The RO will examine this geographic variation in the relationship between SST and kittiwake breeding success and the temporal deviation from this relationship at individual colonies. It will do so in the context of spatial and temporal variation in environmental and biological factors. Abiotic factors will include temperature at the seabed as well as the surface, stratification, current circulation and various measures of weather conditions. Biological factors will include indicators of the structure and function of the food chain including primary production, phytoplankton biomass, zooplankton abundance and if possible, data on phenology of zooplankton spawning and larval fish abundance. This RO can also link to RO3.9 by incorporating data on temporal and spatial variation in kittiwake diet during the breeding season.

Benefits / Key outcomes

This RO will improve understanding about the most likely factors affecting kittiwake breeding success across a range of colonies. This will improve our understanding of what determines population size at colonies of relevance to offshore wind development, e.g. it would assist with understanding why breeding success at Flamborough and Filey Coast is lower than would be expected by SST alone and to explore the role of the Dogger Bank fishery on kittiwake productivity at this colony. This insight will help both improve predictions about how these colonies are likely to respond to additional offshore wind mortality as well as better understanding what effect changes in management might have, e.g. closure of certain fisheries.

Risks / Inter-dependencies

Low – all data used in this study are publicly available. The relationships between kittiwake breeding success and SST that underpin this study have already been established by previous work (e.g. Carroll *et al.* 2015; Cook *et al.* 2014; Frederiksen *et al.* 2004; Mitchell *et al.* 2018).

Predicted resources required to deliver this RO

This is a desk-based analysis based on existing code. The work was originally developed by BTO and JNCC, but expertise is widely available from other UK providers.

LOW resource requirements (one year and less than £100K).

RO3.9 Kittiwake diets during the breeding season, and the relationship between prey availability and productivity

Evidence need / Rationale for doing this RO

Food abundance and availability during the breeding season have been shown to strongly influence productivity in kittiwake populations. By better understanding how kittiwakes respond to spatial and temporal variation in food availability, we can predict with more confidence how these populations might respond to commercial fisheries management and climate change. Since these variables strongly determine kittiwake population size and growth rate, they also determine how resilient a population will be to additional mortality, e.g. from offshore wind development.

Better understanding of what breeding kittiwakes eat in different regions, whether their diet can vary between colonies within a region and between sections of a colony, and how it has changed over time at a given colony, would give us insights on the breadth of their diet, their ability to switch prey, and the relative prevalence of sandeels, as well as non-sandeel prey, in their contemporary diet. This is important as the ability to use other non-sandeel prey resources and the consequence of prey switching on demographic rates determines how well kittiwake colonies are likely to tolerate additional mortality, e.g. from OWF, in the future. Predicting their response to changes in prey availability cannot be addressed solely by looking at the relationship between kittiwake productivity and some averaged indices of prey abundance or biomass, as these indices do not necessarily reflect the availability of prey at different periods of the breeding season, including the most energetically-demanding periods. Accounting for timing of breeding and prey is therefore important.

This RO combines desk-based and field studies that will help build confidence in how kittiwake populations are responding to on-going changes in prey availability and thus assess their resilience in the context of declining sandeel stock biomass in the North Sea.

Work already underway
The Marine Ecosystems Research Programme (MERP) has constructed, and continues to populate, a comprehensive time- and spatially-explicit database of diets for ten seabird species (including kittiwakes) in the British Isles (Krystalli *et al.* 2019). This brings together for the first time all the available information about the food resources of these British seabirds. As of March 2020, diet data was available for 17 different colonies spanning from 1963 to 2015 (between one and 17 years of data per colony). Diet samples from regurgitates were also available at Flamborough and Filey Coast SPA that have yet to be processed and analysed. (https://github.com/annakrystalli/seabirddietDB)

Monitoring of kittiwake breeding success is available at a number of colonies in the UK, some with good long-term time-series of count and productivity data (e.g. Isle of May). Thanks to the RSPB FAME and STAR projects, GPS tracking of kittiwakes was undertaken at a total of 22 kittiwake colonies around Britain and Ireland. These data were analysed to predict UK-wide breeding distribution foraging maps (Wakefield *et al.* 2017) as well as SPA-level hotspot maps (Cleasby *et al.* 2018). Further GPS tracking of breeding kittiwakes is currently ongoing at Flamborough and Filey Coast SPA, St Abbs Head SPA, Fowlsheugh SPA and Buchan Ness to Collieston Coast SPA.

Information on fish distribution, abundance and biomass data, including sandeel, sprat and herring, is publicly available from ICES. Monitoring of fish abundance and biomass is also available from Marine Scotland and CEFAS.

Recently, JNCC and SMRU undertook a piece of work that aimed to map the distribution of harbour seal prey species (“calorific maps”), that include Atlantic cod, whiting, European sprat, Atlantic herring and sandeels (Family *Ammodytidae*) in the North Sea (Ransijn *et al.* 2019).

Work required
It is proposed to break down this RO into three parts.

With the two first parts of this RO (RO3.9a-b), it is proposed to explore the regional and temporal patterns of kittiwake prey types and quality in the UK. For example, do breeding kittiwakes prey on different fish species in different UK regions, colonies or sub-colonies? What types of fish are they eating, what age class, size and quality? Is there evidence of prey switching over time? Assessing how diet varies between sections of individual colonies will also give us insights on why kittiwake productivity may differ within an SPA, as it was observed at Flamborough and Filey Coast SPA. RO3.9a is a scoping exercise involving a review of the existing knowledge base and identification of evidence gaps, while RO3.9b involves collecting additional diet information at colonies to fill in these gaps.

RO3.9c aims to assess the relationship between food availability and kittiwake productivity from colonies where more detailed information could be gained by combining diet studies, breeding success monitoring, GPS tracking and prey availability data.

RO3.9a Spatial and temporal assessment of kittiwake diets, foraging distributions and prey distributions during the breeding season: desk-based study
This RO requires reviewing the existing information on kittiwake diet during the breeding season, their foraging distributions and prey distributions in the UK.

The MERP diet database is a valuable resource for sourcing pre-2018 kittiwake diet studies. Under this RO, UK kittiwake experts would also be contacted to find out whether diet information is available from ongoing unpublished studies. It would also be valuable to source any unpublished diet studies, or anecdotal information, on kittiwake diet pre-1985 when sprats were more abundant in the North Sea (by e.g. contacting Mike Harris). The information acquired will be used to assess the current knowledge base and identify critical evidence gaps. For example:

- What types of diet data already exist for kittiwakes, and where? Has prey been identified to species, age and size classes? When during the breeding season has diet data been collected? What are they eating, of what age class and sizes, and where?
- Has prey consumption data been collected or estimated (or is it just proportional diet data)?
- Is there evidence for differences in chick diet composition between UK regions, colonies and sub-colonies? Is there evidence of prey switching over time within colonies or regions?
- How do these diet composition patterns relate to other UK seabird species that have similar foraging strategies? Can we detect common trends in prey switching across species?
- How many years of chick diet data have been collected for each colony? How many samples were collected and from how many individuals per colony per year?
- Do we have a good understanding of contemporary kittiwake diets at colonies where consenting risk is high (e.g. East Caithness Cliffs SPA, Fowlsheugh SPA, Forth Island SPA, Flamborough and Filey Coast SPA)?

The results of this review will identify current gaps in knowledge. In particular, are there any particular areas where consenting risk is high and contemporary information on kittiwake diet during the breeding season is lacking?

As part of this RO, it would also be valuable to review GPS tracking data for breeding kittiwakes in the UK, as well as contacting forage fish experts and sourcing data on UK fish prey abundance and biomass, to address the following questions:

- For those colonies where diet data is available, is there GPS tracking data available to identify where breeding adults were foraging in years when diet information was collected? How many individuals were tracked and how many individuals were analysed for diet? Are the samples representative of the whole colony?
- Is there evidence that kittiwake colonies are using the same foraging areas over the years? Are they travelling further offshore in some areas?
- What is the current distribution of fish prey species? Is abundance/biomass data available for all kittiwakes' prey types in the North Sea, west coast of Scotland and Irish Sea?
- Can we relate diet and foraging distributions of a particular colony to fish prey abundance and biomass in areas where we know kittiwakes are foraging?

RO3.9b Regional comparison of kittiwake diets during the breeding season: field studies
This sub-RO will involve more detailed field studies at those UK kittiwake colonies with high consenting risk and where contemporary kittiwake diet information is lacking (as identified in

RO3.9a). This could also include colonies in the Irish Sea where several lines of evidence suggest that sandeels may not be an important food source for breeding kittiwakes, therefore informing on the extent of prey switching. Better understanding of what kittiwakes feed on in areas of high consenting risk will help identify relevant fisheries management measures.

Setting up cameras at nests is not appropriate for monitoring kittiwake prey delivery to chicks as chick feeding occurs too quickly and the regurgitate is challenging to identify to prey type from camera observations. Alternative options are to collect prey regurgitates at the nest and collect droppings for genetic analyses. While the former is routinely done in some kittiwake colonies as part of a long-term monitoring of kittiwake diet, the feasibility of analysing DNA in droppings to infer kittiwake diet would need to be assessed. It has been done however on red-throated divers (Kleinschmidt *et al.* 2019). Combining morphological and molecular approaches may be recommended to minimise the limitations of these techniques (Horswill *et al.* 2018).

It is probably not useful to use stable isotope analyses in this instance since this technique will only provide an idea of prey trophic level, as opposed to empirical evidence of adult kittiwakes feeding on sprat, sandeels or other fish species from the same trophic level. Ideally, prey consumption data will include information on prey species, age or size class of prey, and biomass ingested (therefore not just proportional diet data). In addition, using cameras at nests, combined with field observations, will assist with measuring chick provisioning rates, and hence obtain estimates of daily energy intake in relation to types of prey fed to chicks. It is also proposed to assess the extent of diet variation within colonies by simultaneously sampling chick diet in different sections.

RO3.9c Relating prey availability to productivity: desk-based study
This sub-RO will aim at better understanding the relationship between kittiwakes' prey availability during the most energetically-demanding period of the breeding season and productivity. Poor availability of 0-group sandeels during the chick-rearing period may explain why kittiwakes perform poorly, in which case an effective conservation measure should aim at increasing availability of 0-group sandeels during the chick-rearing season in areas where adult kittiwakes are known to forage.

Prey availability during the chick-rearing period will be assessed by obtaining data on fish landings (incl. 1+ and 0 sandeel groups) during that period. Sourcing relevant historic and contemporary landings data will be informed by knowledge of what adults provision their chicks at a given colony and where adult kittiwakes from this colony forage during the chick-rearing season. Chick diet data will be obtained from both historic and contemporary diet studies (as per RO3.9a-b). Knowledge of where kittiwakes are foraging at colonies where diet data is available will be obtained by using existing GPS tracking data, as well as previous research linking colonies with the dependent sandeel populations (Olin *et al.*, in press).

Candidate colonies for this sub-ROs are those where chick diet data is available (with a preference for colonies providing several years of data), as well as GPS tracking and colony productivity data.

Benefits / Key outcomes
These three sub-ROs will improve our understanding of the relative importance of certain types of forage fish for kittiwakes during the breeding season across regions and over time, which will provide insights on the range of relevant measures that could be put in place to compensate for potential additional wind farm mortality.

This work would provide some insights on the ability of kittiwakes to switch prey types in relation to availability, as well as its demographic implications, and therefore their resilience in the context of declining sandeel stock biomass in the North Sea. The findings of these sub-ROs could be directly fed into current advances of PVA modelling approaches, such as the "MSS-funded seabirds-climate change" project led by CEH, which aim to produce better estimates of wind farm effects on future population change in protected seabird populations. This project will incorporate the effects of climate change (through changes in prey availability) on seabird behaviour, demography, abundance and distribution into impact assessments.

This RO could also feed into RO3.8 in terms of examining whether spatial and temporal variation in prey species explains some of the variance in relationships between kittiwake breeding success and abiotic variables (e.g. SST, timing of stratification).

Risks / Inter-dependencies
A key risk of using diet data is that, in general, diet is liable to adapt dynamically to changes in prey availability. This may imply that natural systems are much more buffered from change than is suggested by current data. With this RO, it is proposed to capture diet data from multiple points in time and space, i.e. at different colonies, which will help address the issue and minimise risks.

Another risk is that there are relatively poor fish biomass data for the west coast of Scotland and the Irish Sea, due to the closure of Scottish west coast fisheries. There might be however larval sandeel data from some CEFAS surveys for the Irish Sea; the review (RO3.9a) would investigate this. In areas where there are no data available on fish prey, an alternative option would be to explore options for obtaining live prey abundance and availability data (e.g. by flying a low-flying plane in areas identified as foraging hotspots for kittiwakes), and comparing the fish observed at the surface with the fish found in the regurgitates. However, as doing these surveys will increase the cost of the whole project, a thorough evaluation of the cost and benefits of several alternative means will be required. Sourcing relevant datasets will be facilitated by the availability of an online tool (MERP seabird diet database; unpublished version can be accessed by contacting authors) that compiles seabird diet information, including kittiwakes, in the British Isles.

Field work would be required to collect regurgitate samples at different colonies, involving capturing chicks at nests, but this is routinely done in several kittiwake colonies in the UK, Europe and US.

Information on timing of the chick-rearing period (i.e. date of first chick) is not routinely submitted to the SMP database but this information can easily be collected by experienced recorders.

A thorough evaluation of the potentials and limitations of morphological vs. molecular diet analyses would be required to determine whether genetic analyses are appropriate as an alternative, or complementary, technique.

Predicted resources required to deliver this RO
RO3.9a is a desk-based review, largely based on data that have already been collected and compiled as part of other projects.

LOW resource requirement (less than 6 months and less than £50K).

RO3.9b is a field study and will require ideally more than one field season to capture yearly variability in diet composition and breeding success.

HIGH resource requirement (minimum of two years, more than £200K).

RO3.9c is a desk-based study compiling data from RO3.9a-b and other existing sources.

MEDIUM resource requirement (less than one year, less than £100K).

RO3.10 Assessing the current and future condition of alternative fish prey populations: a desk-based study

Evidence need / Rationale for doing this RO
Building more realistic PVA models requires being able to predict the trajectory of kittiwake population size under predicted scenarios of climate change within the time period over which population size is modelled. Exploring how kittiwake demographic parameters relate to on-going and future changes in prey availability is thus needed to increase certainty in model predictions. While there has been a lot of research looking at how both climate change and fisheries may impact UK kittiwake demographic parameters through changes in sandeel abundance and availability (see e.g. review in Mitchell *et al.* 2020), uncertainty remains around how ongoing and future changes in the distribution and abundance of other prey types (e.g. sprat, herring) in the North, Celtic and Irish Seas may affect kittiwake populations. In particular, previous research has indicated some discrepancy in the relationship between kittiwake productivity and abiotic variables, such as SST and timing of stratification, between colonies (e.g. Carroll *et al.* 2015; Frederiksen *et al.* 2007), and it is unclear whether this lack of regional consistency could be explained by differences in the prey kittiwakes are feeding on (e.g. the drivers that were looked at may not be meaningful in the context of non-sandeel prey).

Given that sandeel populations are declining due to climate change, focussing management measures around one prey species (i.e. sandeels) might not be effective, especially if kittiwakes can exploit other prey resources. The EcoWatt2050 project (https://www.masts.ac.uk/research/ecowatt2050/), in partnership with the University of Aberdeen, has produced 7 by 7km distribution maps for 2050 of where increases vs. decreases in the overlap between predicted kittiwake foraging grounds and sandeel distribution may occur (see results in Sadykova *et al.* 2017). What will happen to kittiwake populations in areas where sandeels are no longer available? Will other prey become available that will support these kittiwake colonies or will these colonies decline to extinction?

RO3.9 above establishes the extent to which kittiwakes currently forage on prey other than sandeels. RO3.10 will follow on from this by improving understanding of availability of alternative prey species. With this RO, it is proposed to review the literature on population status and trends, drivers of population dynamics, current fishery levels and projected impacts of climate change for forage fish other than sandeels, and put this knowledge in the context of how kittiwakes use the marine environment in the UK, what we know they eat during the breeding season and their demography.

This RO would build on results from RO3.9 which would provide evidence for current prevalence of non-sandeel prey in kittiwake diet and how that influences demographic rates such as productivity.

Work already underway
This RO will make use of the various data-sets available below.

Current and historic data on fish distributions in the North-East Atlantic, including data from the herring assessment working group, is available through ICES.

There are also some models available that predict changes in fish distribution in European waters in response to warming seas (e.g. Montero-Serra *et al.* 2015). A critical assessment of the methods and results would be required to assess the quality of the predicted mapping outputs to inform RO3.10.

We have a relatively good understanding of where kittiwakes breeding in UK colonies forage thanks to the intensive GPS tracking work from the RSPB: UK-wide predicted breeding distributions (Wakefield *et al.* 2017) and SPA-level hotspot maps (Cleasby *et al.* 2018).

The Marine Ecosystems Research Programme (MERP) has constructed, and continues to populate, a comprehensive time- and spatially-explicit database of diets for ten seabird species (including kittiwakes) in the British Isles. Information was extracted for kittiwakes on 25 March 2020: diet data is available for 17 different colonies spanning from 1963 to 2015 (between one and 17 years of data per colony).

Work required
As a first step to approach this RO, it would be useful to review the kittiwake diet literature and identify the alternative food sources for kittiwakes, and how diet composition has varied over time (as per Wanless *et al.* 2018) and space. This could be informed by the outputs of RO3.9a or by extracting information from the MERP diet database. This preliminary search will be useful to delineate what species and regions are most relevant for this RO. Then, the relevant information for each species and region would be collated by conducting a systematic literature review on the current and forecasted distributions and trends, drivers of population dynamics and current fishing levels for those prey species and areas.

The outputs of the literature review could be summarised in the form of seasonal distribution maps of Clupeids, Gadidae and other alternative forage fish species, and overlap them with information where and when current fisheries occur, and where kittiwakes are known to forage.

This RO could also make use of the results of the EcoWatt2050 project and explore what predicted changes in kittiwake foraging distributions due to changes in prey distributions mean for the sustainability of kittiwake colonies.

Benefits / Key outcomes
This RO will provide information on the current and future status and condition of non-sandeel prey types, which will help anticipate likely demographic responses of kittiwakes to climate change and changes to fisheries management.

Information gathered from this RO will help re-interpret some of the relationships between kittiwake breeding success and abiotic variables (e.g. SST, timing of stratification) as proposed in RO3.8, in the context of alternative prey types. For example, large-scale studies e.g. Carroll *et al*. 2015 and Frederiksen *et al*. 2007 found very different relationships for different colonies. Could this partly be explained by differences in the prey the kittiwakes are feeding on and what do the drivers they looked at mean in the context of non-sandeel prey?

Undertaking ROs 3.8, 3.9 and 3.10 together would greatly improve our understanding of how prey determines kittiwake demographics and resilience to additional mortality, e.g. from OWF. These three ROs together provide valuable information on how kittiwake populations are likely to change in the near future and the role of prey and fisheries in driving those changes, in the context of climate change. This provides important wider context to assessing the impact of OW development on kittiwake populations; a population that is likely to decline due to an absence of prey will not tolerate additional mortality well whereas a population that is likely to continue to perform well due to suitable prey (sandeel or other species) being available will be more resilient to additional mortality.

Risks / Inter-dependencies
This is a desk-based study, largely based on data that have already been collected and compiled as part of other projects; thus, there are no foreseeable significant risks. This RO will benefit from the outputs of kittiwake diet literature review (as described in RO3.9a) for identifying the prey species of interest.

Predicted resources required to deliver this RO

LOW resource requirement (less than 6 months, less than £100K).

RO3.11 Quantifying the effects of fisheries management on kittiwake demography

Evidence need / Rationale for doing this RO
Kittiwake demographics, particularly productivity, are known to be correlated with prey availability. For example, for kittiwakes breeding in the Flamborough and Filey Coast SPA and feeding on the Dogger Bank, Carroll *et al*. (2017) found lower sea temperatures and lower fishing mortality were associated with greater sandeel biomass, which in turn, had a positive relationship with kittiwake productivity and adult survival. Similarly, Frederiksen *et al*. (2008) reported suppressed productivity for kittiwakes breeding on the Isle of May when the Wee Bankie sandeel fishery was operating.

One possible conservation measure for increasing kittiwake productivity is closure of sandeel fisheries within foraging range of kittiwake colonies (Furness *et al.* 2013). When considering efficacy of conservation measures, the ability to monitor the effectiveness of proposed measures is a key consideration. In other words, if management of sandeel fisheries was proposed as a conservation measure, it would be important to have a monitoring plan capable of quantifying demographic responses to changes in fishing effort.

This RO involves designing a monitoring plan that would maximise power to detect changes in demographic rates that could be attributed to changes in fisheries management. This would be followed by data collection prior to changes in fishing effort, which would provide a baseline against which to assess demographic response to management.

Work already underway
Frederiksen *et al*. (2004, 2008) and Carroll *et al*. (2017) have previously demonstrated a relationship between sandeel fisheries and kittiwake demographic rates but in all cases, additional environmental data were included as explanatory covariates, e.g. sea surface temperature. This previous work should be used to inform both experimental design and subsequent data analysis as part of this RO.

Work required
This work would be undertaken in two stages:

RO3.11a Experimental design
The aim of this sub RO would be to design the optimum data sampling protocol to maximise power to detect change in demographic rates due to changes in fisheries management. This needs to include considerations such as:

- Which demographic rates to measure and what information about these rates is needed, e.g. productivity data could include timing of breeding, number of nesting attempts, number of nests with >1 chick, number of chicks fledging per nest, *etc*.
- At how many colonies should demographic data be collected, e.g. which are optimal control colonies?

- How many years of baseline information would ideally be needed prior to changes in fisheries management?
- What covariates would need to be collected? This would include i. biological covariates (e.g. information on where adult kittiwakes from each colony are foraging during the breeding season, provisioning rates, prey species fed to chicks), ii. evironmental covariates (e.g. sea surface temperature, sea stratification metrics), iii. fishery covariates (e.g. timing and size of fishery landings, fishing effort)?

The experimental design should provide a detailed programme of data collection for each year prior to and during implementation of changes in fisheries management. The design should include recommendations for analysing data collected, including modelling approaches. It should also have an iterative component allowing feedback from the first years of data collection and analysis to inform subsequent years of data collection to ensure maximum power is obtained from data.

RO3.11b Data collection and analysis

This sub RO involves collecting data as prescribed in the experimental design (RO3.11a). Data collection should begin as soon as possible, to maximise data collected to inform baseline estimates of demographic parameters prior to changes to fisheries management. The more baseline data collected, the greater the power to quantify changes in demographic rates following changes to fisheries management, especially given rapidly changing environmental conditions due to climate change. As soon as sufficient data are available, data analysis and interpretation should be initiated as this will inform subsequent data collection. For example, other covariates may be identified as being important explanatory variables in models and additional data collection may be required. Initial model structure could be informed by approaches used by Carroll *et al*. (2017) and Frederiksen *et al*. (2004, 2008) but other approaches may be more suitable, e.g. Bayesian integrated modelling.

Benefits / Key outcomes

This RO would ensure maximum power is derived from demographic data collected as part of monitoring and demonstrating the efficacy of conservation measures. By collecting data prior to changes in fishery management, a high-quality baseline can be established against which to assess changes in demographic rates, thereby increasing the chances of being able to demonstrate effectiveness of conservation measures. Additionally, evidence arising from this RO will assist with both improving the quality of empirical data on demographic rates at colonies of interest that can be used to parameterise PVA models, as well as augmenting our understanding of what drives kittiwake population dynamics and to better anticipate how populations are likely to respond to predicted offshore wind farm mortality.

Risks / Inter-dependencies

Data collection and modelling approaches have already been developed and published previously, making risks to this RO relatively low. However, there is a risk that even with a robust experimental design and high-quality data analysis, no effect from fishery management is found on demographic rates. This could be due to adult kittiwakes not foraging in areas currently subject to fishing pressure, adults switching foraging locations or switching prey or other reasons that mean current fishing pressure is not supressing kittiwake demographic rates.

Another risk is that baseline data are collected but no changes to fisheries management occur. However, the baseline data will still be very valuable for generating more up to date demographic estimates and improving confidence in demographic estimates, which will assist with PVA parameterisation. Additionally, use of covariates to assist with explaining variation in demographic rates will advance our understanding of what determines kittiwake demographic rates and consequent population dynamics. In other words, the results from this RO will still be extremely valuable in better assessing population response to offshore wind farm impacts, even without changes to fisheries management.

This RO would best be delivered concurrent to RO3.8 which aims to explain broadscale patterns in population growth rates at multiple colonies around the UK. Information from these broad scale patterns would help identify optimal control colonies at which more detailed information could subsequently be collected.

Predicted resources required to deliver this RO
RO3.11a is a desk-based study to produce a robust experimental design.

LOW resource requirements (less than 6 months and less than £50K).

RO3.11b would require substantial data collection and analysis. This would need to be informed by the experimental design and so it is not possible to predict resources required but they are likely to be significant, especially if carried out for many years, as would be required to fully understand population response to changes in fisheries management.

LOW-MEDIUM annual resource requirements but required for **many years** (approx. £50-£100k per year including data collection and analysis but likely to require multiple years of work).

RO3.12 Predicting the demographic consequences of various potential measures to manage pressures on kittiwake populations

Evidence need / Rationale for doing this RO
As kittiwakes use both the marine and terrestrial environment, they can be exposed to a wide range of pressures. Quantifying the relative impact of every potential pressure, as well as their interaction, on their population dynamics, is a daunting task. A key knowledge gap is understanding how the removal or release from some of these pressures would enable population increase. This is relevant to offshore wind development as management of pressures has the potential to compensate for mortality from offshore wind development as well as making kittiwake populations more resilient to additional mortality. Whilst reducing one effect might not be enough to permit population increase, the interaction between pressures and demographic processes could mean population responses to reduced anthropogenic mortality could be non-linear. However, a complex model that is parameterised with too many covariates (for which there may be insufficient data) and that is trying to test every conceivable mechanistic hypothesis or combination of hypotheses bears the risk of not being viable (e.g. it is not possible to parameterise the model due to a lack of data), and, even producing spurious results. A more strategic and tractable approach would be to focus on the proximate causes of apparent population decline (i.e. too many birds die, not enough birds fledge, too many birds leave the colony) to help pinpoint the ultimate drivers of apparent decline (e.g. food availability, extreme weather), and then include only those pressures on kittiwake populations that can be managed. For example, while we cannot do anything about climate change directly, we can do something about nest site availability or commercial fisheries (see e.g. Furness *et al*. 2013 for a review of conservation measures).

Work already underway
Demographically structured state-space models can help apportion observed population variability to the proximate drivers of population change (i.e. age-specific mortality, productivity and population movements). This approach identifies which demographic parameter(s) are responsible for an observed decline in population size and then use covariates to try and determine which anthropogenic pressure(s) is/are likely to be influencing that demographic rate. This has been successfully carried out for populations of

marine mammals and seabirds (Caillat *et al.* 2019; Horswill *et al.* 2016a; Matthiopoulos *et al.* 2014; Miller *et al.* 2019). This approach allows the reconstruction of time-series for (often unobserved) demographic rates, which can then be expanded by the inclusion of environmental covariates (Caillat *et al.* 2019; Horswill *et al.* 2016a). In this way, we first find out for instance, that a population decline is due to 1st year mortality, we then obtain an error-corrected time series of that demographic rate and we finally regress that against covariates such as anthropogenic mortality. All three of these steps can be taken simultaneously in the same model to make sure that uncertainty is correctly propagated to the results.

Work required
The proposed modelling framework is structured as a two-stage process: 1) identifying the proximate causes of population decline, followed by 2) testing the effectiveness of a series of candidate management measures.

RO3.12a Identify the proximate causes of population decline
The first step of the modelling framework would be structured as follows:

- Develop an abstracted but realistic demographic model that captures density dependence and metapopulation processes, and accounts for both observation and process uncertainty, such as proposed under RO3.1;
- Test and refine the model by teasing out the effects of various demographic rates;
- Identify proximate causes of decline over time (i.e. the demographic rates that most strongly determine population size and growth rate);
- These different steps would then allow identifying candidate covariates (single pressures and combination of pressures) that can affect these demographic rates, and then those that can be managed. At this point, depending on availability of covariate data (e.g. variation in fishing effort or annual predation rates over time), it may be possible to quantify the contribution of specific pressures by including them as covariates of the most influential demographic parameters identified above. In case data on those specific pressures are not available at all, or not available in the right form to enable easy incorporation into the model, it would be valuable to direct future data collection on those ultimate causal mechanisms of population change to then be able to incorporate these covariate data in the model.

RO3.12b Quantify the relative contribution of candidate covariates on kittiwake population change
This sub-RO would involve incorporating covariate data into the existing model structure (as described in RO3.12a) to quantify their relative contribution in population change. Collection of additional covariate data may or may not be required, but in case it is required, this sub-RO would undertake that. Then, with covariate data in hand, it would be possible to test a series of management measures, by evaluating the population response that could be achieved through a plausible range of reduction in pressure(s) through management. The range of plausible values could be informed by previous research (e.g. effect size of the relationship between sandeel fishery closure and productivity/adult survival).

Benefits / Key outcomes
A similar state-space model structure is proposed to be developed under RO3.1. Therefore, by using a similar model structure, there is the potential for addressing two ROs simultaneously. This RO will differ from RO3.1 by adding additional complexity to the state-space model in the form of additional pressures on kittiwake populations.

This RO will provide key evidence to inform discussions around conservation management measures. It will assist with understanding the relative impact of offshore wind development on kittiwake populations, compared with other pressures.

Risks / Inter-dependencies
The proposed baseline modelling framework has already been developed and tested on kittiwake colonies in Shetland. Expertise also exists among academics in the UK, Europe and US to build, parameterise and interpret these complex models. Altogether, this means that risks are minimised around model development.

A major risk is around availability of covariate data, as they may not be readily available in a suitable form for testing the effectiveness of management measures. However, undertaking this RO in two sequential stages would allow first addressing some of the important questions related to proximate causes of decline and the potential pressures driving the decline. The model could then be expanded as and when covariate data become available.

Predicted resources required to deliver this RO
RO3.12a The first stage of the model can be developed without the need to collect new data and is based on existing code (similar model structure as the “Miller model”).

MEDIUM resource requirements (less than one year, less than 100K)

RO3.12b Depending on the availability and format of the covariate data, there may be additional work required to sort these datasets or collect some new data, before being able to integrate this information into the existing model structure (RO3.12a) and test management measures.

LOW to MEDIUM resource requirements. This depends on whether additional effort is required to work on covariate datasets or collect new empirical data:

- If covariate data exist in a suitable format and only fitting the model with the covariate data is required: about 6 months and less than £50K;
- If covariate data already exist but work is required to re-format datasets: 6 months and less than £100K (in addition to the time and budget required for scenario A);
- If covariate data do not exist and additional work is needed to collect adequate covariate data: from 6 (spanning one breeding season) to +48 months (spanning two breeding seasons) or more (spanning multiple breeding seasons) and about £50-100K per year**.**

5 Synergies and overarching notes

The present report outlines a list of twelve research opportunities (ROs), which either alone or in combination with other project ideas, will improve our understanding of kittiwake population dynamics in the context of offshore wind development. These ROs are a combination of both large-scale strategic approaches and smaller-scale mechanistic approaches, involving both modelling or field work, with varying timescales and resource requirements.

RO3.1 is an important place to start as it provides an overarching framework for testing important hypotheses. RO3.1 will predict how likely kittiwakes are to move between colonies by modelling connectivity as a function of distances between colonies and the arrangement of the entire colony network. These estimates could then be refined by incorporating the results of ringing and relocation studies as proposed in RO3.3. Mark-recapture studies will inevitably take a few years to deliver useful information, but in the meantime, robust modelling approaches could be developed so that this information is analysed in the best way possible. Undertaking RO3.4 in parallel will quickly deliver useful information on population-specific adult survival rates, which could be incorporated to the different population models described under RO3.1, RO3.5, RO3.6 and RO3.12, and be complemented by the outputs of RO3.3. On the other hand, the outputs of RO3.1 will help identify the most influential population parameters for reconstructing time-series and reducing the uncertainty around population trajectories, and hence will inform RO3.3 as for where and how monitoring effort should be targeted. Another direct application of RO3.1 is to allow new functionality to be added to existing PVA modelling approaches (RO3.2) and hence increase biological realism.

Food availability is an important driver of kittiwake population dynamics, and better understanding of what affects food availability during the breeding season and how kittiwakes are able to adapt to these changes is crucial to assess resilience of populations in the context of climate change and fisheries pressures, and identify potential mitigation measures to improve population viability. In this respect, desk-based studies that review the available information on kittiwake diet patterns (RO3.9), current and future prey distribution and status of prey (RO3.10) and examine ecosystem processes driving the relationship between productivity and proxies of climate change (RO3.8) will provide a solid knowledge base to direct future collection of empirical evidence and test hypotheses including the effectiveness of conservation measures (as in RO3.12). Meanwhile, a desk-based study that develops a robust experimental protocol for quantifying the effects of fisheries on kittiwake demography (RO3.11) will inform the effectiveness of possible conservation measures.

6 Conclusions

This report has set out a series of twelve potential research opportunities (ROs) which were suggested and discussed during and subsequent to a workshop of experts in kittiwake population dynamics. Most of the projects described consist of more than one stand-alone piece of work, for example RO3.3 and RO3.9 include a desk-based study and a field element. Although they have been brought together into coherent ‘projects’, an element of ‘pick and mix’ is possible, for example if limited budgets do not allow for each full project idea to be pursued as a whole. Equally, some of these projects represent exploratory or feasibility assessments, and depending on the outcomes of these, could pave the way for much larger data-collection projects, and this has been pointed out and described briefly where appropriate. Furthermore, there are synergies and efficiencies within and across KGs, e.g. RO3.3 is very similar to RO2.3 in KG2, with both ROs exploring the use of mark-re-sighting systems to improve understanding of connectivity between SPAs and OWF as well as between colonies (immigration/emigration). Thus, undertaking one RO may well deliver key evidence to greatly assist with another RO.

The intention is that this report provides a signpost towards research which can contribute to reducing uncertainty around the linkage of effects on kittiwakes seen at a wind farm to populations, and thus contribute to overall reduced uncertainty in offshore wind farm environmental impact assessments. Incremental reductions in uncertainty will become more important as the offshore wind sector expands, in order to facilitate meaningful and precise cumulative impact assessments, therefore maximising the potential for sustainable marine development within the limits set by environmental protection and regulation.

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