined: resting, foraging and travelling. It is important to bear in mind the state estimates of “foraging” and “travelling” are labels that are assumed to correspond to the two movement types observed. In a similar way, the “resting” label simply refers to intervals for which the majority of time was spent on land or at-sea (i.e. not diving) and may be associated with various activities including food digestion (Sparling *et al.* 2007). In contrast to Russell *et al.* (2015), in the current study activity states were defined on a two- rather than the six-hour resolution and as well as being defined using geographic movements (geo-space), activity budgets were also defined in hydro-space using active seal movement data through the water by adjusting geographical movement data using tidal current data. Issues in estimating three activity states for two harbour seals and one grey seal in hydro-space meant that activity budgets were effectively estimated in both geo- and hydro- space for 21 harbour seals (Figure 2a) and 17 grey seals (Figure 2b). Comparisons of activity budgets in geo- and hydro-space revealed that significantly more time was estimated to be foraging when hydro-centric rather than geo-centric movements were considered. However, for the most part foraging locations estimated in geo-space remained so in hydro-space. Activity budgets were similar in grey and harbour seals; this may change in the future as and when competition from grey seals results in the smaller harbour seal having to work harder to fulfil their energy requirements. Further work, using the activity data presented here, to predict key foraging areas for both species will illuminate as to the potential for inter-specific competition and facilitate effective marine spatial planning.

The reasons behind the issues in estimating three activity states for two harbour seals and one grey seal in hydro-space are not fully certain. However, for these individuals the speeds for the intervals which were estimated as foraging were very slow and the speeds for intervals estimated to be travelling encompassed both typical foraging and travelling speeds. Thus it is likely that, for these individuals, the intervals assigned to foraging occurred while the individuals were exhibiting a third diving behaviour such as resting underwater (Thompson *et al.* 1991), which would be associated with very slow speeds. Only two diving states can be assigned in the model thus three inferred diving behaviours would have led to incorrect state assignments. It appears that these three diving behaviours only became apparent once tidal movement had been taken in account as the problem was not apparent when considering geo-centric movements. On the other hand, such issues may have been due to inaccuracies in the hydrographic data; there may have been only two states, foraging and travelling, but issues with the accuracy of the current data and thus the resulting movement data may have resulted in these states no longer being estimable. The predictions of current speed and direction are subject to error which would be influenced by the grid resolution on which predictions were available and by the necessary interpolation of the telemetry data. Furthermore, during a 15-minute period (maximum time between interpolated locations) an individual could travel 1.8 km and thus experience various current speeds and directions. Critically, the hydrographic data used were for the sea surface; in reality seals spent much of their time diving. The tags transmit high resolution dive data but the relatively coarse temporal resolution of the locational data makes the reconstruction of tracks in 3D, required to use hydrographic data from multiple depths, problematic. These caveats mean that only the broad patterns in activity budgets defined in hydro-space should be considered; the individual speed and bearing estimates should not be used directly. Further work is required to understand the magnitude of the error in the estimated movements in hydro-space, particularly to understand the mismatch between the surface currents used and the currents experienced by the seals. A higher proportion of foraging was estimated in hydro- compared to geo-space signifying that foraging is more often misclassified as travelling rather than being misclassified as foraging suggesting that seals rarely move against the current. Although there are some parts of tracks for which foraging is estimated in hydro- but not geo-space (Figures 4-8), reassuringly the intervals estimated as foraging in geo-space remained so in hydro-space.

Despite grey seals exhibiting, on average, longer distance trips (McConnell *et al.* 1999; Sharples *et al.* 2012) activity budgets were similar between harbour and grey seals. This suggests that harbour seals may go on more frequent trips than grey seals; this has never been investigated in telemetry data. Harbour seals in The Wash exhibit longer distance trips than in other areas of the UK so it uncertain whether the similarity in activity budgets between the species would hold in other regions. Despite considerable individual variation in activity budgets, previous analyses on activity budget data on a six-hour resolution revealed discernible patterns with covariates. The harbour seal population may in the future be limited by increased competition from a rapidly increasing grey seal population. The activity budgets defined in this study can be compared with future activity budgets, while controlling for the above-mentioned covariates, to determine if harbour seals exhibit significantly increased foraging effort.

The impact of marine developments on seals is dependent on the stage (construction, operation, decommissioning; Russell *et al*. 2016) and the location of the development relative to foraging areas and haulout sites. During construction, some developments could create a barrier to movement to and from haulout sites. Developments near foraging areas may inhibit foraging during construction but during operation foraging levels may be the same as pre-construction or even enhanced (Russell *et al* 2015). This current study shows that some footprints (of planned or current developments) are predominantly used for travelling and others for foraging (Figures 5 and 7). For example, the footprint of what will be Race Bank windfarm near the mouth of The Wash is predominantly used by harbour seals as a transit route between foraging grounds and the haulout (Figure 5). In contrast, the proposed Hornsea windfarm is far from the coast and is predominantly a foraging area for harbour seals. Whereas grey seals, exhibit both foraging and travelling behaviour in the footprint of the proposed Hornsea windfarm (Figure 7). The activity budgets, generated for this study, can be compared with data from future deployments to examine changes in activity budgets (overall and spatially) over a period of extensive offshore development.

The results of this study suggest that seals rarely move against tidal currents and thus locations estimated as foraging using geo-centric movement data are robust to the presence of tidal currents. Given this and the potential inaccuracies in the hydrographic data used, activities defined in geo-space should be used to predict key foraging areas. The likelihood of important foraging areas not being identified by defining foraging only in geo-space will depend on the strength of currents in the area and the degree to which seals forage in these areas. In addition, the appropriateness of considering movements of individuals in hydro- rather than geo-space may depend on foraging strategy. If an individual is foraging on the seabed, their movements in geo-space should be used to define foraging whereas if an animal is foraging in the water column, then their movements in hydro-space will be more relevant. There is potential that inshore intervals may be misclassified as foraging; although some individuals do not go offshore and thus must forage inshore, many inshore foraging locations occur while tidal sandbanks are not available to haul out on and such apparent foraging may in fact represent other activities such as resting underwater. Investigations of temporal patterns in apparent inshore foraging and the associated dive records are required to elucidate as to what activity is occurring. Foraging appears to occur in multiple MPAs, particularly within ‘North Norfolk Sandbanks and Saturn Reef’, ‘Inner Dowsing’, and ‘Race Bank and North Ridge’ by harbour seals, and ‘Dogger Bank’ by grey seals (Figure 8). For effective marine spatial planning, important foraging areas needs to be defined. This would also allow quantification of the overlap between grey and harbour seal foraging which, along with the available data on their respective diets (Wilson & Hammond 2015), will elucidate as to potential inter-specific competition for prey. Habitat preference analyses, which involves quantifying the association between environmental covariates and foraging, should be used to predict such areas. Foraging habitat preference analysis was conducted for the North Sea area (Russell & McConnell 2014) but was hampered by the inability to reliably distinguish foraging and travelling for harbour seal data collected by SRDL tags. Due to a lack of prey data on an appropriate spatial resolution, static variables such as sediment type and depth may be most appropriate to predict seal distribution. The use of such proxies of prey availability are likely to be quite reliable as the presence of sandeels, a key prey of both species (Wilson & Hammond 2015), is strongly correlated with habitat type. However, trends in abundance of sandeels may vary spatially and the reliance of seals on sandeel appears to vary both temporally and spatially (Wilson & Hammond 2015). Thus it is important to use the most recent telemetry data when predicting foraging usage and where possible, to investigate temporal variation in usage. Such analyses will be possible for harbour seal foraging usage emanating from The Wash, as in October 2016, a project funded by DONG Energy resulted in the deployment of GPS phone tags on 20 harbour seals.

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8 Figures

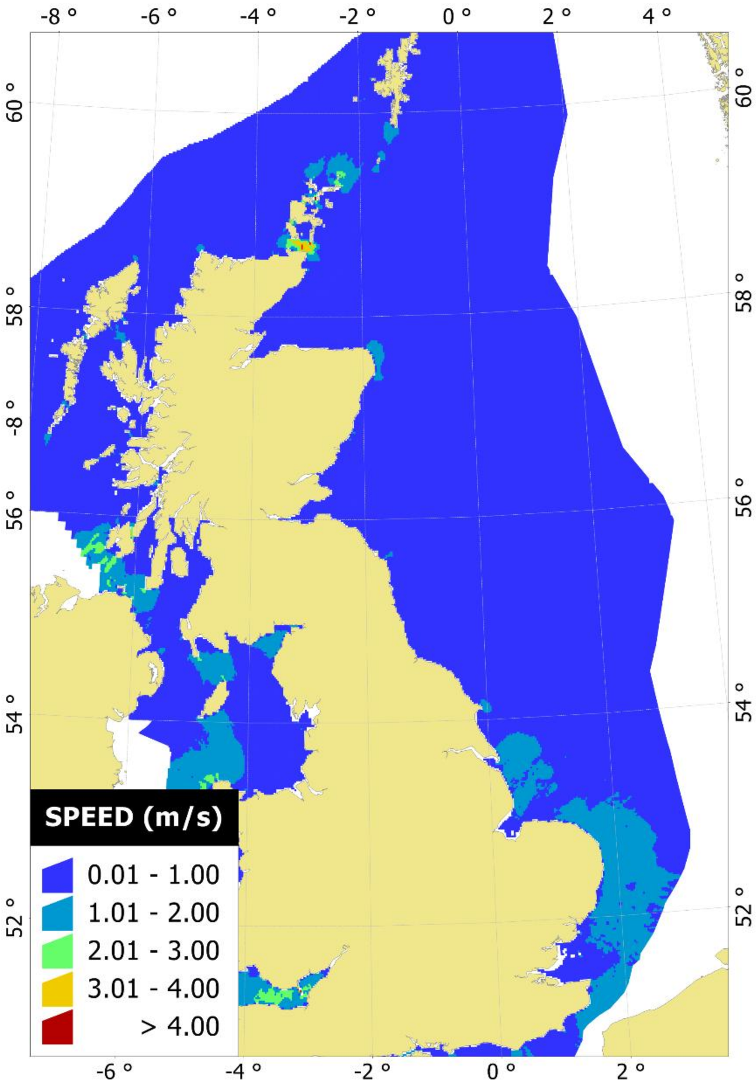

Figure 1. The peak current speeds on a mean spring tide (m/s) around the UK (Atlas of UK Marine Renewable Energy Resources 2008).

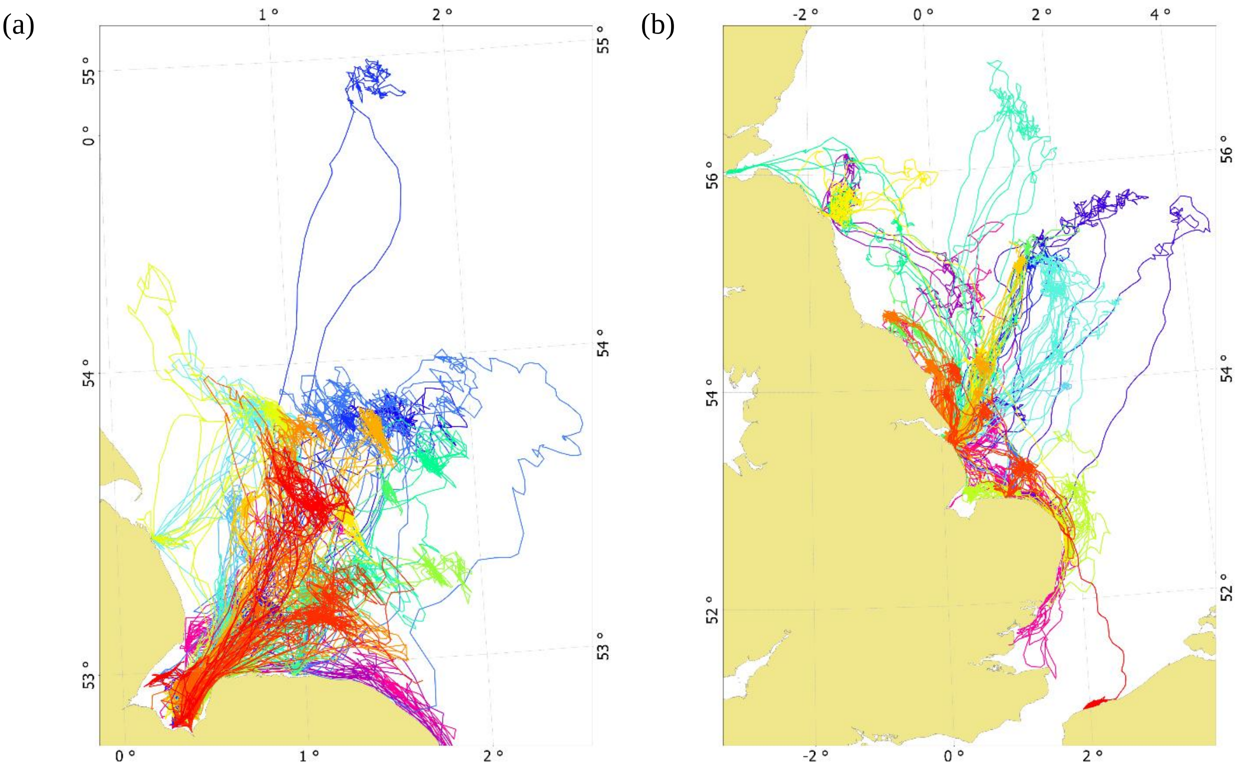

Figure 2. The tracks for which activity data were available, on a two-hour resolution coloured by individual harbour (a) and grey (b) seals.

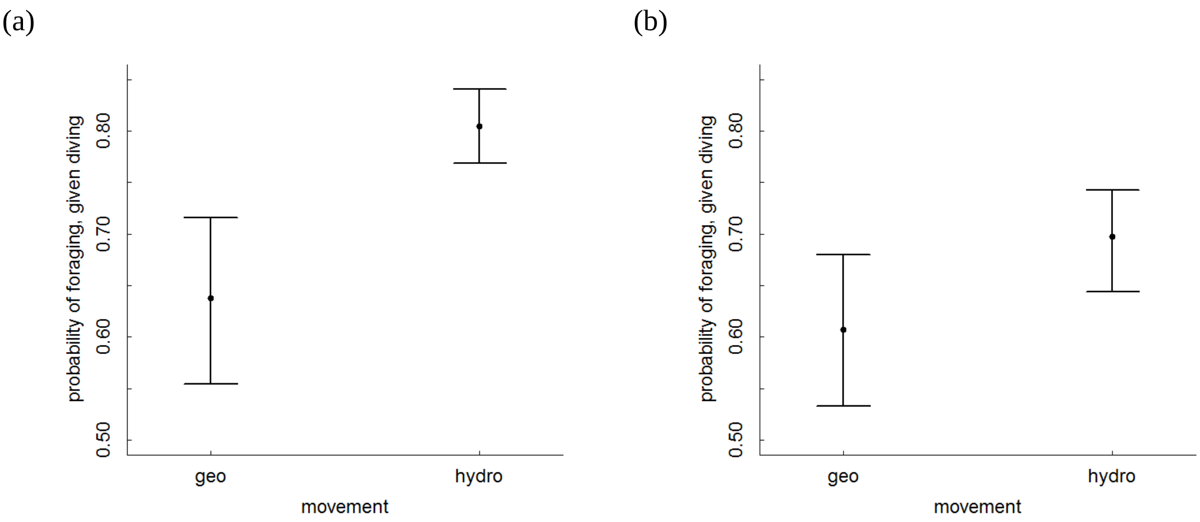

Figure 3. The probability of a diving interval being assigned to foraging (rather than travelling) in geo- and hydro-space for harbour (a) and grey (b) seals. The whiskers extend to the 95% confidence intervals.

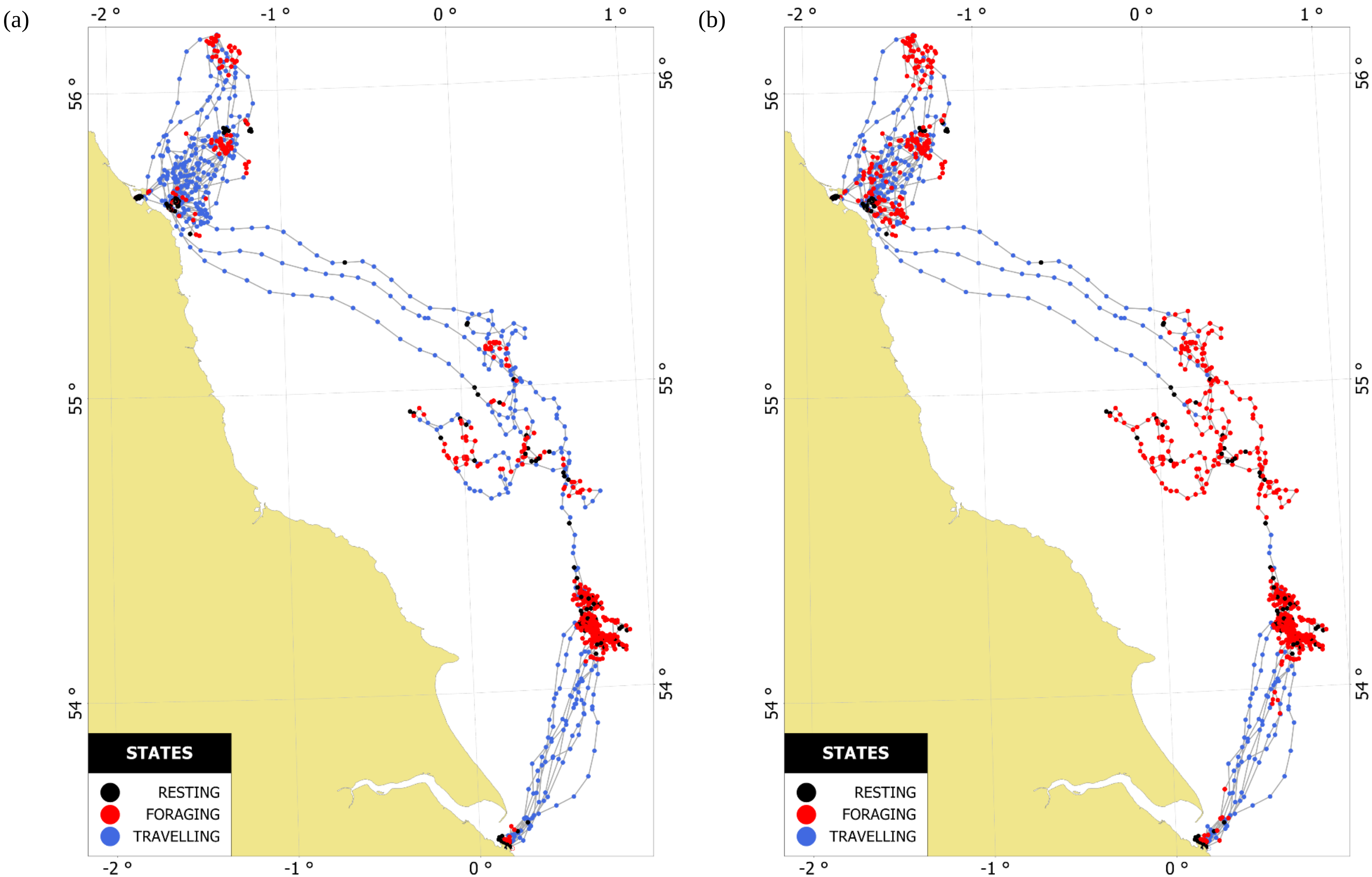

Figure 4. The track of a grey seal with estimated activity states in geo- (a) and hydro- (b) space.

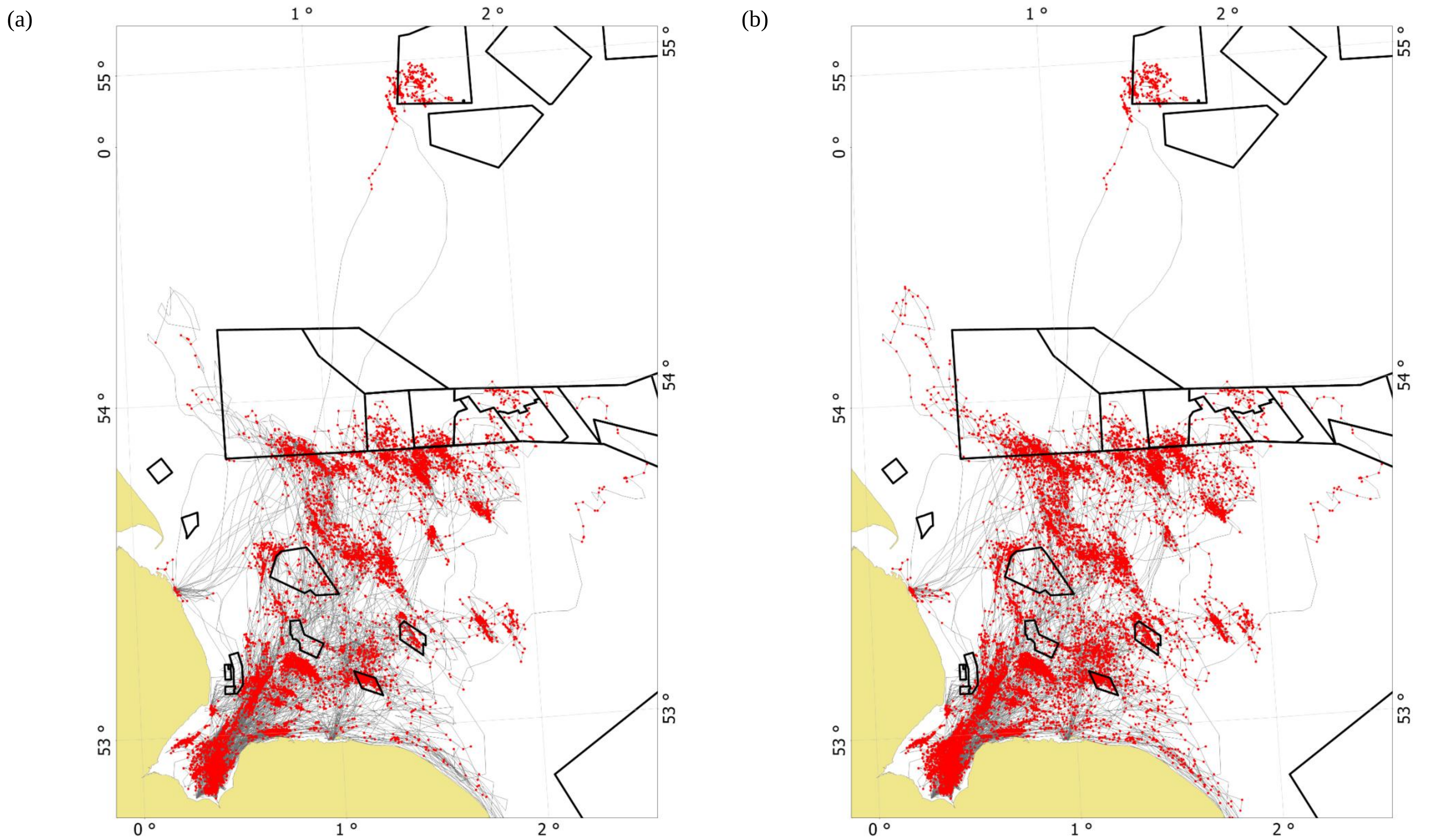

Figure 5. The tracks (grey) and estimated foraging locations (red) of tagged harbour seals in geo- (a) and hydro- (b) space. The outlines of planned and consented windfarms are also shown (black).

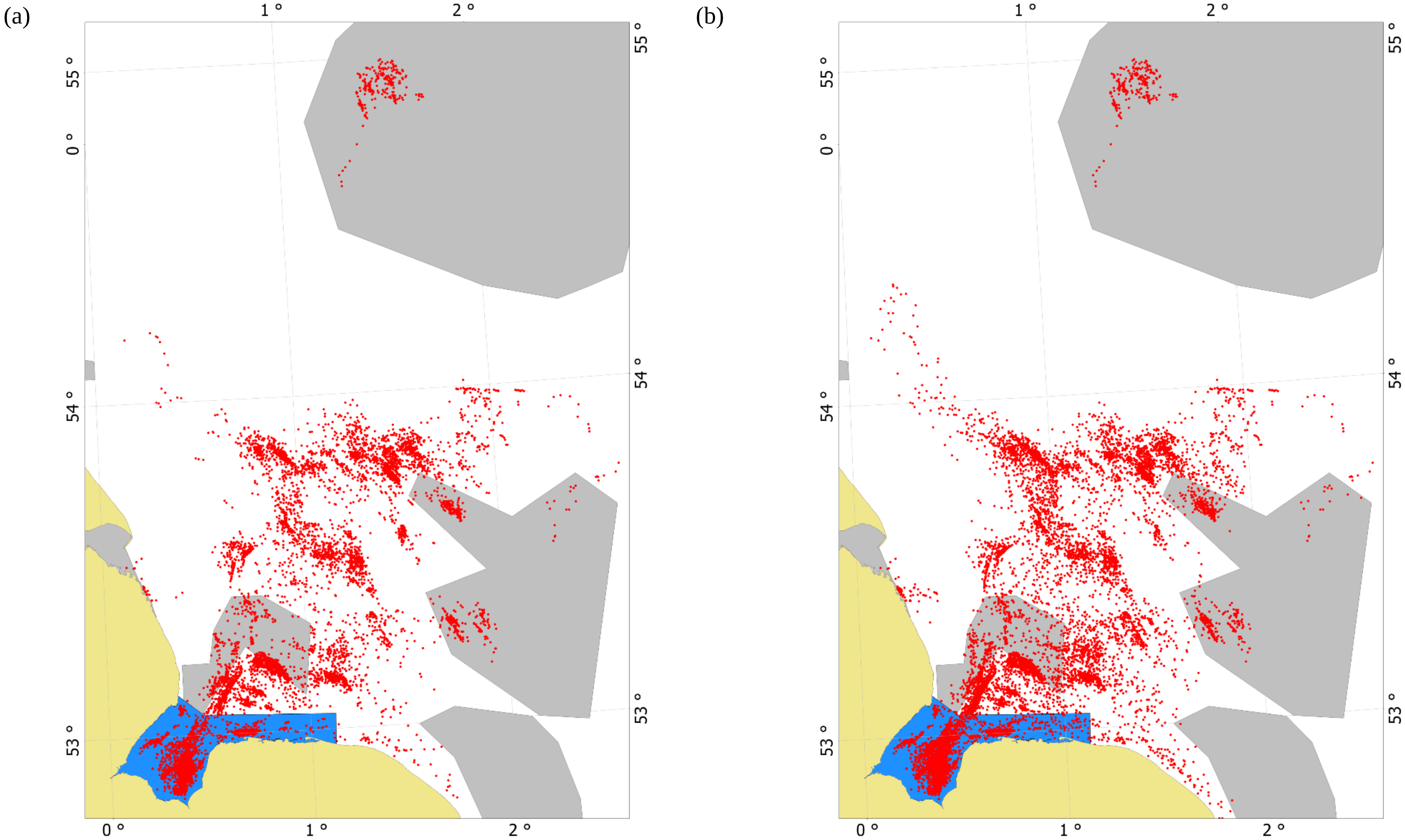

Figure 6. The estimated foraging locations (red) of tagged harbour seals in geo- (a) and hydro- (b) space. UK jurisdiction OSPAR Marine Protected Areas are shown (grey) along with The Wash and North Norfolk Special Area of Conservation (blue) for which harbour seals are primary feature.

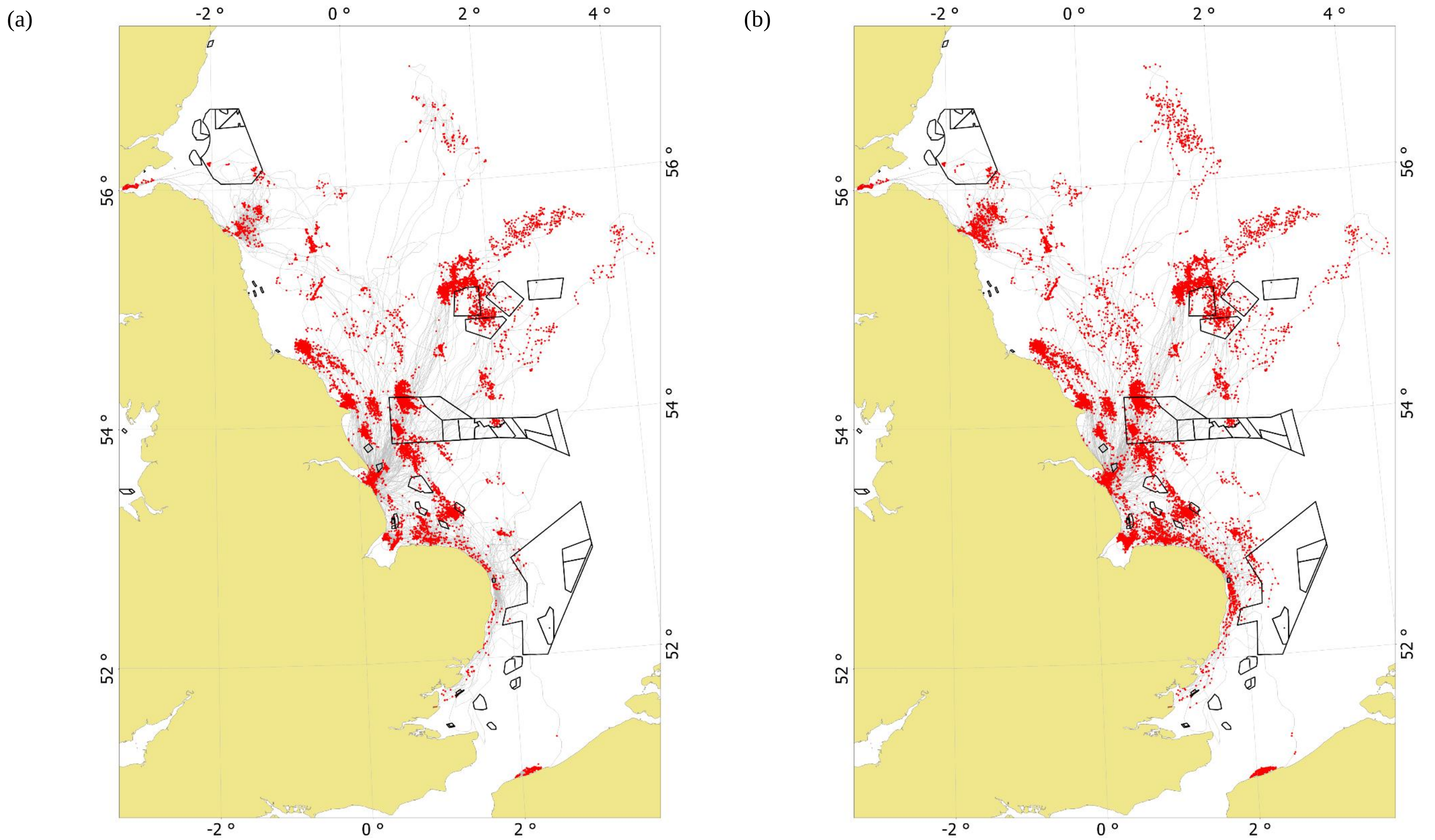

Figure 7. The tracks (grey) and estimated foraging locations (red) of tagged grey seals in geo- (a) and hydro- (b) space. The outlines of planned and consented windfarms are also shown (black).

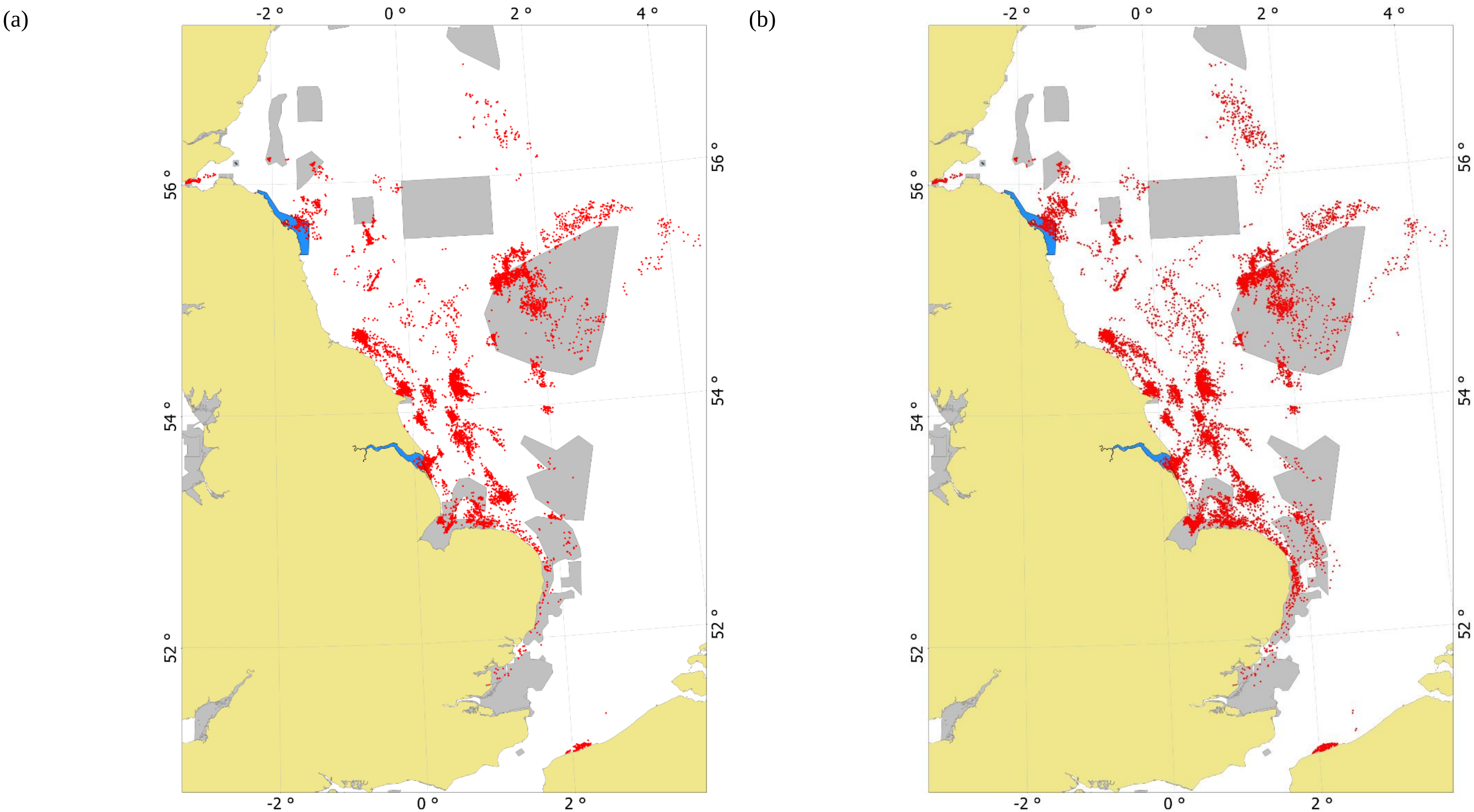

Figure 8. The estimated foraging locations (red) of tagged grey seals in geo- (a) and hydro- (b) space. UK jurisdiction OSPAR Marine Protected Areas are shown (grey) along with Special Areas of Conservation (blue) for which grey seals are a primary (Isle of May, Berwickshire and North Northumberland Coast) or qualifying feature (Humber Estuary).