OWSMRF Scope of Work

Modelling of kittiwake meta-population dynamics

(Research Opportunity 3.1)

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Contents

1. Background

Offshore wind farms (OWF) are seen as a key part of efforts to combat climate change (Snyder & Kaiser, 2009). However, there are a number of concerns about the potential for these wind farms to have a negative impact on wildlife and biodiversity, particularly in relation to birds (Drewitt & Langston, 2006; Gibson *et al*., 2017). To inform the UK planning process, proposed developments require detailed Environmental Impact Assessments (EIA) and Habitats Regulations Appraisals (HRA). EIAs assess impacts to the wider environment, whilst HRAs assess whether a plan or project will have an adverse effect on a site protected under The Conservation of Habitats and Species (Amendment) (EU Exit) Regulations 2019, The Conservation (Natural Habitats, &c.) Amendment (Scotland) Regulations 2019, the Conservation (Natural Habitats, &c.) (Northern Ireland) Regulations 1995 (as amended), and/or The Conservation of Offshore Marine Habitats and Species Regulations 2017 (as amended). As the number of wind energy developments increase globally both onshore and offshore, the potential associated environmental impacts are receiving considerable attention, particularly avian impacts.

This is of particular concern at the cumulative scale (i.e. when considering impacts of wind farms combined rather than of individual developments in isolation). In order to undertake meaningful cumulative impact assessments, there is a need for improved understanding of how birds respond to OWFs and how to quantify the risk to populations of concern. Without such information, decision making is necessarily precautionary, and there is a risk that OWFs may not be deployed at sufficient scale to contribute fully to emission reduction targets as outlined under the Climate Change Act 2008.

The Offshore Wind Strategic Monitoring and Research Forum (OWSMRF) Pilot Year identified uncertainty around in-combination and cumulative impacts of offshore wind development on black-legged kittiwake (*Rissa tridactyla*) populations as posing the greatest consent risk (https://jncc.gov.uk/our-work/owsmrf/). Three knowledge gaps (KG) to inform cumulative/in-combination assessments for black-legged kittiwake were identified:

- KG1: reducing uncertainty around estimates of wind farm collision mortality
- KG2: improving understanding of connectivity between OWFs and SPAs
- KG3: improving confidence in modelling population consequences of wind farm effects

As part of the impact assessment process, the likely effects (e.g. collision, barrier effects and/or displacement effects) of a planned OWF on birds are estimated (KG1). Once the magnitude of these effects has been estimated, it is necessary to understand which SPA colonies (if any) and wider populations these affected birds originate from (KG2). The potential SPA (for HRA assessments) and/or wider population (for EIA assessments) response to these OWF effects (i.e. reduced productivity or increased mortality) are then assessed using population modelling (KG3). In the particular context of HRAs, where an adverse effect on the integrity of a SPA site cannot be ruled out beyond any reasonable scientific doubt and there is no alternative to the project, compensation should be provided to maintain the overall coherence of the SPA network. Overall, data to inform these processes are frequently scant, leading to high uncertainty in magnitude of effects, a lack of confidence in predicted population responses to effects and uncertainty in the effectiveness of proposed compensatory measures.

This Scope of Work aims to obtain better evidence with which to parameterise Population Viability Models and improve understanding of the wider spatial scale at which kittiwake meta-population processes might be operating. This novel knowledge will help improve confidence when modelling population responses to predicted OWF-induced mortality, as well as inform the design and effectiveness of proposed compensatory measures.

1.1 Kittiwake inter-colony movements and OWF impact assessments

Many SPAs with kittiwake interest features have Conservation Objectives of maintaining or restoring populations. In order to better understand the way these populations are likely to respond to additional mortality from OWFs along with other drivers of population change and to identify the most effective measures to compensate for predicted OWF-induced mortality, it is necessary to look at kittiwake population dynamics over a wider spatial scale (i.e. at the scale that ecological processes function). For example, to understand what maintains population size at an SPA, we need to know whether breeding adults are being recruited from another colony acting as a source for the focal SPA. To inform the locations of compensatory measures designed to support an impacted colony (e.g. artificial nest sites supporting a colony with poor productivity), we need to know the location of source colonies that are exporting birds to the impacted colony. Therefore, understanding the extent to which immigration and emigration play a role in population persistence at the scale of individual colonies and more widely is of critical importance.

It has long been acknowledged that many seabird colonies do not function as strictly closed entities, with movement rates varying between species, individuals, colonies and years, depending on factors related to e.g. breeding performance, social cues, quality of breeding habitat and anthropogenic pressures. In kittiwake, GPS tracking of adult breeding birds in the North Atlantic indicate that prospecting movements can occur both locally (within 50km; Ponchon *et al*. 2015, 2017) and regionally (up to 200km; McCoy *et al*. 2005). Ring recoveries also revealed that recruitment of breeding kittiwake ringed in Eastern England was more likely to occur at a different colony to where chicks were fledged, and over a wide range of distances (mostly within 600km; Coulson & De Mevergnies 1992). However, due to difficulties related to colony accessibility, monitoring effort and technology, empirical evidence of inter-colony movements in kittiwake is currently limited to a small number of monitored birds from a handful of study sites (not necessarily in the UK) or based on old colony surveys. Uncertainty therefore remains around the frequency of dispersing individuals, where dispersing birds settle and what the drivers of these movements are.

In order to evaluate the impacts of OWF mortality on SPA bird features, a common approach in impact assessments is to use Population Viability Analyses (PVA). PVAs typically use demographic population models to project the population size of the modelled species across the operational life span of a wind farm (e.g. 25 years). A quantification of the relative impacts of additional mortality can then be performed by comparing the projected trajectories of impacted and non-impacted populations. In the absence of robust empirical evaluation of connectivity, PVAs are typically performed using closed population models, which do not allow for exchanges of individuals between colonies. Yet populations affected by OWF development would be predicted to respond very differently to additional mortality if meta-population processes were included in PVAs. For example, immigration from neighbouring colonies may help buffer against the negative impacts of anthropogenic mortality. Depending on the level of connectivity between the focal colony and the wider network of colonies that constitutes a meta-population, rescue effects can also prevent extinction of a declining colony. On the other hand, a population can experience further declines if emigration occurs. The assumption that kittiwake populations are closed to immigration and emigration is a strong one, and potentially wrong for many colonies. Therefore, considering closed populations when predicting population vulnerabilities is likely to have contribute to high levels of uncertainty in the predicted impacts of OWF mortality and hence result in inaccurate impact assessments. Answering the question about the role of movements between colonies in the dynamics of kittiwake populations and their persistence therefore requires a quantitative evaluation of the rates at which movements occur. Better understanding of connectivity between colonies within a wider colony network will increase confidence when modelling the vulnerability of kittiwake populations to predicted OWF mortality. This is particularly relevant to kittiwake colonies on the east coast of Britain, which are currently considered to be adversely impacted by OWFs (in-combination; e.g. see Hornsea 3 Offshore Wind Farm and Offshore Wind Leasing Round 4 Plan). Therefore, future consents for a wind farm that will further impact the same populations are likely to be required to put in place measures to compensate for their impact as part of the HRA derogation process.

Another pertinent applied ecological question relates to the directional patterns of movements (i.e. where do immigrating birds come from, where do emigrating birds go), and their relative strength, within the meta-population, and how movement rates between colonies relate to population growth. Identifying source-and-sink population dynamics will help anticipate the potential consequences of changes at other colonies on the focal SPA populations. For example, if the Flamborough and Filey Coast SPA is a sink population, identifying the source population(s) would help anticipate what would happen if these sources stopped exporting birds. Determining what role ("bad"/"sink" or "good"/"source") each colony may play within a meta-population has also implications for designing and measuring the effectiveness of conservation measures, in the context for example of the HRA derogation provisions. For instance, if newly created or restored colonies are identified as playing a key role for supplementing breeding kittiwakes to an SPA population with poor breeding success or adult survival, then conservation measures could be directed to support and protect these source colonies. As legislation requires that compensation is provided to maintain the ecological coherence of the SPA network, for kittiwake this can only be delivered by understanding their meta-population dynamics.

A quantitative evaluation of kittiwake inter-colony movements on the east coast of Britain will therefore provide in the first instance a more accurate and confident prediction of the size of the impact, and in the second instance a clearer understanding of the linkage between conservation measures and impacted colonies, thus allowing for identification of an appropriate location and scale of conservation measure that is required to compensate for the impact.

1.2 Modelling of kittiwake meta-population dynamics

Improving our understanding of the scale and strength of connectivity between colonies within a meta-population network is key to bringing greater realism to current impact assessment modelling approaches. However, obtaining robust empirical evidence of kittiwake inter-colony movements is challenging. O'Hanlon et al. (2021) estimated that at least 10 years of mark-recapture data would be required to estimate kittiwake adult dispersal rates with 2% of accuracy. Given these field logistical constraints, a promising alternative approach to quantitatively estimate connectivity rates where empirical data is not currently available is to make use of meta-population modelling tools. For example, Miller *et al*. (2019) developed demographic models open to rescue effects (i.e. immigration) for UK kittiwake populations, which form the basis of our current understanding of the effect of extrinsic (i.e. environmental conditions) and intrinsic (i.e. density-dependence) regulation on kittiwake population size. Further work by Miller *et al*. (2020) has shed light on the effect of connectivity on the vulnerability of Shetland kittiwake populations to additional mortality. With this Scope of Work, it is proposed to focus on UK kittiwake colonies that are currently causing, or will cause in the near future, the greatest consent risk for OWF developments through both the impact assessment and derogation processes. It is proposed to develop a modelling framework for improving understanding of how kittiwake populations function within a meta-population network, therefore providing the relevant evidence that would assist with a more robust evaluation of the impacts of OWFs on kittiwake populations from UK SPA sites, and would help inform the locations where compensatory measures are likely to be most effective.

The work described under this Scope of Work (SoW) has been developed from the Research Opportunity (RO) 3.1 described in Ruffino *et al.* (2020). This RO, along with other research ideas, was identified by experts and stakeholders (at a workshop held in February 2020) as key research needed to fill evidence gaps around population-level impacts of OWFs on kittiwake. This SoW can be broken down into four objectives. Firstly, a demographic model (Model 1) will be developed to quantitatively estimate the strength of connectivity between kittiwake populations, focusing on SPAs presenting a high consenting risk for offshore wind developments but also on colonies where good quality count and demographic data exist. Secondly, a range of plausible immigration and emigration rates estimated from Model 1 will be used as inputs to Population Viability Analyses (Model 2) to test the robustness of the closed population assumption when modelling population vulnerability. Third, kittiwake meta-population dynamics will be modelled (Model 3) to assess spatial variation in population dynamics and determine the source/sink status of colonies. Fourth, sensitivity analyses will be performed on components of Models 1, 2 and 3 to identify key demographic data gaps, which will then inform future data collection to improve confidence in model predictions (not included in this SoW).

Given the inherent complexities of parameterising meta-population models for large networks of colonies, it may be sensible to address some of the ecological questions presented under Objectives 1 and 3 as part of a unified modelling framework (as opposed to two separate model structures as presented below). For each of the three first objectives, the choice of the modelling framework and structure will ultimately depend on a trade-off between data quality, computational time/resources and the relevance of the information obtained to the offshore wind industry. This will need to be discussed in detail with the Contractor(s) prior to the start of the project.

2 Aim and objectives

2.1 Aim

This Scope of Work primarily aims to provide a quantitative evaluation of the scale and strength of kittiwake colony connectivity for UK regions relevant to the offshore wind industry, and to evaluate the demographic implications of inter-colony movements for determining the vulnerability of SPA breeding kittiwake populations to OWF mortality. This understanding will greatly improve our ability to predict how SPA populations will respond to estimated OWF mortality, by bringing greater biological realism to current PVA modelling approaches. In addition, novel knowledge on which colonies may operate as “source” or “sink” populations, and the consequences of sustained immigration and emigration fluxes on population growth, will help inform the design and effectiveness of compensatory measures.

2.2 Objective 1: Estimating connectivity between kittiwake colonies (Model 1)

Are focal colonies open to immigration and emigration, and if yes at what frequency are these movements occurring and where? A first objective is to quantitatively estimate the strength of connectivity between kittiwake colonies in UK regions presenting a high consenting risk, by modelling their meta-population dynamics.

This includes:

- defining focal regions to be modelled,
- building and parameterising a demographic model for kittiwake populations open to immigration and emigration (the model will be informed by empirical data and allow for movement rates to be captured at biologically-relevant scales),
- running the model and estimating the strength of connectivity between colonies, and
- validating model outputs.

2.3 Objective 2: Predicting population responses to OWF predicted mortality in closed vs. open systems (Model 2)

Is there enough immigration going on to supplement a colony that has poor breeding success? Is emigration accelerating the risk of decline from anthropogenic mortality? A second objective is to evaluate the importance of inter-colony movements in driving the vulnerability or resilience of SPA populations to anthropogenic mortality, and then assess the sensitivity of current impact assessment approaches to the assumption of closed populations.

This includes:

- performing PVA analyses informed by plausible estimates of connectivity derived from Model 1;
- comparing population trajectories and evaluating the risk of population decline in both open and closed population systems under various anthropogenic mortality scenarios;
- interpreting the results of this analysis in the context of offshore wind impact assessment; i.e. how “wrong” can the predictions be when assuming closed populations, and what are the implications of this error for consent decisions, and for the scale of compensatory measures that is required?

2.4 Objective 3: Modelling source and sink dynamics (Model 3)

Within the focal region, which colonies are operating as “source” and “sink” populations? A third objective is to explore the wider meta-population processes and mechanisms maintaining population size of both single colonies and the wider colony network, by modelling source and sink population dynamics.

This includes:

- building and parameterising a meta-population dynamic model for kittiwake colonies likely to be connected by dispersal events;
- estimating demographic rates for different colonies within the network, and evaluating the relative contribution of these to population growth rate,
- evaluating directional patterns of movements between colonies;
- identifying which colonies act as “source” and “sink” within the wider population network.

2.5 Objective 4: Identifying key demographic data gaps

Which data gaps create the most uncertainty in model outputs? A fourth objective is to identify demographic data needs that will improve confidence when predicting the strength of connectivity (Model 1), population trajectories (Model 2) and population growth rates (Model 3).

This includes:

- performing sensitivity analyses on some components of Models 1, 2 and 3;
- identifying which new empirical data will help the most with reducing uncertainty in estimates of connectivity, predicted vulnerability to OWF mortality and population growth rates;
- producing recommendations to inform the collection of new empirical data.

2.6 FOLLOW-ON WORK: Improving confidence in model predictions through adaptive management

Once key demographic gaps have been identified (Objective 4), it will then be possible to refine and improve model predictions (Model 1, 2, 3) by incorporating new empirical data on those key demographic rates once they become available. **Note that this work is a long-term aspiration and is not included in this SoW**, as its realisation depends on the completion of projects outside the scope of this work.

This work would typically include:

- obtaining new demographic information either by undertaking targeted empirical data collection as informed by Objective 4 or making use of the outputs of relevant kittiwake demographic population projects (e.g. colour-ringing, telemetry, modelling of population dynamics), and
- re-running Models 1-3 with new demographic data to generate improved estimates of connectivity, population size and growth rates.

3 Detailed tasks

3.1 Objective 1: Estimating connectivity between kittiwake colonies (Model 1)

Key ecological questions are:

- Are focal colonies open to immigration/emigration?
- How frequently do individuals disperse between colonies?
- Where do individuals disperse to? Where do they disperse most/least frequently to?
- Do dispersing rates vary with distances to the nearest colonies?
- What is the spatial scale of the meta-population?

To derive estimates of the strength of connectivity between kittiwake colonies, it is proposed to develop a demographic model for kittiwake populations open to immigration/emigration and informed by empirical demographic and count data. The choice of the modelling approach will ultimately be dictated by data availability and structure as well as computational time, and full details of the model structure will be provided by the Contractor(s). However, some important considerations are described below.

3.1.1 Modelling framework

When modelling population dynamics, a common approach for estimating demographic rates is to use capture-mark-recapture models. However, these models are data hungry, and for kittiwake a substantial mark-recapture effort would need to be deployed to obtain precise estimates of immigration and emigration rates (O'Hanlon *et al.* 2021). Moreover, field data will inevitably be patchy, of various quality, scattered across a small number of colonies and coming from different datasets. Time-series of kittiwake demographic parameters or count data are also likely to be truncated or associated to various levels of measurement error.

Various statistical approaches have been developed to overcome these limitations. One of them is state-space models (SSMs). SSMs have become an increasingly popular tool for modelling complex animal population dynamics, particularly imperfect time series (e.g. Auger-Méthé *et al*. 2021). One of the great advantages of SSMs is that they can account for two important levels of variability: biological stochasticity and imprecision in the data collection methodology. Because observations of cliff nesting birds are often associated with large measurement errors, SSMs are a desirable tool to derive demographic information from time-series of kittiwake colony data (as done in Miller *et al*. 2019).

When single datasets alone do not allow for the robust estimation of critical demographic parameters, there are clear advantages of combining time-series of population count data with additional demographic models, as commonly done in Integrated Population Models (IPMs) (e.g. Riecke *et al*. 2019). For example, while annual kittiwake colony count data alone would not be good enough to estimate movements between colonies, IPMs would provide the means for making inferences about the strength of connectivity between colonies by exploiting information from modelled demographic processes.

Furthermore, allowing the model to reconstruct missing data will improve model parameterisation and hence the robustness of the model predictions. For example, when count and demographic rate data are missing for a colony, empirical estimates may be reconstructed using prior knowledge of the relationship among these parameters obtained from other colonies (Horswill *et al*. 2021).

Fitting these models may be done either within a classical likelihood-based or Bayesian framework. Consideration should be given to a Bayesian approach, as it would allow the integration of multiple datasets of varying structures and quality, including expert opinions, old monitoring data and demographic information from closely-related species, within a single unified framework.

3.1.2 Model covariates

The meta-population model is primarily intended to estimate the strength of connectivity between kittiwake colonies as a function of distance between colonies and the arrangement of the entire colony network. Given the potential relative importance of density-dependence in regulating kittiwake populations (e.g. Miller *et al*. 2019), it is highly desirable to account for density-dependence when modelling meta-population dynamics. Although this would increase biological realism, it would potentially also increase model complexity. In addition, it may also make sense to model connectivity rates across age classes. Ultimately, what can be achieved within this project will depend on data availability/quality and computational time, and this will be discussed with the Contractor(s) before the project starts (see also below a proposal for developing a pilot meta-population model).

3.1.3 Defining focal regions

When defining focal regions for modelling kittiwake meta-population dynamics, colonies where impacts of OWF on kittiwake populations are predicted to be highest will be prioritised. Meta-population regions will be defined using empirical knowledge of kittiwake inter-colony movements in North Sea regions (e.g. from telemetry and mark-recapture studies). As kittiwake movements from UK colonies are likely to extend over a wide spatial area (up to Norway), careful consideration should be given to the biological and ecological factors driving the spatial scale of movements (e.g. regional patterns of productivity, prey distribution). Defining the spatial extent of a region will be a compromise between ecological relevance and the number of possible connections between colonies. In addition, close consultation with offshore wind industry developers, SNCBs and kittiwake experts will be essential for defining and delineating focal colonies and regions that are relevant to both kittiwake ecology and OWF consenting.

3.1.4 Pilot meta-population modelling appraoch

Gathering empirical data to feed into a meta-population model is likely to constitute a substantial preliminary part of this work, especially if rolled out at large spatial scales. It may therefore be sensible to initiate this project by developing a pilot meta-population modelling approach on a relatively small geographic region with a few colonies, where demographic data on e.g. productivity and survival rates are available. This will allow testing and validating the proposed modelling framework, before increasing the spatial scale of the meta-population model at a later stage. When considering large regional scales, the Contractor(s) will need to bring clear solutions for approximating meta-population dynamics of very large networks.

3.1.5 Model validation

A crucial part of the modelling process is the validation of model outputs. While developing a theoretical meta-population model and deriving “some” estimates of demographic parameters may not be too computationally demanding, without a robust model validation process, there is a high risk that any model predictions are not realistic. Any model predictions should therefore be tested against empirical data (e.g. from mark-recapture or telemetry studies, or any other means). The Contractor(s) will need to explicitly detail their model validation approach, specifying what ecological datasets will be used and how, in order to ensure model predictions are realistic.

3.2 Objective 2: Predicting population responses to OWF predicted mortality in closed vs. open systems (Model 2)

A second objective of this Scope of Work is to evaluate the sensitivity of PVA models to the assumption of closed populations when modelling the impacts of predicted OWF mortality. For doing so, the information derived from modelling population dynamics under Obj.1 will be extracted and used as an input to PVA models for open populations. A range of plausible connectivity values would be used to develop a demographic model, and kittiwake populations would then be projected within a period of 25 years to reflect the operational timeframe of an OWF. Various anthropogenic mortality scenarios could be applied to the system, and their relative impacts on kittiwake population persistence would be assessed by comparing population trajectories between open and closed population systems (as done in Miller *et al*. 2019). The outputs of this modelling exercise would then need to be interpreted in the context of offshore wind impact assessments; i.e. how much do the predictions of both modelled systems differ and what does it mean for the OWF industry in terms of both consent risk, and requirements for compensatory measures and scale of such?

Key ecological questions are:

- Do open and closed populations differ in their projected trajectories?
- Does immigration help maintain population size despite predicted OWF mortality?
- Is there a threshold above which emigration rapidly exacerbates the risk of decline of a colony suffering from predicted OWF mortality?
- What immigration/emigration ratio is needed to maintain population size despite poor breeding success?
- Is there a threshold above which the negative effects of anthropogenic mortality cannot be compensated for by immigration?

Similarly to what was presented under Obj.1, a range of different modelling tools as well as data quality and availability issues should be considered, and the Contractor(s) would need to present detailed justification for using a particular modelling tool. In particular, consideration should be given to the development of a unified framework whereby the outputs of the demographic Model 1 (Obj.1) could easily by integrated into population projection models.

3.3 Objective 3: Modelling source-and-sink dynamics (Model 3)

Determining what role each colony may play in source-and-sink dynamics will depend on their relative contribution to the wider meta-population network, and this depends on productivity, survival and immigration/emigration rates. A colony/population can be defined as operating as a source if it is self-sustaining (e.g. high productivity or survival rate) in the absence of immigration, while a sink colony/population depends on immigration for its growth.

Key ecological questions are:

- How do different colonies differ in their demographic rates and intrinsic population growth rates?
- Are SPA colonies that are currently presenting a high consent risk for offshore wind development, acting as source or sink?
- If these colonies are acting as sink, can we identify source colonies and what would happen if these source colonies stopped exporting birds?
- Can we identify source colonies within the network where compensatory measures are likely to be most effective?
- Does the source/sink status of colonies change over time, e.g. due to changes in local conditions?

Some key features of the meta-population model to be developed to answer these questions will need to be considered, for example:

- Spatial scale of the meta-population network; i.e. number of colonies and distance range from focal colony(ies) (this would be a compromise between biological relevance and computational time);
- Availability and quality of demographic rate data to model spatial variation between colonies and population growth as a function of productivity, survival and immigration/emigration rates.

3.4 Objective 4: Identifying key demographic data gaps

Model outputs will be associated with a level of uncertainty. It is proposed to use sensitivity analyses to identify where new empirical data may help the most with improving confidence in model outputs. For example, it will be possible to extract and quantify the amount of uncertainty around outputs parameters, such as the strength of connectivity between colonies, predicted change in population size or population growth rate. It would then be envisaged to identify the input parameters that have greatest influence over outputs; e.g. what is the increase in output parameters' (e.g. estimates of connectivity) precision/confidence from a reduction in variance in a given input parameter (e.g. adult survival, productivity). The outputs of sensitivity analyses will inform targeted data collection that will lead to better understanding of connectivity, population change and population growth rate.

3.5 FOLLOW-ON WORK: Improving confidence in model predictions through adaptive management

The idea here is to make use of the outputs of other kittiwake population dynamic projects to update the models developed under Objectives 1–3 and then refine model predictions. This would include projects that target demographic data with the greatest potential for reducing uncertainty around model outputs. For instance, more accurate estimates of adult survival could improve confidence in predictions of connectivity between populations. Some of the demographic data could be delivered through a mark-recapture study (e.g. colour-ringing at many colonies) and a component of this work may include deploying or making use of more recapture effort at certain colonies to improve recapture rate, leading to more precise estimates of survival rates. The new empirical data could be used to parameterise Models 1–3 and run new iterations of the models. This may then lead to reduced uncertainties in the relative importance of connectivity in determining population size and growth at a colony.

4 Outputs

The Contractor(s) will produce a detailed report that includes the following:

- Objective 1:
    - detailed justification of the choice of focal colonies and regions to be modelled;
    - detailed description of the modelling approach developed, including hypotheses tested, model structure and assumptions, model selection and validation processes, model parameter outputs with associated uncertainty, and analysis scripts;
    - review of empirical colony data to be used to parameterise the model and validate model outputs;
    - quantification of the strength of connectivity between kittiwake colonies;
    - spatially-explicit summary figure highlighting where inter-colony movements are predicted to occur, with an indication of relative strength.
- Objective 2:
    - detailed description of PVAs, including hypotheses tested, model structure and assumptions, nature and quality of empirical input data, model selection and

    - validation processes, model parameter outputs with associated uncertainty, and analysis scripts;
    - population trajectories of closed kittiwake populations given various scenarios of anthropogenic mortality;
    - population trajectories of open kittiwake populations given various scenarios of connectivity and anthropogenic mortality,
    - quantitative evaluation of the relative contribution of immigration and emigration to population persistence given various scenarios of connectivity and anthropogenic mortality (ideally presented as a matrix of model outputs);
    - discussion of the implications of the findings in the context of current impact assessment modelling approaches.

- Objective 3:
    - detailed description of meta-population model, including hypotheses tested, model structure and assumptions, nature and quality of empirical input data, model selection and validation processes, model parameter outputs with associated uncertainty, and analysis scripts;
    - quantification of key demographic parameters and population growth rates of a network of colonies;
    - evaluation of the contribution of immigration and emigration rates to population growth, and identification of source/sink status of colonies within the network, and
    - map identifying colonies where conservation measures are likely to be most effective.

- Objective 4:
    - detailed description of sensitivity analyses, including hypotheses tested, parameter value manipulation and model parameter outputs with associated levels of uncertainty;
    - list of key data gaps, ranked from high to low relative contribution to uncertainty in key model outputs;
    - guidelines for developing an approach to address key data gaps and improve confidence in model predictions.

A draft report will be submitted to the Project Team and Funders towards the completion of the project. Additional presentations and updates will be given throughout the course of the project, typically following completion of major milestones to allow for any emerging issues to be addressed promptly.

5 Timescale

An indicative timeline of work is provided below, and the Contractor(s) should provide a detailed Gantt chart, showing how long each objective will take to deliver and when delivery will take place.

- **Objectives 1–2**: 6 to 12 months to deliver. Time required to complete the modelling work would strongly depend on the overall remit and the size of the meta-population network modelled. Below are two scenarios:

    - ***Pilot modelling work*** - Development of a kittiwake demographic model, estimate connectivity and generate predictions of population viability for given mortality rates: **6 months** to deliver for a **region the size of north-east England**. This includes script writing and debugging, data cleaning and estimating colony-colony distances (about 3 weeks) as well as running models to satisfactory diagnostics (about one month) and running PVA simulations or doing further exploratory work (about 2 months). These estimations depend on the size of the region as well as the number of colonies included. Defining the spatial extent of a region will be a compromise between ecological relevance and the number of possible connections between colonies.
    - ***Rolling out*** - Application of meta-population model to the **wider UK network**: **12 months** to deliver. This is more open-ended and at least 2–3 months of work would be needed to develop the approach. Running times may go into weeks or months, but these only push the delivery time back, not increase the costs of the project.
- **Objective 3**: 6 months to deliver. Note that the overall time to complete Objectives 1–3 may be reduced if a unified modelling framework is developed, allowing for example to estimate different parameters using the same model structure. This needs to be discussed with the Contractor(s) prior to project start.

- **Objective 4**: 2 months to deliver (but potentially highly variable depending on model complexity).

Objective 5, if undertaken, should be delivered under a separate timetable as it has dependencies beyond the scope of work under this contract.

6 Contractor requirements

The Contractor(s) would need to demonstrate the following expertise and experience:

- excellent knowledge of black-legged kittiwake ecology and population dynamics (with experience in collecting colony data in the field desirable);
- strong quantitative analytical skills, with expertise in modelling complex population and meta-population dynamic systems (e.g. Hierarchical State-Space Models, Integrated Population Models, Bayesian inference);
- good understanding of the interactions between OWFs and seabird populations;
- good understanding of OWF impact assessments;
- previous experience with delivering similar work.

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