Man-made structures and Apex Predators: Spatial interactions and overlap (MAPS)

Final report to INSITE

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Summary

Marine mammals and seabirds are long-lived apex predators that can be considered indicators of marine ecosystem health. Furthermore, it is possible to monitor their abundance and distribution on a large spatial scale (using survey and animal-borne tag data) and their movements on a fine spatial scale (using animal-borne tag data). These features make them excellent model species on which to study the impact of man-made structures, in comparison to the spatial and temporal ecological variability in the North Sea. The impact of man-made structures will vary with structure type and life-stage from construction, operation, decommissioning and ultimately removal. The noise levels associated with construction and removal may cause displacement of apex predators. For example, previous research has demonstrated displacement of harbour porpoise and harbour seals during pile driving. Once operational, displacement may result from habitat degradation and operational activities. Conversely, the fishing and shipping restrictions associated with structures mean they have the potential to provide refuge to marine animals including both predator and prey species. In addition, such structures can host artificial reefs, which may concentrate prey species. Such reefs are likely to have been the cause of the relatively high harbour porpoise activity observed at some structures. Despite the potential impacts of structure presence, little is known of their impact on apex predators at the population scale.

The MAPS project sought to use existing datasets to examine INSITE Objective 1 – establish the magnitude of the effects of man-made structures compared to the spatial and temporal variability of the North Sea ecosystem, considered on different time and space scales – with regard to apex predators. We considered the association between structure presence (ie. excluding commissioning) and apex predators on two spatial scales: at the **scale of the North Sea** using species' distributions (MAPS Aim 1) and at a very **fine spatial scale** using the movements of individuals in relation to structures (MAPS Aim 2). For Aim 2, we focussed on whether, at a population level, encounters with structures were associated with foraging, which would likely be mediated through the artificial reefs they host. The structures considered were mainly those relating to oil & gas infrastructure; platforms and pipelines. Note that wind farms were deliberately excluded from the examination of any seabird data; their impact would likely differ from any impact of oil & gas infrastructure, and for Aim 1 there were not sufficient numbers of windfarms to examine their impact on seabird distribution.

To address Aim 1, we built statistical models to quantify the comparative influence of man-made structure presence (oil & gas and offshore renewables structures for seals; oil & gas structures only for seabirds and cetaceans) and the dynamic environment on species' distributions. We considered the two UK seal species (harbour and grey seals), three common cetacean species in the North Sea (harbour porpoise, minke whale and white-beaked dolphin), and five common seabird species (black-legged kittiwake, common guillemot, European shag, northern fulmar and razorbill). Seal data were available from GPS tags deployed on seals along the UK coast of the North Sea. Cetacean and seabird data were derived from North Sea wide aerial and boat-based surveys. Reviewing the literature enabled us to select

key potential environmental drivers of distribution for our study species: distance to coast (distance to haul-out site for seals), water depth, and two proxies of prey availability (winter sea-surface temperature and sediment type). In addition, structure presence (within 1 km) was incorporated in the models to examine whether it could help explain species' distributions. Model selection supported an association between structure presence and predator distribution for three species: grey seal and northern fulmar (negative association), and harbour porpoise (positive association). The distribution of grey seals and northern fulmars was driven by environmental covariates, with the presence of structure having a very weak association with distribution. The apparent influence of structure presence on harbour porpoise distribution was comparable to the influence of other environmental covariates. The models built to explain seal distribution fitted particularly well and thus can be used to predict the at-sea distribution of the population of seals that hauls-out on the UK coast of the North Sea. Such predictions will be used in marine spatial planning. Specifically, they will allow estimation of the proportion of the population affected by disturbance resulting from commissioning and decommissioning individual structures.

For Aim 2, we used GPS location data from animal-borne tags deployed on the above-mentioned seal and seabird species, to examine whether proximity to structures (oil & gas and offshore renewables structures for seals; oil & gas structures only for seabirds) increased the probability of foraging. Visual inspection of the tracks suggested that some tagged seals (grey and harbour) spent prolonged periods of time at structures including wind turbines, pipelines and platforms; their behavioural patterns were synonymous with foraging. In addition, a small proportion of tagged seabirds appeared to preferentially associate with oil & gas structures, although the underlying mechanism for any effect was not clear. To allow us to quantify the impact of oil & gas structures on foraging at a population level, data from individual seabirds were pooled by species and the movement patterns used, within a modelling framework, to classify tracks into different types of behaviour. At a population level, encounters (defined as within 500 m) with oil & gas structures did not lead to increased foraging in any of the seabird species.

Overall, our results suggest that for the marine predators considered here the current North Sea oil & gas infrastructure is not a key driver of at-sea distribution, nor does it influence the foraging behaviour of the considered seabird species at a population level. However, it should be noted that in order to maximise power to detect effects of structure presence on predator distribution and foraging, different structures types were pooled for both Aims 1 and 2. This means that impacts restricted to a certain structure type or age, may not have been detectable. Additional data on fine scale movements of apex predators and on oil & gas structures (e.g. which sections of pipelines are exposed) are required to determine the impact of different structure types and ages on species' distributions and behaviour. Such an understanding is a critical step in assessing the potential impact of structure presence on species demography and ultimately their status.

The landscape of man-made structures in the North Sea is entering a period of rapid change with the decommissioning and potential removal of oil & gas infrastructure, and the expansion of the marine energy industry. The disturbance associated with structure commissioning, decommissioning, and removal has the potential to have considerable short-term impact on species distributions. Furthermore, this expansion will lead to significant infrastructure in areas that have not previously been developed and result in man-made structures constituting, or at least potentially influencing, a large proportion of the available habitat for marine predators such as cetaceans, seals and seabirds. Near shore developments, in particular, are likely to substantially increase the number of encounters between man-made infrastructure, and seals and breeding seabirds. Although such structures may provide foraging habitat and refuge for some species, the effects of renewable developments differ from oil & gas infrastructure, with greater predicted rates of collision, displacement and barrier effects. This is particularly pertinent when considering the association between wind farms and seabirds, and between diving predators and underwater turbines. We therefore anticipate that the relationship between marine top predators and infrastructure is likely to change, and should be a priority for future research.

1. Introduction & Background

The landscape of man-made structures in the North Sea is entering a period of rapid change. Both oil & gas exploration and production is now in decline; a stage that requires decommissioning and removal of structures (OSPAR Decision 98/3). In contrast, the marine renewable energy industry, especially the wind industry, is undergoing a period of rapid expansion. The potential future development of tidal stream and wave energy industries is also likely to lead to significant infrastructure in coastal waters that have not previously been developed, and offshore gas storage and carbon dioxide sequestration in former hydrocarbon fields may result in new pipelines and construction of other subsea structures. Taken together, these developments ensure that man-made structures constitute, or at least potentially influence, a large proportion of the available habitat for marine predators such as cetaceans, seals and seabirds. Evidence regarding the impact of both the presence and removal of these structures on the ecosystem is urgently required to inform the review of the current OSPAR regulations and also to inform ongoing decommissioning. This led to INSITE, an industry-sponsored programme, with the aim of providing independent scientific evidence to better understand the influence of man-made structures on the ecosystem of the North Sea (http://www.insitenorthsea.org/).

The impact of man-made structures on marine predators will vary depending on their life-stage from installation to operation, decommissioning, and ultimately removal. There may be negative impacts associated with the construction and installation of structures through habitat degradation and displacement due to noise pollution (Dähne *et al.* 2013; Hastie *et al.* 2015; Russell *et al.* 2016). Once established, structures may exclude animals due to their physical presence, or as a result of perceived barriers from operational noise or increased vessel activity. However, with the exception of interactions between windfarms and seabirds (Johnston *et al.* 2014), and between diving predators and tidal turbines (Hastie *et al.* 2017), the limited evidence available suggests that once installed (post construction), man-made structures do not exclude and may in fact attract some species of marine predator (Todd *et al.* 2009; Scheidat *et al.* 2011). The fishing and shipping restrictions associated with structures mean they have the potential to provide refuge to predators and their prey. Furthermore, the subsea components of structures often host artificial reefs (Claisse *et al.* 2014), which may provide foraging opportunities for predators. It has recently been demonstrated that some individual harbour (*Phoca vitulina*) and grey seals (*Halichoerus grypus*) systematically forage at some structures including pipelines and wind turbine foundations (Russell *et al.* 2014), presumably driven by the presence of such artificial reefs.

The biological importance of man-made structures as foraging opportunities for predator populations is currently unknown. If the observed behaviour of foraging at structures by seals (Russell *et al.* 2014) is exhibited by only a small number of individuals then, at a population level any foraging resource provided by man-made structures is unlikely to be important. The prevalence of foraging at structures will depend on the degree of spatial overlap between areas with structures and areas used by marine predators as well as the foraging strategies shown by individual animals. Quantification of the spatial overlap between structures and

species' distribution is also required in order to inform the decommissioning process. It will allow estimation of the potential magnitude, in terms of proportion of the population, of disturbance resulting from commissioning and decommissioning individual structures.

Studies focussing on the distributions and movements of a range of marine mammal and seabird species have resulted in data appropriate for the investigation of the impact of structures on distribution and foraging behaviour. Animal-borne GPS tags have been deployed on both harbour and grey seals at a range of locations along the UK coast of the North Sea (Sharples *et al.* 2012; Russell *et al.* 2014, 2015). The resulting data allow investigation of the impact of structures on seals at multiple spatial and temporal scales. Similar movement data are available from tags deployed on five species of seabirds; black-legged kittiwake (*Rissa tridactyla*), common guillemot (*Uria aalge*), European shag (*Phalacrocorax aristotelis*), northern fulmar (*Fulmarus glacialis*) and razorbill (*Alca torda*) at colonies along the UK North Sea coast (Wakefield *et al.* 2017; unpublished data) which can be used to examine foraging responses to subsea structures. Line transect data (European Seabirds At Sea (ESAS) database) allow examination of the large-scale distribution on seabirds across the North Sea over multiple years and seasons. Although there are no comparable cetacean behavioural data, information on the distribution and densities of harbour porpoise (*Phocoena phocoena*), minke whale (*Balaenoptera acutorostrata*) and white-beaked dolphin (*Lagenorhynchus albirostris*) are available from a multi-platform ship and aerial line transect survey of the North Sea in 2005 (SCANS II; http://biology.st-andrews.ac.uk/scans2/; Hammond *et al.* 2013).

This project (Man-made structures and Apex Predators: Spatial interactions and overlap; MAPS) aimed to use these existing datasets to examine INSITE Objective 1 – establish the magnitude of the effects of man-made structures compared to the spatial and temporal variability of the North Sea ecosystem, considered on different time and space scales – with regard to apex predators. We considered the association between apex predators and structures at two spatial scales: at the scale of the North Sea using species' distributions (MAPS Aim 1) and at a fine spatial scale by exploring the movements of individuals in relation to structures (MAPS Aim 2). To address Aim 1, we examined the comparative influence of man-made structures and the dynamic environment on the distributions of the above-mentioned seal, seabird and cetacean species. The seal data allowed examination of both the foraging and overall distributions. To address Aim 2 we used animal-borne GPS data to quantify the impact of structures encountered by seals and seabirds on their foraging behaviour. Any such impact could then be combined with the overlap between man-made structures and distributions (Aim 1) to estimate the population-level use of man-made structures for foraging by seals and seabirds in the North Sea. Note that for both aims, only oil & gas infrastructure were considered for seabirds and cetaceans, whereas offshore renewable developments were also considered for seals.

2. Methods

2.1 Man-made structures

For both Aims 1 and 2, data on the location of man-made structures were required. For all analyses, oil & gas structures (platforms and pipelines) were considered. Although wrecks may also provide hard substrate, they were not included because their status is often unknown. The platform data were taken from the Oil and Gas UK Database of North Sea fixed platforms (2012) and the OSPAR Offshore Installations Inventory (2015) compiled by INSITE partners at Cefas. Information on the location of oil & gas pipelines was taken from the SeaZone HydroSpatial One database made available through EDINA Marine Digimap. We excluded pipelines that were smaller than 10 km in length as the majority of these were coastal and their inclusion could have led to issues of collinearity with other covariates. Although buried pipelines are unlikely to host artificial reefs, information on which sections of pipeline are buried is not available, and thus all pipelines over 10 km in length were considered.

Wind farms were only included in the analyses of the seal data which spans 2006 to 2016. The structures were not included in the seabird habitat preference analyses because wind farms presence has the potential to displace birds which may mask any attraction to oil & gas structures. The very limited number of windfarms present during the ESAS surveys (1979-2011) prohibited examining the impact of windfarms on seabird distribution. Windfarm presence was not included in examining cetacean distribution; in 2005 when SCANS II was conducted, only five windfarms were operating, most of which were very small. Information on the location and commissioning date of wind farm areas was taken from the 2015 OSPAR Offshore Renewable Energy Development database, and 4C Offshore, respectively.

2.2 Aim 1

2.2.1 Environmental Covariates

Environmental covariates were selected on the basis that they had been previously shown to impact our focal species. The selected covariates were depth, winter sea-surface temperature lagged by one year ($wSST_{t-1}$), sediment type and distance to coast (distance to haul-out site for the two seal species). Initial analysis also included thermal stratification, but this was removed in favour of depth as the two were collinear. It has previously been demonstrated that depth is a driver of the distributions of harbour porpoise (Hammond *et al.* 2013), minke whale (Hammond *et al.* 2013) and grey seals (Aarts *et al.* 2008). Furthermore, European shags often forage benthically and in the North Sea are restricted to a dive depth of 50-60 m; Watanuki *et al.* 2005). Many of the species we considered in this project forage on sandeels, but spatio-temporally accurate estimates of sandeel abundance are unavailable. Nevertheless, studies have identified links between sandeel survival and winter temperature (Arnott & Ruxton 2002), and consequently seabird reproductive success (Frederiksen *et al.* 2007a; Frederiksen, Furness & Wanless 2007b). SST has also been linked to the distributions of grey seals (Aarts *et al.* 2008), black-legged kittiwakes and European shags (Wakefield *et al.* 2017). Sediment type also serves as a proxy for prey availability, because different prey species inhabit different sediment types (e.g. sandy sediments or rocky sediments). Sediment

type influences grey seal distributions (Aarts *et al.* 2008) and seabird distributions during the breeding season (common guillemot, European shag and razorbill; Wakefield *et al.* 2017). Distance to coast can also influence the distribution of marine predators (e.g. harbour porpoise; Hammond *et al.* 2013) and, because seals return to land to haul-out between foraging trips, distance to haul-out is likely to be a key driver of distribution (Aarts *et al.* 2008). To enable cross-taxa comparison of results, the same covariates were considered for all species.

We extracted information on depth and sea floor sediment type from the European Marine Observation and Data network (EMODnet). Depth data were taken from the General Bathymetric Chart of the Oceans (GEBCO) and sediment data from the EUSeaMap broad-scale habitat map (Populus *et al.* 2017). The EUSeaMap sediment types are classified following Folk (1954) and provide 13 classifications of sediment based on the sand:mud ratio and percentage of gravel, at a 250 m spatial resolution. Temperature data were extracted from the Forecasting Ocean Assimilation Model 7 km Atlantic Margin Model (FOAM AMM7) maintained by the UK Met Office and accessed via the Copernicus Marine Environment Monitoring Service. This product provides daily estimated sea-surface temperature between 1985 and 2014 for the North West Shelf on a regular grid with 1/15° latitudinal resolution and 1/9° longitudinal resolution (approximately 7 km square).

For both seabirds and cetaceans, a spatial smooth of longitude and latitude was also included in the models. To understand the impact of environmental covariates on species' distribution, conventionally a spatial component would not be included because it may explain variation which would otherwise be explained by environmental variation. However, due to the discrete nature of the structures, the ability to detect an effect of structure would be maximised by accounting for any large scale variation in distribution. This was not necessary for the seal habitat preference as the environmental covariates explained a substantial proportion of the variation in the data.

2.2.2 Models of seal distribution

To determine the drivers of the distribution of seals in the North Sea we used data from animal-borne GPS tags (SMRU Instrumentation GPS Phone Tag; http://www.smru.st-andrews.ac.uk/Instrumentation/Overview/) deployed on 30 grey seals and 55 harbour seals on the UK coastline of the North Sea (2006-2016). These tags were deployed by the Sea Mammal Research Unit under Home Office Licences 60/3303 and 60/4009. For more details of capture and deployment techniques refer to Sharples *et al.* (2012). Although additional animal-borne tag data were available from prior to 2006, these were of comparatively low location accuracy and thus were not considered here.

The tags transmitted data on an animal's location and activity (e.g. whether the animal was hauled-out or diving). Prior to analysis, the location data were interpolated to a two-hour resolution and locations removed if an individual was hauled-out on land. Foraging trips were then defined as the period between an individual departing from a known haul-out location

and returning to the haul-out (or hauling-out at a new location). In total, 33,639 and 36,433 interpolated locations were available for the analysis of grey and harbour seal distributions, respectively.

In order to be able to examine foraging distributions we classified apparent behavioural modes using activity and locational data within a Bayesian hidden-Markov framework (Russell *et al.* 2014, 2015). These were non-diving (labelled as resting); slow tortuous movements (presumed to be foraging) and faster more directed movement (presumed to be travelling; Russell *et al.* 2015). In total, 18,443 and 21,731 interpolated locations were available for the analysis of grey and harbour seal foraging distributions, respectively.

The use of space by an animal is a function of both their preference for particular habitats, and the availability of those habitats to the animal (Matthiopoulos 2003). In order to understand habitat preference, it is therefore necessary to account for habitat availability in a 'use-availability' design. Each seal location was paired to a pseudo-absence point randomly located within the area accessible from the haul-out from which the animal had departed. These pseudo-absences can be considered as providing a contrast between the habitat that is used by an animal and the habitat that is available to them in the environment (Boyce 2006; Beyer *et al.* 2010). We defined the area accessible to an individual during a foraging trip using the maximum at-sea distance that an individual travelled from a haul-out during a foraging trip.

To allow for non-linear relationships, we estimated the habitat preferences of grey and harbour seals using binomial (0 as pseudo-absence and 1 as presence) Generalised Additive Models (GAMs) fitted with the packages mgcv (Wood 2006) and MuMIn (Bartoń 2015) in R v. 3.3.2 (R Core Team 2016). Depth, $wSST_{t-1}$, and distance to haul-out site were included as cubic regression splines fitted with a maximum of 6 knots; knots were penalised via shrinkage during model fitting to prevent over-fitting. Sediment type and the presence of structures within 1 km of a location were included as factor variables. To account for non-independence of locations within individuals and to allow potential differences in response between individuals, we included individual ID as a random effect spline (Wood 2008). Four maximal models were fitted in order to examine both the foraging and overall habitat preferences of grey and harbour seals separately.

There was no evidence of any violation in model assumptions; variance inflation factors were low (VIF < 3), spatial variograms and Moran's *I* statistic revealed no significant spatial autocorrelation, and autocorrelation plots revealed no significant temporal autocorrelation in model residuals. Backwards model selection was conducted based on Akaike's Information Criteria (AIC), with parameters excluded if their inclusion did not improve the model by more than 2 ΔAIC relative to the lowest AIC (Burnham & Anderson 2002).

2.2.3 Models of cetacean distribution

Data from the Small Cetaceans in the European Atlantic and North Sea (SCANS-II) survey in 2005 were used to estimate the distribution and habitat preferences of harbour porpoise, minke whale and white-beaked dolphin in the North Sea. For the purposes of INSITE, the analysis of Hammond *et al.* (2013) was extended to assess the influence of man-made structures.

The abundance of animals (previously corrected for estimated detection probability by Hammond *et al.* (2013)) along each segment of a transect was modelled as a function of environmental covariates using Generalised Additive Models (GAMs) fitted within the packages mgcv (Wood 2006) and MuMIn (Bartoń 2015) in R (R Core Team 2016). To account for variation in the lengths of transect segments (median 4.9 km), which were delimited by changes in sighting conditions, we included segment length as an offset in all models. While the original SCANS-II analysis had assumed an over-dispersed Poisson distribution, we utilised the Tweedie distribution as it offers a more flexible alternative (Miller *et al.* 2013). As in the seal models, depth, $wSST_{t-1}$ and distance to coast were fitted as cubic regression splines with a maximum of 6 knots; knots were penalised via shrinkage during model fitting to prevent over-fitting. Sediment type and the presence of structures within 1 km of a location were included as factors. Following Hammond *et al.* (2013) we included a tensor product smooth of the longitude and latitude of the transect segment centroid. Including the location as a smooth term in this way can account for spatial autocorrelation; spatial variograms and Moran's *I* statistic revealed some clustering at sub-200 km scales. As with in the grey seal modelling, backwards model selection was based on AIC with parameters excluded if their inclusion did not improve the model by more than 2 ΔAIC relative to the lowest AIC (Burnham & Anderson 2002).

2.2.4 Models of seabird distribution

Data from the European Seabirds at Sea (ESAS) database were used to examine the drivers of seabird distribution. This database is maintained by the Joint Nature Conservation Committee (JNCC). The database included approximately 940,000 records across the North Sea collected year-round between 1979 and 2011. Data were mostly collected from boat-based surveys using 300 m wide strip transects (Camphuysen *et al.* 2004). The transect data were divided into discrete temporal segments (10 minute time intervals – midpoint location provided in the ESAS database), each with a count of seabirds observed and their distance from the survey platform. We combined data for birds on the water and flying, and removed data pre-1987 because concurrent covariate data were unavailable.

The five species considered here are black-legged kittiwake, common guillemot, European shag, northern fulmar and razorbill. As not all birds within the strip transects would have been seen by observers, distance sampling techniques were used to estimate how the probability of detection decreased with distance from survey vessel (Buckland *et al.* 2001). This was conducted in R using package 'mrds' (Laake *et al.* 2017) to produce half-normal detection functions for each of the five species of interest. Perfect detection i.e. a detection

probability equal to 1, was assumed for flying birds (Camphuysen *et al.* 2004; Bradbury *et al.* 2014). Modelling was performed using the package 'MRSea' in R (Scott-Hayward *et al.* 2013). It fits spatial models using the Complex Region Spatial Smoother (CReSS) method in a Generalised Estimating Equations (GEE) framework using Spatially Adaptive Local Smoothing Algorithms (SALSA) for model selection (Mackenzie *et al.* 2013). The GEE framework ensured the variance surrounding the parameters estimated would be robust to any residual autocorrelation within transects. Count data for each species were fitted assuming an over-dispersed Poisson distribution. Depth, $wSST_{t-1}$ and distance to coast were fitted as splines, and sediment type and the presence of oil & gas structures within 1 km of a location were included as factors. As in the cetacean models, a spatial component was included as a 2-D smooth of the longitude and latitude coordinate of the transect segment centroid. Following Long (2017), forwards model selection, based on cross-validation and model fit criteria, was used to arrive at a minimum adequate model.

2.3 Aim 2

2.3.1 Foraging behaviour of seabirds at oil & gas structures

To estimate the fine-scale use of structures by seabirds in the North Sea we used animal-borne GPS tag data collected by the Royal Society for the Protection of Birds (RSPB) and the Centre for Ecology & Hydrology (CEH; see Acknowledgements). These data were available for the five above-mentioned species. Tags were deployed at 12 breeding colonies (latitudinal range: 54.08 - 59.85 °) along the British coastline of the North Sea including the Isle of May. The high temporal resolution of the data (100 second intervals) allowed a finer-scale assessment of potential interactions and so we examined potential changes in behaviour within 500 m of a structure.

GPS locations were processed to remove periods of colony attendance, when individuals would be engaged in breeding activities or loafing around the colonies. Initially trips were defined as animals spending more than 40 min further than 500 m from the breeding colony (Wakefield *et al.* 2015). Visual inspection indicated bimodality in trip lengths, and so to remove "loafing" around the colony (Carter *et al.* 2016) trips were excluded using a species' specific distance to colony threshold (black-legged kittiwake:1 km; common guillemot: 5 km; European shag 1 km; razorbill: 2 km; northern fulmar: 10 km). At the end of this process, suitable data were available for 267 black-legged kittiwakes, 73 European shag, 125 razorbill, 32 northern fulmar and 64 common guillemot.

To examine the at-sea foraging behaviour of each species, we used hidden Markov models (HMMs) fitted using the R package moveHMM v.1.0 (Michelot, Langrock & Patterson 2016). The foraging trips for all individuals within a species were pooled to investigate the impact of oil & gas structure presence on the probability of foraging. The movement of an individual along a foraging trip was decomposed, within the model, into either two or three underlying behavioural modes by characterising the distributions of step lengths and turning angles between consecutive locations (Langrock *et al.* 2012). This process classified each animal location into one of three behavioural modes; short step lengths and small turning

angles (presumed resting), short step lengths and large turning angles (presumed foraging) and long step lengths and small turning angles (presumed travelling). To assess differences in behaviour in relation to oil & gas structures we included the presence of a structure within 500 m of an individual as a covariate in the HMM framework, acting on the state transition probabilities (Patterson *et al.* 2009). Comparing the Akaike's Information Criterion (AIC) of HMMs with and without the structure covariate allowed us to determine whether proximity to structure influenced the likelihood of foraging for each species. To assess the frequency with which seabirds encountered oil & gas structures, we also calculated the proportion of each foraging trip that was spent within 500 m of a structure (pipeline or platform).

2.3.2 Foraging behaviour of seals at structures

Data from the animal-borne GPS tags used to examine the influence of the environment on distribution were also used to examine fine-scale behaviour of seals around structures (see Section 2.2.2). A subset of the tag data considered here have previously been used to examine the behaviour of seals at structures (Russell *et al.* 2014). In that study, individual grey and harbour seals showed directed movements towards structures at which they demonstrated behaviour synonymous with foraging. However, the probability of an individual that encounters a structure foraging at them is unknown.

In a similar way to the methods described for the fine-scale seabird analyses (section 2.3.1), here we aimed to examine how man-made structures influenced seal behaviour on a population-level. To examine behaviour at a population level we used the Bayesian hidden Markov framework previously fitted to the seal telemetry data (see section 2.2.2 for details), but with the data interpolated to a finer temporal resolution (15 min).

3. Results

3.1 Aim 1

3.1.1 Models of seal distribution

The minimum adequate model of grey seal habitat preference retained depth, distance to haul-out site, $wSST_{t-1}$, sediment type and presence of structure within 1 km (Figure 1). These covariates were retained in models examining all locations and models based on foraging locations only. Both the minimum adequate models of overall habitat preference and foraging habitat preference fit the data well (Adj-R^2 = 79.0% and 79.3%). Grey seals showed a preference for waters of approximately 100 m and 30 m deep, the use of shallower waters was elevated when considering only foraging locations. They were also more likely to occur within 200 km of the haul-out, and in waters in which the winter sea surface temperature in the previous year was approximately 7 °C. There was a weak negative correlation man-made strctures and grey seal abudance; grey seals were slightly less likely to occur within 1 km of a structure, but this term explained less than 1% of the deviance in the model.

The minimum adequate model of harbour seal habitat preference retained depth, distance to haul-out site, $wSST_{t-1}$ and sediment type. These covariates were retained both in models examining all locations and models based on foraging locations only (Figure 2). Both the

minimum adequate models of overall habitat preference and foraging habitat preference fitted the data well (Adj-R^2 = 78.7% and 79.2%). Harbour seals showed a similar depth preference to grey seals, mainly using waters of approximately 100 m and 30 m deep. However, the preference for shallower waters was stronger and amplified further when considering only foraging locations. Harbour seals prefered inshore waters, mainly staying within 50 km of haul-outs. The preference for temperature was similar to that of grey seals, but the response was much stronger when considering only foraging locations. There was no support for the inclusion of structures in the models of harbour seal habitat preference. The strongest driver of harbour seal habitat preference was distance to haul-out site.
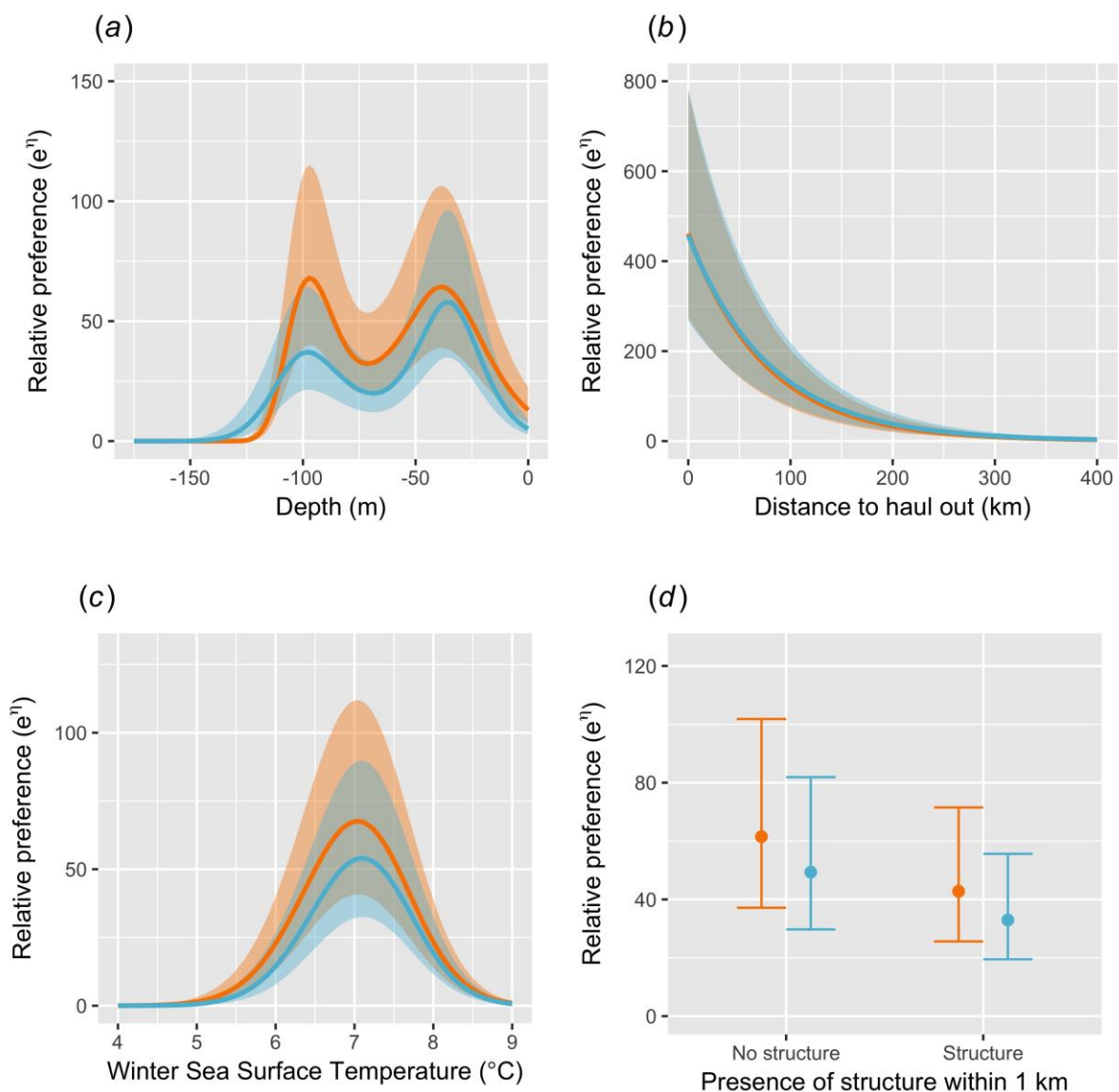
Figure 1 Model estimated relative preference of grey seals for (*a*) water depth, (*b*) distance to haul-out, (*c*) sea surface temperature in the previous winter and (*d*) presence of structure within 1 km. Lines (points in lower right panel) indicate model estimated response and shaded areas (lines in lower right panel) are 95% Confidence Intervals for all locations (orange) and foraging locations (blue).
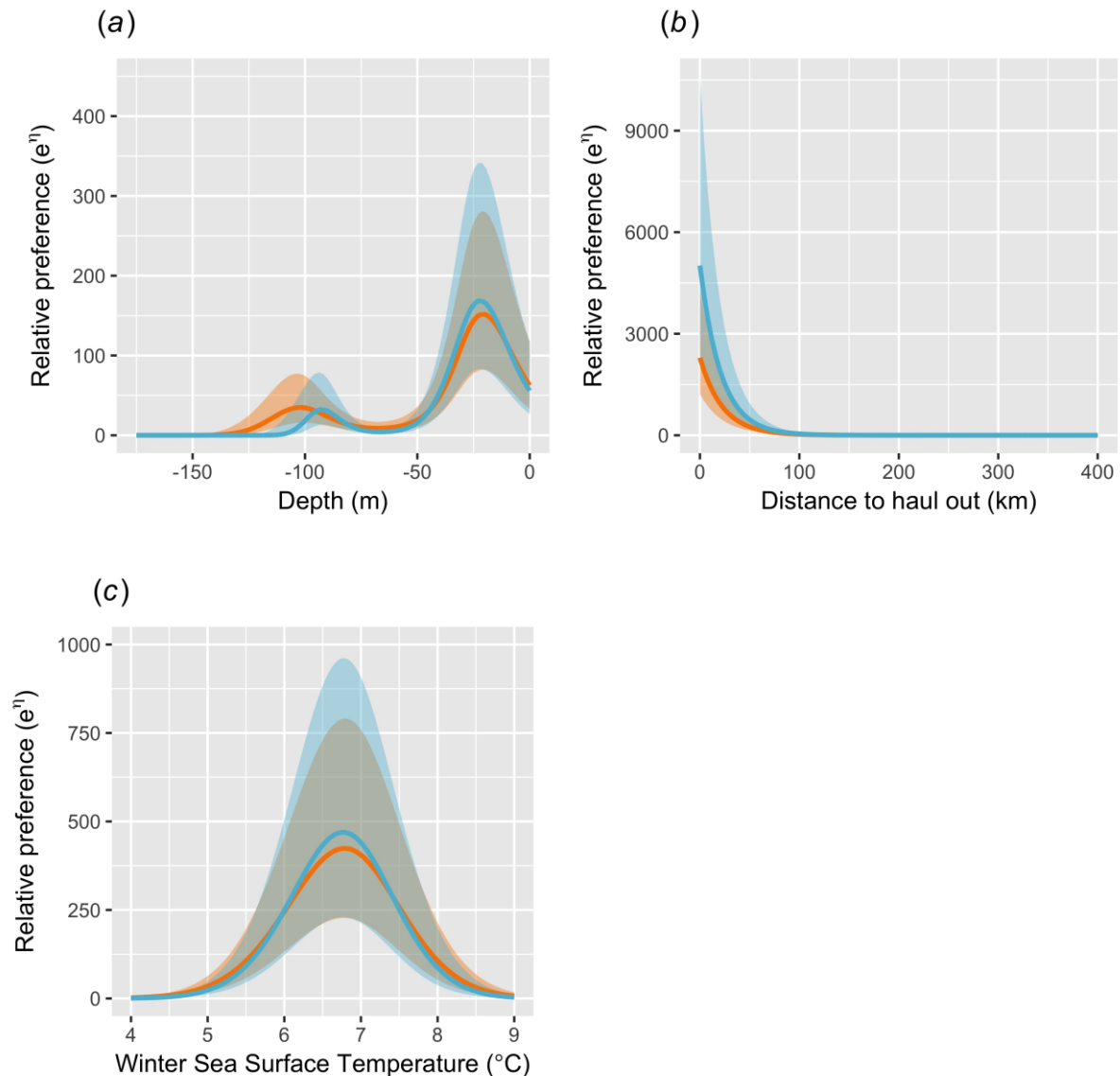
Figure 2 Model estimated relative preference of harbour seals for (*a*) water depth, (*b*) distance to haul-out and (*c*) sea surface temperature in the previous winter. Lines indicate model estimated response and shaded areas are 95% Confidence Intervals for all locations (orange) and foraging locations (blue).

3.2.2 Models of cetacean distribution

The minimum adequate model of harbour porpoise distributions included depth, distance to coast, $wSST_{t-1}$, presence of structures within 1 km of the transect, and the transect segment centroid. Harbour porpoise were more likely to occur in shallow waters, close to the coast and in areas with relatively warm winter temperatures (Figure 3). There was also a positive association with structures; more animals were estimated to occur within 1 km of a pipeline or platform. The minimum adequate model explained a limited amount of variation in the data (Adj-R^2 = 12.3%); structure term explained 1.5%.
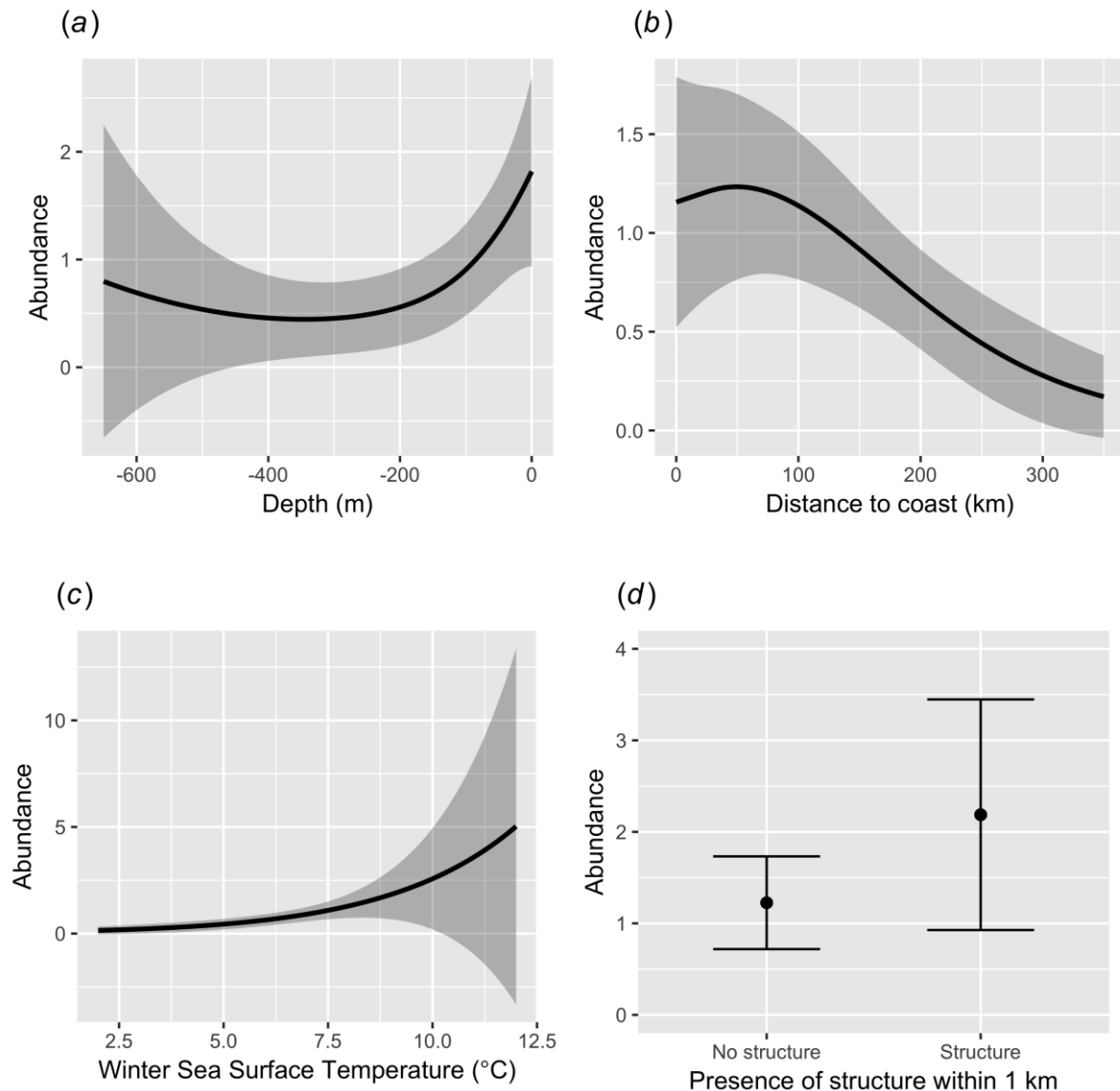
Figure 3. Model estimated relationship between the abundance of harbour porpoise in the North Sea and (*a*) depth (m), (*b*) distance to coast (km), (*c*) winter sea surface temperature lagged by 1 year and (*d*) presence of structure within 1 km of a transect. Lines (points in d) indicate model estimated response and shaded areas (lines in d) are 95% Confidence Intervals.

The minimum adequate model of minke whale distribution included only the transect segment centroid as a spatial smooth term. The minimum adequate model explained only 2.2% of the minke whale data.

The minimum adequate model of white-beaked dolphin included only wSST$_{t-1}$; animals were more likely to occur in areas which had a SST of between 7.5 and 8°C during the previous winter. The minimum adequate model explained only 3% of the data.

In comparison to harbour porpoise, the minke whale and white-beaked data showed a clustered distribution with a small number of observations, which likely could only support relatively simple models.

3.2.3 Models of seabird distribution

Habitat preference models were successfully fitted to the European Seabirds at Sea (ESAS) data on black-legged kittiwake, common guillemot, European shag and northern fulmar. Unfortunately the models of razorbill distributions did not converge and so could not provide information on any association with structures. The lack of convergence was likely caused by the high numbers of zeros in the database.

The minimum adequate model of northern fulmar distribution retained distance to coast, sediment type, and oil & gas structure within 1 km as covariates. Model estimates indicated that northern fulmar abundance peaked at between 50 and 100 km from shore. The models estimated a slight negative association with structures, with fewer individuals predicted to occur within 1 km of a structure than further from them. In contrast the minimum adequate model of common guillemot distributions retained only depth, with the majority of individuals occurring at shallow depths (<100 m). The models of black-legged kittiwake and European shag retained no environmental parameters.

3.2 Aim 2

3.2.1 Foraging behaviour of seabirds at oil & gas structures

Visual examination of tracks suggested that, for a small number individuals, oil & gas infrastructure may have influenced behaviour – the most striking example of which is shown in Figure 4. The hidden Markov model identified three underlying states in the black-legged kittiwake and northern fulmar data, which likely represented resting on the water (short step lengths and small turning angles), foraging (short step lengths and large turning angles) and travelling (long step lengths and small turning angles). In diving species (common guillemots, razorbills and European shags), birds sit on the water to rest between foraging bouts and so distinguishing between the two behaviours is difficult. Therefore, only two states could be identified which were labelled foraging (which would also include resting) and travelling. Furthermore, there were issues with fitting HMMs to the European shag data; the relatively inshore nature of foraging trips made it difficult to distinguish between animals foraging and travelling and so the HMMs would not converge.

Model selection retained the presence of structures in models of black-legged kittiwake movement, but not in models of common guillemot, northern fulmar or razorbill movement. However, model assessment suggested that there was very little effect of structures on black-legged kittiwake movements; individuals were slightly less likely to switch from transiting to foraging (probability of transitioning = 0.096 vs 0.087) when within 500 m of structure.

The encounter rate of foraging seabirds with man-made structures was relatively low; the median number of GPS locations recorded within 500 m of either a pipeline or platform was less than 5% for all species. There was a wide range of encounter rates though; for example one third of all GPS locations recorded during one black-legged kittiwake foraging trip occurred within 500 m of a structure. When animals did encounter structures the probability of foraging did not increase (Table 1).
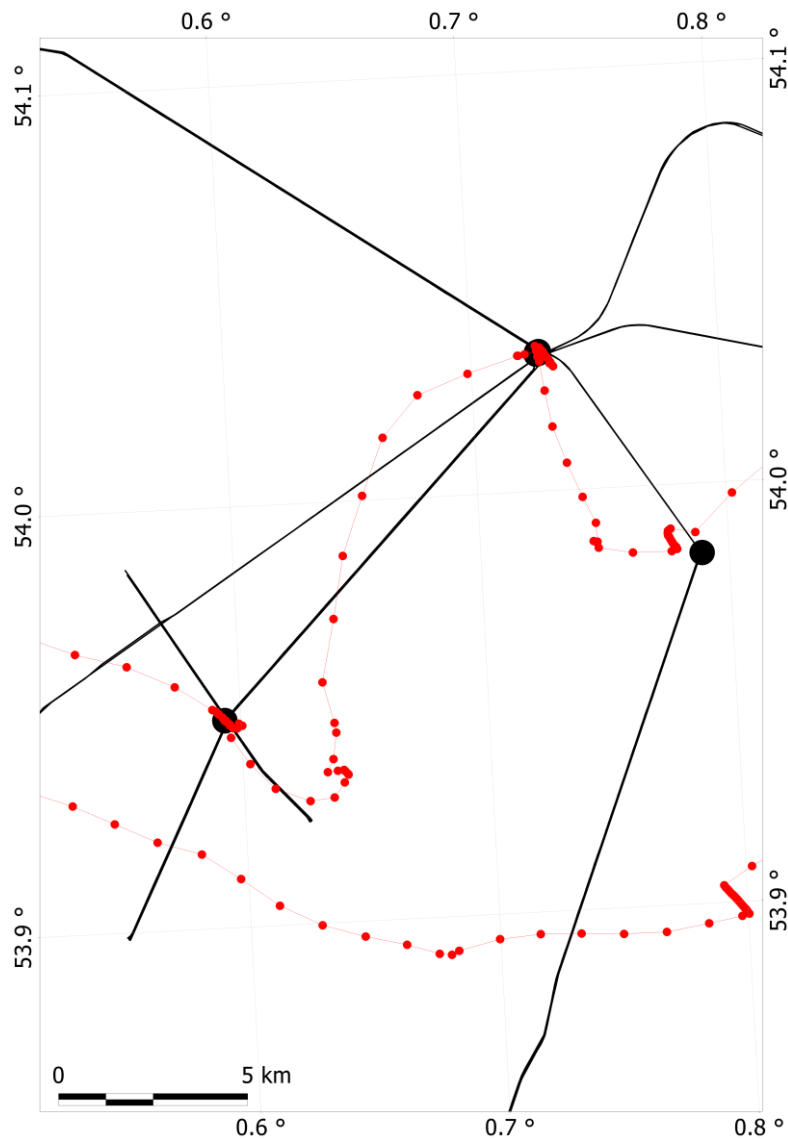

Figure4. The most striking example of a potential interaction between oil & gas infrastructure (platforms; black dots and pipelines; black lines), and the track (red line) of a black-legged kittiwake. The track is made up of GPS locations regularised onto a two minute resolution (red points).

Table 1. Summary statistics for seabird GPS data indicating; the number of individuals tracked from breeding colonies in the North Sea, and the number of foraging trips that were recorded, the number of those trips that encountered man-made structures. To estimate an encounter rate we calculated the proportion of time, within a trip, that was spent within 500 m of a structure.

Species	Individuals	Trips	Trips encountering structure	Encounter Rate: (trip median & range)
Black-legged kittiwake	267	615	110	0.04 (0.001 - 0.364)
Common guillemot	64	117	15	0.01 (0.001 – 0.065)
Shag	73	93	6	0.00 (0.000 – 0.134)
Northern fulmar	32	43	27	0.02 (0.001 - 0.133)
Razorbill	125	252	58	0.01 (0.001 - 0.140)

3.2.2 Foraging behaviour of seals at structures

The amount of data being used to classify behavioural states on a 15 minute (in comparison to the 2 hour resolution used previously; section 2.2.2), made the fitting of seal movement models prohibitively slow. Thus work is ongoing to fit the seal movement models. After which the tracks will be visually examined to allow us to understand to what extent structure presence drives any proximal foraging. However, an initial inspection of the tracks revealed some association with oil & gas infrastructure (e.g. Figure 5).
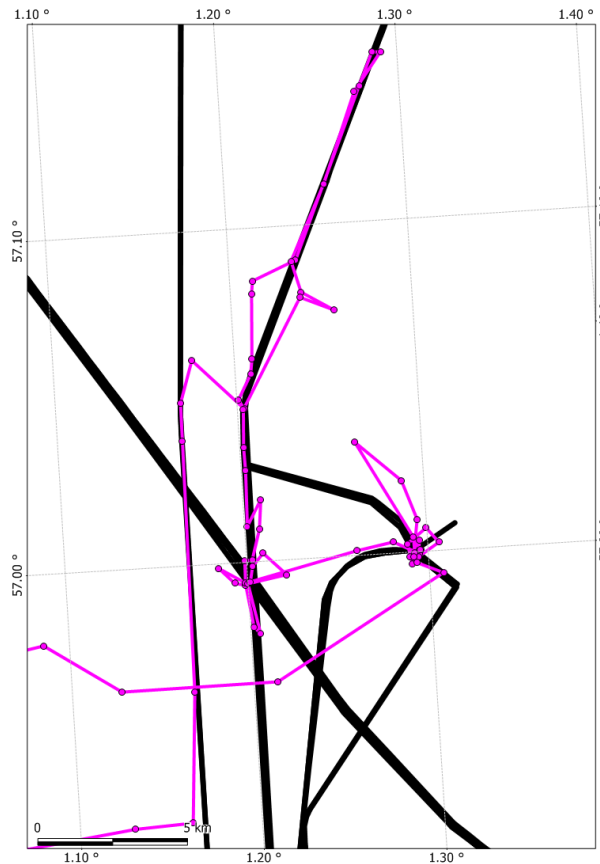
Figure 5. The GPS track of a harbour seal (pink lines) through interpolated locations (pink points) in relation to oil & gas infrastructure (black)

4. Discussion

The MAPS project sought to examine INSITE Objective 1 by increasing our understanding of the effects of oil & gas structures on apex predators. We considered the association between apex predators and structures at two spatial scales: at the scale of the North Sea using species' distributions (MAPS Aim 1) and at a fine spatial scale using the movements of individuals in relation to structures (MAPS Aim 2). Models generated to address Aim 1 revealed an association between structure presence and distribution for three of the nine species considered: grey seal and northern fulmar (negative association), and harbour porpoise (positive association). However, for the most part, the distribution of the first two species was driven by environmental covariates, with the presence of structure having a weak association with distribution. In addressing Aim 2, we examined GPS location data from animal-borne tags on five seabird and two seal species, to examine foraging behaviour in relation to structures. Visual inspection of the tracks revealed a potential influence of oil & gas structures on the movements of a small number of individuals. A relatively small proportion of individual seals appeared to forage along pipelines and at installations. However, at a population level, proximity to oil & gas structures was not associated with increased foraging effort in any of the seabird species. Work is currently ongoing to determine whether, at a population level, seals exhibit increased foraging effort in the proximity of structures.

Seal data, from animal-borne tags deployed along the UK coast of the North Sea, were used to examine Aims 1 and 2. The foraging and overall distributions of both species could be largely explained by the covariates considered in the models. Despite the expectation that foraging behaviour might be related more than other behaviours to the environmental covariates used as proxies for prey availability, results showed that this was not the case. This is likely to be because the key driver of distribution in all models was distance to haul-out site; seals need to return to land between foraging trips. Grey seal habitat preference was found to be broadly similar to that found in a previous study that focussed on a part of the area considered here (Aarts *et al.* 2008). Even though some individual seals focus their foraging efforts at structures (Russell *et al.* 2014), there was no evidence that structure was positively associated with the distribution of the UK North Sea seal populations. For harbour seals, this may be partly because their relatively coastal distribution means they have comparatively little overlap with structures. However, the fundamental explanation for the lack of positive association is likely to be individual variation in foraging behaviour within the population (Bolnick *et al.* 2003). At a population level, harbour and grey seals are generalist predators, but their populations are composed of individual specialists (Araújo, Bolnick & Layman 2011). Despite individual variation in responses to the environment the clear effect of multiple environmental covariates indicates that there was a population level association with covariates, suggesting the tagged individuals were representative of the UK population. This assumption can be examined with further animal-borne tag data. Given the attraction of some individuals to structures, the negative association between structures and grey seal distribution was unexpected. Although this apparent association warrants further investigation, current evidence does not support a negative causal relationship (Russell 2016; Russell *et al.* 2016). The predicted distributions of seals from our models will allow quantification of the potential magnitude, in terms of proportion of the UK population, of disturbance resulting from commissioning and decommissioning individual structures. More generally they will replace the current maps of the North Sea distribution of seals hauling out in the UK Russell *et al.* 2017) used in marine spatial planning. These were generated by combining animal-borne tag and haul-out count data to predict at-sea seal distributions, but are not mechanistic and thus have low predictive power in areas for which there are no animal-borne tag data. Our mechanistic models also allow predictions of foraging distributions which would facilitate the required identification of harbour seal foraging areas (Jones *et al.* 2017). Unfortunately, it was not possible to address Aim 2; the Bayesian techniques previously used to classify seal behaviours were not suitable for use with the amount of high resolution data. It has recently become possible to fit such complex models (combined activity and movement data) within a maximum likelihood framework (as used for the simpler seabird movement models; Michelot, Langrock & Patterson 2016).

The relationship between seabirds and oil & gas structures was examined both at a large scale, using ship survey data, and at a fine scale using data from animal-borne tag data. There were difficulties in fitting models using the ESAS data; for example the models for razorbill distribution did not converge. These difficulties were likely a result of low species occurrence in many places. A previous study, in which the ESAS data were used to model razorbill

distribution, was restricted to a smaller area (English Territorial Waters; Bradbury *et al.* 2014), in which there is a relatively high abundance of razorbill (Stone *et al.* 1995). In an attempt to address the issue of high numbers of transects in which no individuals were observed, observations of flying birds and birds on water were combined, but this may have led to issues with detection of environmental drivers and in interpretation because flying birds and those on the water are likely to be associating with different habitats. The issues with model fitting also restricted the complexity of the models; although the maximal model incorporated seasonal variation in total abundance, it was not possible to account for the likely seasonal changes in environmental drivers of distribution. Thus distance to coast was incorporated into each model (following Bradbury *et al.* 2014) assuming a single effect throughout the annual cycle. However, during the breeding season (March to July), at-sea distributions of seabirds become more closely associated with the distribution of breeding colonies because a large proportion of the population is constrained by breeding activities and individuals commute between the breeding site and foraging areas. This inability to incorporate seasonal variation in these North Sea wide models of seabird distribution may be the reason that no environmental covariates were retained to explain black-legged kittiwake and European shag distributions, and only one was retained to explain common guillemot distribution. In contrast, the distribution of northern fulmar which extends across the North Sea (Stone *et al.* 1995) was associated with distance to coast and sediment type. Northern fulmar are capable of extraordinarily long foraging trips during the breeding season (Edwards *et al.* 2013), and so their distributions are less constrained by the location of their breeding colony than the other species considered here, which may have increased detectability of environmental drivers. In addition to environmental covariates, northern fulmar distribution had a weak negative association with structure presence. The causal mechanism underlying this association is unclear. Indeed, northern fulmars rely heavily on fisheries discards (Camphuysen & Garthe 1997; Bicknell *et al.* 2013) and fishing boats associate with oil & gas structures in the North Sea (Rouse *et al.* 2017).

The movements, during the breeding season, of the five focal seabird species were examined using data from animal-borne GPS tags. Overall the frequency with which oil & gas structures were encountered on trips was low; between 0 and 4% (range of medians for each species) of time was spent in the proximity of a structure (within 500 m). However, there was a wide range of variation between trips; for some razorbill and northern fulmar trips, more than 10% their time was spent in the proximity of structures. On one foraging trip, a black-legged kittiwake spent more than 35% of its time in the proximity of structures. For trips for which there was a relatively high proportion of time in the proximity of oil & gas structures, visual inspection of the tracks suggested that for some individuals, structure presence (structures and pipelines) affected behaviour. It may be that in some cases these individuals are using such structures for navigation. Even if there was an overall tendency in the population for individuals to use structures for navigation, detection of such behaviour would be difficult. However, it is unlikely that birds can see benthic pipelines from the air, and so further work is required to understand the mechanisms underlying this behaviour. Recent evidence of fishing boats targeting pipelines (Rouse *et al.* 2017) provides one potential

avenue for exploration. To determine whether structures influenced movements on a population level, we pooled all track data within a species. Movement models were successfully fitted for four species (black-legged kittiwake, common guillemot, northern fulmar and razorbill) and revealed that proximity to oil & gas structures only influenced black-legged kittiwake foraging behaviour. There was a slight reduction in the probability of foraging, when in the proximity of a structure. The mechanism behind such a relationship is unclear and warrants further investigation.

The impact of man-made structures on cetaceans was investigated only at a large spatial scale because animal-borne tag data are not available. Our predicted distribution of harbour porpoise in the North Sea is similar to that predicted in Hammond *et al.* (2013) in the original SCANS-II analysis. Harbour porpoise were more likely to occur in shallow waters, close to the coast and in areas with relatively warm winter temperatures. These findings are also broadly comparable to other estimates of harbour porpoise habitat preference in a different area based on inshore boat surveys and acoustic data (Booth *et al.* 2013). Our habitat models also indicated a positive association with structures; more porpoise were estimated to occur within 1 km of a pipeline or platform. Proximity to structure only explained 1.5% of the deviance in the model of harbour porpoise abundance, meaning that there was only a weak association. However, it is likely that any association between man-made structures and harbour porpoise distribution would be underestimated in the current study because foraging over hard substrates appears to be particularly apparent at night (Todd *et al.* 2009; Mikkelsen *et al.* 2013) when there is no survey effort. In contrast to the harbour porpoise model, the model for the minke whale only retained the spatial component and the model for white-beaked dolphin only retained $wSST_{-1}$. There were very few observations of either minke whale or white-beaked dolphin in the database, and while the Tweedie distribution offers a more flexible alternative to the Poisson distribution used in the original analysis, the large number of zero counts led to issues with the how well the statistical model fitted the data. Minke whale were predicted to be largely restricted to the central North Sea in 2005 To increase the power to detect any influence of structure on their distribution, it may be pertinent to restrict future analyses to that area or other relatively high density areas.

To increase our ability to detect any effect of man-made structures at the population-level, we need to increase our understanding of the underlying mechanism of any impacts. In this study, the lack of knowledge of how any impact of structure on apex predators varies by structure type, the availability of relevant infrastructure data, and our aim to maximise our ability to detect any effect of structures, led to all structures being considered together and some key structures being excluded (in particular, offshore wind farms in relation to seabirds). However, this means that any impacts restricted to a certain structure type or operational stage, may not have been detectable. It also means that the weak associations detected may be have been driven by a strong association with a certain structure type. For example, it is possible that grey seal and northern fulmar distributions were strongly negatively impacted by a certain type of oil & gas structure and this was evident as a weak overall association. The strength and type of impact may differ with structure type. For

example, as well as hosting reefs, structures with a larger footprint may encompass relatively high prey densities due to fishing restrictions (Inger *et al.* 2009). Structures with above-surface components may also provide navigational aids (Biro *et al.* 2007).

Determining structure stage- and type-specific effects on marine predators will become increasingly possible in the coming years since marine renewable developments are increasing in coastal areas used by marine predators and because of increasing samples sizes of tagged individuals. Large-scale tagging programmes at individual seabird colonies (e.g. Isle of May; Centre for Ecology and Hydrology), and along the UK coast (e.g. RSPB FAME and STAR projects) are ongoing. A project funded by the Department for Business, Energy & Industrial Strategy (BEIS), will result in a doubling of the fine-scale tracking data available for adult grey seals in the UK. While there was no evidence of use of windfarms by grey seals in the southern North Sea (Russell 2016), the majority of structures in that region were newly installed and it may take time for reefs to become established. The BEIS project will collect data on the foraging behaviour and distribution of grey seals in the vicinity of more than 600 turbines foundations, providing a timeline of structure age from less than one year old to more than 10 years old.

Information on the mechanisms underpinning the impact of structures on marine predators will determine which type of structure should be incorporated into any distribution models. In addition, SCANS-III (https://synergy.st-andrews.ac.uk/scans3/) conducted in 2016, could provide a further opportunity to investigate the impact of man-made structures on cetacean distribution, particularly the robustness of the apparent influence of structures on harbour porpoise distributions. The ESAS database was a useful data resource because the long time series, year-round coverage and large spatial extent allowed us to investigate the association between oil & gas structures and seabird distribution in the context of environmental variability both within and between years, across the extent of the North Sea. Unfortunately, our findings suggest that, for most seabird species, modelling the impact of oil & gas structures on a North Sea wide basis using such data is problematic due to the clumped nature of distributions resulting in a high number of transects with no observations. With the increasing amount of seabird tag data available, such data could be used, applying similar techniques to those used here with seal tag data, to investigate the large scale distribution of seabirds with regard to structures. Although the relatively limited spatial and temporal extent of the data may have implications for the analyses, investigating movements of individuals during the breeding season, in which intrinsic processes are better understood, may have enabled the external drivers of distribution to be more detectable. Indeed, a recent analyses of RSPB tag data (a subset of which we used in Aim 2), has revealed several key environmental drivers of the at-sea distribution of breeding seabirds (Wakefield *et al.* 2017). Such analyses provide an ideal opportunity to investigate the impacts of structures and the dynamic environment on distributions of breeding seabirds.

5. Conclusions & Recommendations

Our objective was to determine the effects of oil & gas structures on the at-sea distribution and foraging behaviour of apex predators, compared to the spatial and temporal variability of the North Sea (INSITE Objective 1). Further research is required but the available data indicate that the distribution of top predators (with the potential exception of harbour porpoise) would be similar whether oil & gas structures were present or not. At the scale of population-level distributions, our findings suggest that these structures have little or no effect in comparison to the spatial and temporal variability in the environment. The exception was harbour porpoise; the apparent influence of structure on harbour porpoise distribution was comparable to the influence of other environmental covariates. This finding is supported by other studies indicating relatively high harbour porpoise activity at individual structures in the North Sea (Todd *et al.* 2009). Modelling the impact of oil & gas structures using North Sea wide survey data was problematic for seabirds, minke whale and white-beaked dolphin, likely because of the limited number of observations in the datasets used. Utilising fine-scale data, there was little evidence that the presence of oil & gas infrastructure affected seabird foraging behaviour at a population level. There was evidence of an effect of structure on the foraging movements of a few individual seabirds but the underlying mechanism of any effect is not clear. For seals, there was strong evidence that structures can drive the movements and behaviour of some individuals, with repeated trips to forage at structures.

Further work to address INSITE Objectives for apex predators should focus on understanding whether particular types of structure and/or life-stage affect predator distributions and what are the key mechanisms involved. For seabirds and seals this can be achieved through further analyses of additional animal-borne tag data, and by the incorporation of offshore renewable developments into analyses. Such knowledge will increase the ability to detect any effect of structures on population distribution. For harbour porpoise, the robustness of our findings can be examined by investigation of data from the most recent survey (SCANS-III). The influence of structures on the distribution of seabirds in the North Sea could be re-examined using animal-borne tag data collected over multiple years during the breeding season. However, it is important to consider that modelling the population-level relationship between oil & gas structures and apex predator distributions will not fully address INSITE Objective 1 with regard to predators. Our findings suggest that the impact of structures on apex predators is likely to be complex. Potential influences, such as the provision of locations on which to rest (thus possibly extending the foraging range from the coast), use as navigational aids and increased foraging success mediated through discards from vessels fishing along pipelines would be difficult to detect and therefore quantify at a population level.

6. Outreach

Some of the preliminary results were presented at the University of St Andrews Science Discovery Day which attracted more than 700 participants (https://synergy.st-andrews.ac.uk/biooutreach/2016/03/08/science-discovery-day/). Now that the majority of the work is finished, the results will be disseminated though peer publications and also by targeting wider audiences. SMRU has an active social media presence and participates in

many outreach events including Dundee and Glasgow Science Festivals, and these avenues will be used introduce the public to the project's findings. Furthermore, SMRU is organising a workshop aimed at UK regulators, policy makers, and statutory agencies to embed the latest knowledge and understanding of SMRU research on the impacts of marine developments. This event will be ideal to showcase the project's results and increase the overall impact of the findings.

7. Author Contributions

DJFR led and conceived the project, with the exception of the analysis of ESAS at-sea survey data which was conceived and undertaken by EM. WJG undertook the analysis of mammal/seabird tracking data and mammal at-sea survey data and, with DJFR, drafted the report. PSH provided data and expertise on the cetacean survey data. EO, FD and SW provided data and expertise on seabird tracking data. All co-authors provided comments on the report.

8. Acknowledgements

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