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Towards better estimates of Manx shearwater and European storm-petrel population abundance and trends, demographic rates and at-sea distribution and behaviour

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Summary

This report presents a summary of existing evidence, and potential research opportunities, to improve the estimates of population abundance and trends, demographic parameters and at-sea distribution and behaviour for Manx shearwater (*Puffinus puffinus)* and European storm-petrel (*Hydrobates pelagicus*). This work has been undertaken on behalf of the Offshore Wind Strategic Monitoring and Research Forum (OWSMRF) (https://jncc.gov.uk/our-work/owsmrf/). OWSMRF is an industry-led collaborative forum that aims to identify and develop research to fill critical knowledge gaps in our understanding of the impact of offshore wind development on the marine environment.

OWSMRF stakeholders identified baseline data for Procellariiformes as the priority need for improving understanding of offshore windfarm environmental impacts, with the focus on Manx shearwater and European storm-petrel. Improving understanding of population, demographic and distribution parameters were identified as the key knowledge gaps in this area. JNCC has collaborated with experts in this field to provide a summary of potential research which might help to reduce uncertainty in these estimates. This report provides a summary of existing relevant research and evidence, and research opportunities that have been identified to help reduce uncertainty. This report follows on from the Pilot Year Knowledge Gaps (KG1, KG2 and KG3), hence these research opportunities (ROs) are numbered from four.

The ROs suggested as potentially very useful and presented in this report are listed below, ordered by topic; population abundance and trends estimates, demographic rates and at-sea distribution and behaviour. Most of them would need to be undertaken in stages and are structured as sub-ROs.

RO 4.1: Carry out a strategic review of the current knowledge and research on population estimates and demographic rates for Manx shearwaters and European storm-petrels:

- RO 4.1a Strategic review of historic and ongoing population and demographic rate monitoring.
- RO 4.1b Gap analysis to identify specific locations or topics to focus future research on, for example identifying new sites for monitoring.
- RO 4.1c Conduct a power analysis to ascertain the monitoring requirements to collect robust data efficiently, for example the sample sizes and length of studies required.

RO 4.2: Understand and reduce sources of uncertainty in breeding abundance estimates, with direct comparison of abundance estimates produced by sample plot and whole colony counts:

- RO 4.2a Review of current available population abundance estimates data to identify factors potentially introducing uncertainty in abundance estimates.
- RO 4.2b Assessment of the relative contribution of variables identified in RO 4.2a to error/uncertainty in population abundance estimates.
- RO 4.2c Direct comparison between sample plot and whole area/colony counts at a selected colony.
- RO 4.2d Review of field techniques for burrow monitoring and development of best practice guidelines.

RO 4.3: Improve estimates of response rate in playback surveys:

- RO 4.3a Identify the key sources of error in tape playback calibration work, and review alternative methods for calculating response rate, such as hierarchical modelling techniques.
- RO 4.3b Investigation of use of hierarchical modelling techniques to predict population abundance in un-surveyed areas.

RO 4.4: Investigation into the suitability and applications of acoustic monitoring, particularly their utility in monitoring at remote/inaccessible locations where traditional census monitoring may be logistically difficult:

- RO 4.4a literature review to examine the utility and limitations of acoustic monitoring and any complementary technology/methods for analysis. This review should also include investigation and comparison with alternative techniques such as thermal imaging.
- RO 4.4b Dependant on the outcomes of RO 4.4a, establish a methodology/sampling strategy for either identification and assessment of colony extent, or colony density and ability to estimate abundance.
- RO 4.4c Field test to assess the ability to deploy in remote locations and investigate the limitations of the technology. A field test should also act as a calibration alongside other monitoring methods.
- RO 4.4d Based on the outcome of 4.4b and 4.4c, deployment to remote colonies where traditional monitoring is very difficult or not possible.

RO 4.5: Development of Species Distribution Models (SDMs) to predict suitable colony locations:

- RO 4.5a Review of terrestrial and at-sea variables that may predict Manx shearwater and European storm-petrel distribution.
- RO 4.5b Apply “Häkkinen model” to known Manx shearwater and European storm-petrel colonies to test data sufficiency and the ability of the model to predict potential colonies.
- RO 4.5c Apply SDMs, using terrestrial and marine variables, to Manx shearwater and European storm-petrel to predict potential currently unidentified colonies.
- RO 4.5d Validation of model predictions.

RO 4.6: Apply habitat models to assess extent and distribution of suitable habitat within accessible colonies to increase efficiency of survey effort:

- RO 4.6a Obtaining or conducting habitat mapping using high resolution imagery, ground-truthed using habitat surveys/dogs.
- RO 4.6b Apply “Arneill model” using habitat mapping produced in RO 4.5a to islands where access is very difficult to assess extent of suitable habitat, potentially predict population, and allow direction of survey effort to reduce time required/staff needed for surveys.
- RO 4.6c Validation of models.

RO 4.7: Explore the use of trained scent-detection dogs to explore/characterise new colonies:

- RO 4.7a Training of scent-detection dogs to recognise seabird scents and to be able to differentiate between species.
- RO 4.7b Conduct a trial to validate the dog’s detection ability.

- RO 4.7c Use of dogs to identify new colonies or survey existing colonies.

RO 4.8: Expansion of annual monitoring, where this is found to be required (from previous ROs):

- RO 4.8a Feasibility review to estimate resources required to establish new sites or enhance existing ones.
- RO 4.8b Roll out of census monitoring to multiple colonies and over multiple years.

RO 4.9: Improving estimates of Manx shearwater adult survival through use of existing data and roll-out of survival monitoring to additional colonies:

- RO 4.9a Review of existing data for colonies to assess the demographic influences on survival and recapture probability.
- RO 4.9b Use modelling methods as set out by Wood *et al.* (2021) to undertake modelling of available data.

RO 4.10: Improving confidence in Manx shearwater productivity estimates using existing data and roll-out of monitoring to additional colonies:

- RO 4.10a Using a site where Manx shearwaters are well understood (e.g. Skomer) as a pilot, use high-resolution vegetation/topography mapping to identify potential areas for new study plots, which will allow comparison of productivity across different habitat types.
- RO 4.10b Design a sampling strategy and establish new study plots in a variety of different habitat types across a sample island, such as Skomer as described in RO 4.9a.
- RO 4.10c Analysis of productivity between study plots to establish the degree to which productivity varies with habitat and hence representativeness of existing study plots.
- RO 4.10d Based on the outcomes of sub-ROs a-c, this stage would see the roll-out of additional study plots to other sites if habitat is shown to significantly affect productivity and there is a need to review study plots at other sites for their representativeness.

RO 4.11: Improving confidence in juvenile survival estimates of Manx shearwaters through collation of existing data, exploring the feasibility of analytical methods and potential new analysis.

- RO 4.11a Collation of existing data and feasibility review of analytical methods.
- RO 4.11b Analysis of juvenile survival data.

RO 4.12: Investigating the assessment of rate of sabbaticals, mature birds not undertaking breeding in a given year, in Manx shearwaters and storm-petrels. As very little is currently understood this would be largely exploratory RO, assessing potential sources of existing data, analysis, and recommendations for future data collection.

RO 4.13: Conduct a review of existing at-sea distribution data and carry out a gap analysis to identify research needs to direct future monitoring effort.

- RO4.13a Review of tracking data and Special Protection Area colonies (SPA, possibly also non-SPA) within foraging range of OWFs.
- RO4.13b Gap analysis to determine suitable strategic locations for geographic expansion of monitoring.

RO 4.14: Produce gap-free at-sea distribution maps for Manx shearwater and European storm-petrel by collating existing information, mapping distribution (including behavioural states/diurnally and nocturnally where possible) and identifying gaps to direct future work:

- RO 4.14a Feasibility review.
- RO 4.14b Produce behavioural distribution maps.
- RO 4.14c Longer-term incorporation of additional colonies as data become available.

RO 4.15: Identify the change in at-sea distribution over time. This project would be based on long-term datasets and, where these are available, further analysis will assess spatial and temporal variation.

RO 4.16: Better understanding of resource partitioning between breeding adults/non-breeding adults/immatures through assessment/analysis of existing data and expanded tracking of non-breeding birds.

RO 4.17: Explore the use of foraging radius models as an alternative to tracking data to improve understanding of distribution for colonies where tracking data are unavailable or not possible:

- RO 4.17a Identify colonies with sufficient dual-foraging strategy tracks for Manx shearwater.
- RO 4.17b Carry out assessment of foraging radius models.
- RO 4.17c Expand modelling approach to data-poor colonies/regions.

RO 4.18: Apportioning of seabirds-at sea to colonies using tracking data through review/improvement of existing methods:

- RO 4.18a Review of apportioning methodologies.
- RO 4.18b Amended/new apportioning methodology for Manx shearwater and European storm-petrel.

Contents

1. Overall introduction

In order to meet the ambitious climate targets set by the UK Government, designed to reduce greenhouse gas emissions by 78% by 2035 and achieve Net Zero by 2050, offshore wind farm (OWF) development will need to be deployed at a large scale. The ambition to increase capacity of offshore wind energy to 50 gigawatts (GW) by 2030 (HM Government 2022) has been bolstered by the initiation of Offshore Wind Leasing Round 4 in England, Celtic Seas in Wales and ScotWind. Such climate change mitigation will have the added benefit of addressing a main driver of biodiversity loss.

Future offshore wind (OW) development is dependent on consent, which is underpinned by impact assessments. We currently have a limited understanding of the effects of OW development on marine wildlife, particularly seabirds. This is particularly true for protected birds, as there are a number of ways in which wind farms can potentially negatively impact seabirds at a population level (Drewitt & Langston 2006; Gibson *et al.* 2017). To inform the planning process of the potential impacts of the effects associated with wind farms, detailed Environmental Impact Assessments (EIAs) and Habitats Regulations Appraisal (HRA) are required. 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 Regulations (Amendment) (EU Exit) 2019 and The Conservation of Offshore Marine Habitats and Species Regulations 2017 (as amended).

Numbers of renewable energy developments, both offshore and onshore, are increasing globally and their potential impacts will continue to receive growing scrutiny. The cumulative effects of multiple developments, in addition to existing anthropogenic activities, have the potential to exert unacceptable pressure on seabird populations. In this case, the bird populations we are considering in this report have the potential to pose a significant consenting risk to developments, but at this stage this risk is linked to substantial gaps in our knowledge of even basic aspects of seabird ecology and behaviour for some species.

The potential impacts of OW developments on seabird species can only be measured if the effects can be assessed against population trends and be resolved in terms of additional mortality or impacts on productivity. The potential impacts of OW developments on seabirds can be broadly split into three categories: collision; displacement and/or attraction; and barrier effects (e.g. Cook *et al.* 2018; Vanermen *et al.* 2015). The assessment process seeks to identify and estimate the likely effects of a wind farm on seabird populations. Once the magnitude of these effects has been estimated, it is necessary to understand which SPA colonies (if any) these affected birds originate from, to be able to assess the impact of these effects (for HRA purposes) and/or which wider population these affected birds are part of (for EIA assessments). Finally, population modelling is frequently used to evaluate the likely population response to reductions in survival or productivity predicted to occur once the scale of effect and population linkages have been established (Cook *et al.* 2018).

Uncertainty around input parameters can be due to either high levels of natural variation (stochastic uncertainty) or due to lack of information (systematic uncertainty). In both cases, additional information can either reduce uncertainty (systematic uncertainty) and/or improve understanding of causes of natural variation and provide data for further refinement of parameters (for example, if data show that productivity is particularly low at some colonies the impacts of displacement from foraging areas by OWF may be more significant for that colony which will impact consenting).

It is therefore important to have basic information on seabird species of interest, such as accurate population and demographic rate estimates and a good understanding of their distribution and ecology. In addition to providing the justification for site designation and conservation objective setting, population data and the trends over time are vital baselines for screening and detailed assessments as part of an HRA. An understanding of a species' at-sea distribution and density will inform the assessment of the impact of an OW development, it can demonstrate the relative importance of a specific area within a marine SPA or OWF footprint and highlight connectivity to SPA colonies by identifying key foraging, roosting, or commuting hotspots. If further assessment is required, that may be conducted through population modelling (for example Population Viability Analysis, PVA), for which demographic data such as adult and juvenile survival rates, productivity, and age of first breeding are required.

1.1. OWSMRF background

The Offshore Wind Strategic Monitoring and Research Forum (OWSMRF) is an industry-led collaborative forum that aims to identify and develop research to fill critical knowledge gaps in our understanding of the impact of offshore wind development on the marine environment. OWSMRF was initiated by JNCC and six offshore wind developers who oversaw the Pilot Year between May 2019 and April 2020. Building on the success of the Pilot Year, the second phase of OWSMRF started in April 2021 and will run until April 2023. JNCC will continue in its secretariat role alongside the original developers: EDF Renewables, Equinor, Ørsted, RWE (originally Innogy) and Scottish Power Renewables, and new developers to the forum: Shell and SSE Renewables (Scottish and Southern Electricity), who together form the Developer Group (DG).

During the Pilot Year, the focus was on ornithological issues, which will remain the focus of the continuation. A workshop was held in July 2021 with the OWSMRF DG and Key Stakeholders to identify the species and knowledge gaps that may lead to the greatest uncertainty in current and future impact assessments for offshore wind developments

1.2. The OWSMRF process

OWSMRF uses a collaborative process to identify knowledge gaps and research opportunities to fill those gaps. The process involves consulting OWSMRF Key Stakeholders (Department of Agriculture, Environment and Rural Affairs (DAERA-NI), Natural England (NE), Natural Resources Wales (NRW), NatureScot (NS), Marine Scotland Science (MSS), and Royal Society for the Protection of Birds (RSPB)) on what species and knowledge gaps pose greatest consenting risk to OW development in the near future. Following a review of what is already known about the species and evidence base, academics and other experts are invited to suggest research that would address those knowledge gaps. Key Stakeholders are then invited to review the proposed research opportunities, providing feedback on which they see as most beneficial, before finally selected Research Opportunities (RO) are developed into Scopes of Work. The DG, who are funding OWSMRF, agree and provide a clear position to JNCC on what work OWSMRF should do, comment on draft OWSMRF products and are given opportunity to engage throughout the whole OWSMRF process. Throughout the continuation, JNCC will also undertake a Research Development and Promotion Role which will include a variety of tasks, including identifying project partners and collaborators, building project teams, and facilitating the progression of high-level academic ideas into feasible research projects that can be delivered.

1.2.1. OWSMRF Continuation

At a workshop on 14 July 2021, OWSMRF Key Stakeholders agreed that black-legged kittiwake (*Rissa tridactyla*), the focus of the Pilot Year, was still a key area of uncertainty but that there were unlikely to be any “new” ROs to be identified (see reports available through the OWSMRF webpage). In addition to identifying new Knowledge Gaps (KGs), through the continuation JNCC will also perform a promotional role to endorse the ROs identified during the Pilot Year. Procellariiformes, particularly Manx shearwater (*Puffinus puffinus*), European storm-petrel (*Hydrobates pelagicus*) and Leach's storm-petrel (*Hydrobates leucorhous*) were agreed as species which convey significant uncertainty, with particular concern around new developments (ScotWind/Round 4) and floating wind.

Two priority Knowledge Gaps to inform offshore wind farm assessments were identified:

- KG4: reducing uncertainty around estimates of Procellariiformes abundance, demographic rates and distribution.
- KG5: improving understanding of the impact pathways affecting Procellariiformes as a consequence of OWF.

Concurrently, Marine Scotland Science (MSS) are undertaking a project, "Study to examine the risk of collision and displacement in petrels and shearwaters from offshore wind developments in Scotland", looking at the above species as core focus (with a synopsis on two further Procellariiformes, sooty shearwater (*Ardenna grisea*) and northern fulmar (*Fulmarus glacialis*)) in a Scottish context and with a particular focus on the Sectoral Marine Plan, Plan Options. The MSS project will attempt to review the current evidence base, identify gaps, and make recommendations in the following areas:

- Species accounts
    - General Population Ecology
    - Risks from collision, displacement, and lighting attraction
- Examination of challenges and recommendations for assessing the impacts of offshore windfarms, particularly in reference to the Sectoral Marine Plan Options (e.g. determining baseline density and distribution)
- Remaining evidence gaps

To prevent duplication and effective use of resources, OWSMRF KG4 will focus on building on existing knowledge and expertise around strategic monitoring, to develop specific Research Opportunities in this topic area, with a UK-wide focus on Manx shearwater and European storm-petrel. Leach's storm-petrel will not be in scope for this phase of OWSMRF work, given its Scottish distribution. MSS will take more of a Scottish focus, looking at the impact pathways of OWFs, including potential attraction to lights and collision risk which will be relevant across the UK. While making recommendations for research, developing ROs will not form part of the MSS project and therefore after completion of both projects, knowledge and outcomes will be shared so that OWSMRF KG5 can identify and develop specific ROs around impact pathways.

1.2.2 Strategic monitoring of Manx shearwater and European storm-petrels

The first Knowledge Gap of the OWSMRF Continuation (KG4) seeks to improve our understanding around some of the basic parameters of abundance, distribution, productivity, and survival of two procellarid species that are of significant conservation concern in the UK. Manx shearwaters are of great importance in the UK as nearly 80% of the world population (~300,000 breeding pairs) breed here each year (although this estimate is based on a previous census and more recent counts (2018) put Wales's population at 500,000 pairs alone; Mitchell *et al.* 2004; Perrins *et al.* 2020). The UK has a lower but not insignificant proportion of the global European storm-petrel breeding population, holding 5% of the breeding population (~25,000 pairs) (Mitchell *et al.* 2004). This estimate may increase following Seabirds Count (2015–2021), the most thorough census of this species to date, and more breeding colonies are still being identified (e.g. Isle of May).

Manx shearwaters and storm-petrels are coming into focus for OW now as the scale and speed of development is increasing, particularly in areas that overlap with the known distribution of these species. With the focus of previous OWF development on the east coast of the UK and in the North Sea, the likely impact on these species has not thus far been significant. However, a general lack of knowledge about some basic aspects of their ecology, poor understanding of the potential impacts from OWF, and the planned expansion of OWF capacity in areas overlapping with their known distribution, has led to them being considered a high priority for future research.

To make assessments about the potential impacts of OWFs on these species, we need to be able to answer questions such as:

- What is the vulnerability of their populations to OWF impacts?
- Do their at-sea distributions overlap with future OW development areas?
- How are they likely to interact?

To answer these questions, a certain level of knowledge is required, including baseline data on their abundance, population trends and at-sea distribution. To then make further assessments, an understanding of broad-scale behaviour (i.e. is an OWF array within an area used by birds for foraging, commuting, or resting?) is helpful to understand potential vulnerabilities. An assessment of the population consequences of impacts is likely to include the use of population modelling, in which case predictions of population persistence, requires reliable estimates of demographic rates, particularly productivity, adult survival, juvenile survival and age at first breeding.

In the short-term, issues such as distribution and at-sea behaviour from certain colonies could be addressed using Global Positioning System (GPS) tracking data, with, for example, nearly two decades of Manx shearwater tracking from Skomer Island as well as data from five other colonies within the Celtic/Irish Seas (Guilford *et al.* 2008; Dean *et al.* 2015). There is also the potential to use environmental variables to predict at-sea distributions. Interim adult and juvenile survival rates may be better estimated using existing data, while further refining demographic rates, as well as improving our understanding of population dynamics, refining population estimates and productivity measures are longer-term aims.

This review aims to identify and provide details on key Research Opportunities that will aim to improve our understanding of the key Knowledge Gap, KG4. It follows on from previous evidence reviews, such as those conducted through the Offshore Wind Evidence and Change Programme (OWEC) and the Offshore Wind Environmental Evidence Register (OWEER), which have already been through a thorough review and prioritisation process. These have highlighted priority evidence needs around abundance data, demographic rates, and at-sea distribution for all seabirds (TCE 2022). This report takes direction from ongoing work such as the Seabird Monitoring Programme (SMP), the current census plan and ongoing tracking that has been established for Manx shearwater and to a lesser extent European storm-petrel across multiple colonies.

This was completed by conducting a thorough review of the existing knowledge and evidence, identifying the gaps, and seeking the input of key stakeholders and experts in the field to provide realistic and appropriate solutions and approaches to fill the gaps.

Throughout the OWSMRF process, input has been sought from stakeholders. In addition to the Key Stakeholders, the advice of specialists and academics in the field was sought. This included expertise from the University of Oxford, Wildlife Trust for South and West Wales, MacArthur Green, RSPB, Cardiff University, University College London, Bardsey Island, University of Exeter and University of Gloucestershire. This consortium held a (remote) workshop (31 January 2022) in order to identify projects and research opportunities, that could be carried out in order to address some of the uncertainties associated with estimating population abundance and trends, key demographic rates, and at-sea distributions and behaviours of Manx shearwater and European storm-petrel. The outcomes of the workshop, including Research Opportunities, are presented in this report, on which comments were sought from stakeholders prior to publication.

This report is formed of five main sections: an introduction; an exploration of knowledge gaps; existing evidence and understanding; gaps in understanding; and potential research opportunities. This structure has been adopted to set out how and why ROs were identified and defined during the OWSMRF process, where evidence is lacking and what can be done to improve understanding.

In each section, both Manx shearwaters and European storm-petrels will be addressed in turn with respect to the three research areas we focussed on, “Population abundance and trend estimates”, “Demographic rates”, and “At-sea distribution and behaviour”. Section 2 – Knowledge Gaps – sets out what is unknown in the context of OW for each of the three research areas and why improvements in empirical data are vital. Section 3 outlines what is currently known, including the methods of data collection/analysis, the geographic and temporal distribution of evidence and potential for new methods. Section 4 explores the gaps in understanding for each research area and species, sets the scene in the context of OW development and summarises the topics covered in the previous sections. Section 5 outlines the ROs identified as priority areas for future work and direction of resources; each RO contains a rationale, summary of work underway and work required, benefits, risks, and an estimation of resources requirements.

2. Knowledge Gaps

2.1. Population abundance and trend estimates

Consistent monitoring across multiple colonies is important for estimating overall seabird population size and trends, understanding site-specific factors, and improving confidence in impact assessments. Underlying population trends at national, regional and colony scales are also important variables within PVA and determination of population consequences of offshore windfarm impact.

Seabirds Count, the latest breeding seabird census had good coverage of UK *Procellariiform* breeding colonies. However, previous censuses had less complete coverage. For example, Seabird Colony Register and Operation Seafarer broadly guessed at colony locations for European storm-petrel, while Manx shearwater populations were based solely on order of magnitude estimates. Therefore, neither censuses can be compared to estimates from Seabird 2000, which were significantly more thorough and accurate (see Section 3.1) (JNCC 2021a and 2021b). The frequency of national censuses is between 15 and 19 years (JNCC 2021c):

- Operation Seafarer 1969–1970
- Seabird Colony Register Census 1985–1988
- Seabird 2000
- Seabirds Count 2015-2021

The lack of substantial data on both species is a consequence of their life history (they breed on islands, nest in burrows and are nocturnal). However, long-term monitoring at colonies such as Skomer, Skokholm, Bardsey, Rum, Canna, Sanday and Lundy (Manx shearwater), and Mousa, Treshnish Isles, Skokholm, Skomer and Lundy (European storm-petrel) demonstrate that monitoring is possible. Lundy, Skomer and Skokholm are surveyed annually for Manx shearwater to provide an estimate of population trends; however, these surveys are conducted in small plots relative to island size (e.g. Skokholm study plot 8,000 m^3). These sites are probably the more accessible of the UK colonies, and extension of monitoring effort of more remote sites would be logistically more difficult, time consuming and inherently expensive.

However, increasing the temporal resolution of *Procellariiform* census (possibly on a subset of colonies) has the potential to improve understanding of population trends at different geographic scales, and to determine any colony/regional differences.

Current census monitoring techniques also introduce uncertainty in their abundance estimates, for example through uncertainties and variability of response to call play-back and assumptions about occupancy of different habitat types. These lead to potentially large confidence intervals around abundance estimates when extrapolating out to whole-colony estimates. There have been steady improvements to methods for both data collection and analysis (for example use of dual play-back, and accounting for sources of error such as response rate when analysing data (Perkins *et al.* 2017)). These improvements have led to wider confidence intervals, but this is the result of more realistic and robust results where the actual population number is likely to be closer to the estimate. While it is felt by practitioners that the population abundance estimates are now the best available, there is still the potential to reduce uncertainties around these estimates and temporal trends derived from them, through methodological and analytical improvements.

Total population numbers, colony size and population trends are fundamental baselines against which impact is assessed. Uncertainty in these estimates will lead to the continued use of precaution when assessing impact.

2.2. Demographic rates

The most widely recognised definition of the precautionary principle is contained in Principle 15 of the 1992 Rio Declaration (United Nations 1992):

“In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation.”

In essence, the principal guides decision-makers to take action to protect the environment, safety, and public health when there is scientific uncertainty. Where there is uncertainty in an outcome, an appropriate level of precaution should be applied in planning.

Legislation requires assessment of the potential environmental impact of an OWF development prior to consent. For SPAs where a Likely Significant Effect (LSE) cannot be ruled out, a more detailed assessment of the population consequences of a predicted impact is required.

Sanderson (2006) stated:

> “Because the demographics of populations have been long studied by ecologists and are amenable to mathematical modelling, a family of related tools, under the name population viability analysis (PVA), has been developed to model the future sustainability of populations.”

Such models are now the standard basis for predicting the population consequences of impacts, such as estimated collision mortality. PVA (different types include matrix approach and fitting count data) is commonly used in impact assessments, and uses the demographic rates of a given population to generate projections of the future scenarios of population growth and decline, and then predictions of impact (often direct mortality from collision, but also indirect from displacement). In the case of impact assessments for OWF, these are predictions of the trajectory of a population of interest under the predicted impact as a consequence of that OWF, compared to the prediction for the population if it were to remain unimpacted. High-quality demographic rate data are important for reducing uncertainty in making predictions. This uncertainty, along with data quality, underlying trends, pressures, and the level of impact contribute to the level of precaution applied in consenting conditions.

However, the demographic rates required as inputs to population modelling are not always well defined either in accuracy or confidence (e.g. Cook & Robinson 2016). Horswill and Robinson (2015) highlighted that at the time of their study, it was unclear how many UK seabird species had sufficient data to support the development of species-specific models. That study collated the published estimates of demographic rates for the 32 seabird and sea-duck species thought to be most vulnerable to offshore renewable developments in the UK. It forms the current best available evidence for demographic rates of seabirds in the UK, but it should be noted that there are weaknesses in the estimates for shearwaters and storm-petrel species (as well as other species particularly when it comes to juvenile rates). The review does not make recommendations for either European or Leach’s storm-petrel, and while there are recommended rates for Manx shearwater, they are derived from a limited number of studies and breeding colonies:

- Adult survival derived from two colonies (Skomer and Skokholm);
- Juvenile survival derived from one colony (Skokholm);
- Productivity: Productivity derived from colonies (Bardsey, Canna, Rum, Sanda, Skomer, Skokholm);
- Incidences of non-breeding from one colony (Skokholm); and
- Age of recruitment from two studies in one colony (Skokholm).

Therefore, except for productivity, all demographic rates are derived from the Welsh breeding population, and of those, all except adult survival are derived from a single colony (Skokholm).

In addition, data quality and representation are of variable confidence for the above parameters, with high confidence in data quality for adult survival and productivity, but medium or low (or no) confidence in data quality for other parameters, and data representation for all parameters (see Horswill & Robinson 2015: Supporting Information). The NE PVA Tool does not parameterise any of the three species and is therefore not available to estimate the population consequences of impact.

Cook *et al.* (2019) states:

> "It is also unknown whether existing monitoring of seabird populations at a colony level has sufficient statistical power to detect changes of the magnitudes predicted in response to the effects associated with offshore wind farms".

Cook *et al*. (2019)'s study only examined those SPA colonies identified at the time where Adverse Effects on Site Integrity (AEoSI) could not be ruled out as a consequence of impact from OWF (i.e. Welsh colonies). In addition, Cook and Robinson (2016) examined the sensitivity of PVA metrics to uncertainties in demographic parameter estimates. Of the demographic parameters considered (adult survival, first-year survival, immature survival, and productivity), all metrics were most sensitive to misspecification of adult survival, even after accounting for adult survival being generally easier to estimate, and realistic ranges of uncertainty in demographic parameter estimates. Taken with the results of Horswill and Robinson (2015), there is scope for improvement of demographic rate estimations at UK and regional scales, which would lead to improvements of the population-level impacts of OWFs on shearwaters and petrels.

2.3. At-sea distribution and behaviour

Assessing the distribution and behaviour of Procellariiformes at sea is vital as it allows us to understand where they are foraging, the key commuting routes between colonies and foraging grounds and the areas that are important for key maintenance behaviours such as rafting or loafing and preening. All of this information is key to the identification of important hotspots of activity and is vital in assessing the connectivity between Offshore Wind (OW) footprints and colonies when considering potential impacts such as collision and displacement. For Procellariform species, in this case Manx shearwater and European storm-petrel, this is of increasing importance following the progression of OW in Round 4, ScotWind and floating wind that are likely to increase the interaction between these species and developments.

The distribution of Manx shearwaters and European storm-petrels may be difficult to quantify by traditional at-sea survey methods (boat-based or digital aerial survey) as a proportion of their activity is nocturnal, and distribution will vary considerably between night and day. Current evidence from tracking studies suggests that Manx shearwater foraging and flying occurs mostly during the day and European storm-petrels demonstrate a more pelagic distribution during daylight hours (Bolton 2021; Dean *et al.* 2013). Both species avoid coastal areas near their colonies during daylight hours as they are vulnerable to predation and are likely to be more pelagic than many other seabird species (Bolton 2021; Richards *et al.* 2019).

Other approaches to understanding at-sea distributions and behaviours (e.g. GPS tracking) would need to be deployed either alongside, or instead of these standard methods. GPS tracking data on Manx shearwaters has been collected for almost two decades for academic research, particularly around the Irish/Celtic Seas, and is available from Lundy, Skomer, Skokholm, Bardsey, Copeland, High Island, Great Blasket and Rum (Figure 6) (Brown and Eagle 2015; Critchley *et al.* 2020; Dean *et al.* 2015; Guilford *et al.* 2008; Kane *et al.* 2020; Wilson *et al.* 2009; Wischnewski *et al.* 2019). More recent advances in sensors have allowed GPS deployment on smaller species such as storm-petrels (see Figures 9 & 10) (Bolton 2021; Critchley *et al.* 2020; Wilkinson 2021). These studies demonstrate that alternative methods of determining distribution are available and feasible but, as with population monitoring, are likely to be logistically difficult and only possible for a subset of breeding colonies in the UK.

An important aspect of at-sea distribution is the use of certain areas for different behaviours, of which three of the most significant are foraging, commuting, and loafing or rafting. These three behaviours present different challenges when considering conservation actions or potential development impacts. Foraging hotspots are of critical importance as these are likely to have specific geographic, bathymetric, and oceanographic features that partly determine prey species abundance there, for example, the Irish Sea Front (Lee *et al.* 2005). Any disruption to the ecosystem within these foraging hotspots could reduce their value as a resource and lead to displacement, causing birds to travel to less productive or more distant areas that will place energetic costs on them. Commuting routes are also potentially at risk in terms of barrier effects, as birds may not be willing to enter into windfarm footprints, with potential increased energetic costs if birds have to make detours around the sites, (Humphreys *et al.* 2015). Finally, loafing or rafting is a vital maintenance and resting behaviour of Procellariiformes, which sit on the sea to rest and preen (Richards *et al.* 2019). While this activity usually occurs near the colony, birds may be sensitive to displacement when rafting occurs further offshore (Richards *et al.* 2019). Nocturnal seabirds, including shearwaters and storm-petrels may also be sensitive to the impacts of artificial light, to which they may be attracted, this has the potential to cause disorientation and may impact behavioural responses to OWF that lead to increased collision and displacement risks (this issue is not addressed in this report but will be covered by a Marine Scotland Science project).

3. Existing evidence and understanding

3.1. Population abundance and trend estimates

3.1.1. UK-wide census

These census accounts are overviews and will not go into detail on the colonies assessed. Detailed accounts can be found as part of the census reports which are presented on the JNCC Seabird Censuses webpage, data and any known trends can be found through the Seabird Monitoring Programme website. For the majority of UK colonies, abundance estimates are only made during censuses, although there are some exceptions which are discussed below.

To date there have been four UK wide seabird censuses, with the most recent results yet to be released. All monitoring carried out as part of these studies has been in accordance with the Seabird Monitoring Handbook (Walsh *et al.* 1995). The methods are broadly similar, having always been based around eliciting responses to a playback of the species call, using a correction factor (based on a response rate), and extrapolating to a wider area. The formula for estimating the total number of occupied burrows or Apparently Occupied Sites (AOS) is:

No. of burrows × (No. Responding/No. sampled) × (1/Response rate)

Over time these methods have been refined and improved to the current method which provides the most robust and accurate results, but with wider confidence intervals than previous estimates. Although confidence intervals are wider, this is a more realistic representation of the true uncertainty around population estimates, as sources of uncertainty associated with, for example habitat type and response rates, are better captured and quantified.

3.1.1.1 Methods

All methods described are as detailed in Walsh *et al.* (1995) and carried out as part of the Seabird Monitoring Programme.

Tape playback

Burrow nesting, nocturnal seabirds are incredibly difficult to monitor, and cannot be surveyed using traditional methods such as visual colony counts. Playback surveys have been used across all censuses, as when birds are in burrows, they can be very vocal and often respond to calls being played down their burrow. A recording of a bird is played down the burrow entrance using a tape or MP3 player to elicit a response from an incubating bird. The use of this technique is not fool proof as not all individuals in a burrow will respond even if they are present; this is particularly true of female birds (Perrins *et al.* 2012). In early years, only a male call was played down the burrow, and this was shown to rarely elicit a response in female birds. In more recent surveys, a dual call (a duetting pair of birds), has been used, which improves and reduces variability in response rate (Perkins *et al.* 2017).

The method to carry out playback surveys is relatively straightforward. An area is delineated, usually by the selection of a random point within a plot, then defined using a rope to create a circle. All burrows within the plot are counted in addition to the number of responses that are elicited to tape playback, and a correction factor is applied to account for birds that do not respond to give an estimate of occupied burrows within the plot.

Response rate – correction factor

As using a dual call does not guarantee a response, a response rate is calculated. A sample plot is established with several accessible burrows so that presences or absences of birds are known. A tape is then played down these burrows to establish the response rate, and the number of responses is divided by the number of birds in burrows. This response rate is calculated multiple times across the season to gain an overall response rate, which can then be applied to the number of responses across the whole study site.

Calibration using response rates is known to be a source of error for population estimates. Response rates are usually low and can be extremely variable, for both shearwaters and petrels, with rates varying between islands, habitats, and times of day (Perkins *et al.* 2017; Soanes *et al.* 2012). European storm-petrels produced a response rate of 0.31 from burrows that were all known to be occupied, and on Mousa the response rate was 0.25 in 1997 but 0.75 at the same colony in 1992 (Ratcliffe *et al.* 1998). This result is replicated on Priest Island, where in 1999 the rate was 0.41 and dropped to 0.27 in 2004 (Ratcliffe *et al.* 1998). Work conducted on Skomer Island found that tape quality has a significant effect on number of responses and using improved response rates led to a large increase in AOS when historic data were reanalysed (Brown 2006).

Evidence from multiple studies on Manx shearwater have demonstrated that response rate can vary between 0.32 and 0.55 (Murray *et al.* 2003; Newton *et al.* 2004; Perrins *et al.* 2012). Additional anecdotal evidence suggests that response rate can vary between 0.2–0.8 for the same sample of burrows over a 24-hour period (Padget, O. Pers. Comm.). Response rate is higher at night, as they are more nocturnally active at the colony, there is a lower risk of predation and birds are less willing to advertise their location during the day, although at most colonies surveying at night is not always practical or safe (Ratcliffe *et al.* 1998). Lower response rates are associated with wider confidence intervals of population estimates and tape playback has been shown to give lower population estimates than mark-recapture methods (Hounsome *et al.* 2006). Seabird 2000’s results for the two most abundant Irish colonies carried 95% confidence limits between one third and twice the mean (Newton *et al.* 2004). In addition, tape playback cannot differentiate when there are multiple nests in close proximity, for example under boulders (Soanes *et al.* 2012).

Extrapolation

It is not logistically possible to sample all burrows across an entire island, therefore extrapolation of responses is carried out. This is done by assessing the total area of suitable habitat across a site and multiplying up from the responses gained in a known sample area. Evidence has shown that response rate can vary widely, including between habitats, therefore where appropriate and feasible, habitat-specific response rates should be used.

3.1.1.2. Census accounts

Operation Seafarer was conducted between 1969 and 1970 and provided the first comprehensive estimates of the abundance and distribution of seabirds in the UK. It demonstrated the difficulties in counting seabirds, particularly burrow nesters such as Manx shearwaters and storm-petrels (Cramp *et al.* 1974).

This was followed by the Seabird Colony Register, 1985–1988, which covered around 3,300 coastal sites (Lloyd *et al.* 1991). Although these censuses have both made attempts to count Manx shearwaters (Table 1), they were not thorough and do not provide a robust estimate of population sizes and cannot be compared with subsequent censuses (Mitchell *et al.* 2004). There were no estimates of European storm-petrel population size made by either of these counts.

Seabird 2000 was carried out over five years between 1998 and 2002 and covered 3,200 colonies over 40,000 km of coastline. It has provided the best assessment of both Manx shearwater and European storm-petrel populations to date (Mitchell *et al.* 2004) (see also Table 1). This census employed more accurate methods than prior censuses and was significantly more thorough than previous counts. Tape playback, calibration to account for response rate, and counts of burrows across colonies were carried out. There were still some gaps across the Northern Isles, and methods were not uniform across all sites with a few estimated using best guesses, however the largest colonies in terms of population size employed the more advanced methods (Mitchell *et al.* 2004).

Table 1. Estimates of population size for Manx shearwater and European storm-petrel made over four UK national censuses.

National census	Year	Manx shearwater: population size estimate	European storm-petrel: population size estimate
Operation Seafarer	1969-1970	175,000–300,000 AOS	N/A
Seabird Colony Register	1985-1988	250,000–300,000 AOS	N/A
Seabird 2000	1998-2002	299,678 AOS	25,650 AOS
Seabirds Count	2015-2021	TBC*	TBC

* Results are expected to be published in full in 2023

The most recent census, Seabirds Count, completed in 2021 with results expected to be released in 2023, is the most comprehensive in terms of coverage for both species with all known colonies being surveyed. This wide spatial coverage is combined with the most accurate and robust methods of all the censuses. Advances in methods, such as the use of dual-call playback, improved coverage and accounting of different habitat types will all have contributed to an improved estimate of populations and will, with caveats, be comparable with Seabird 2000 data and provide the first UK-wide trend estimates for these species.

3.1.2. Representative sample plots

Given the logistical, resource and time requirements of UK-wide census efforts, smaller annual sample plots have been established at some colonies to improve our understanding of population dynamics in a more manageable way. The methodology is broadly similar to the census methods; each year the total number of burrows within the sample plots are counted, in addition to the total number of responses elicited by tape playback.

3.1.2.1. Manx shearwater

Skomer Island holds the best understood colony of Manx shearwaters in the world and annual sample plots to assess population trends have been monitored since 1998 (Newman *et al.* 2021). Eighteen different plots are monitored representing a wide range of habitats and are well distributed around the island. Population change is measured by counting the total number of responses to playback across all plots, the number of burrows within the plots are also counted each year (no surveys carried out in 2013 and 2020). 2017 saw the introduction of MP3 for playback, run alongside the traditional tape playback and was solely used in 2018 (Stubbings *et al.* 2018).

As whole island counts that coincide with sample plot counts have only occurred three times on Skomer (1998, 2011, 2018), comparison between the results is not particularly reliable, partly due to the changes to the methodology of the whole island counts (Table 2).

Table 2. Comparison of population changes of Manx shearwaters on Skomer Island between whole island population estimates and representative sample plots (data from SMP and Skomer Seabird reports).

Year	Skomer Whole Island Census (% increase)	Skomer Sample Plots (% increase)
1998–2011	212.0	35.6
2011–2018	13.9	28.9
1998–2018	255.5	74.8

Similar data are available for neighbouring Skokholm Island where seven representative sample plots (7,000 m^2) have been continuously monitored for 22 years (since 1999) (see Figure 1). In 2019, the wardens began the process of moving from tape cassette playback to a digital .WAV playback. This change was planned to be a gradual process over several years to ensure that results were still comparable to previous estimates generated with the old method. This was not possible in 2020 or 2021 due to staff shortages so just the .WAV playback was used using a Skokholm-specific correction factor of 1.39 (Brown and Eagle 2021). Cautious comparison suggests that the population is remaining stable, particularly considering that the number of birds breeding in the accessible study burrows is also relatively constant (Brown and Eagle 2021).

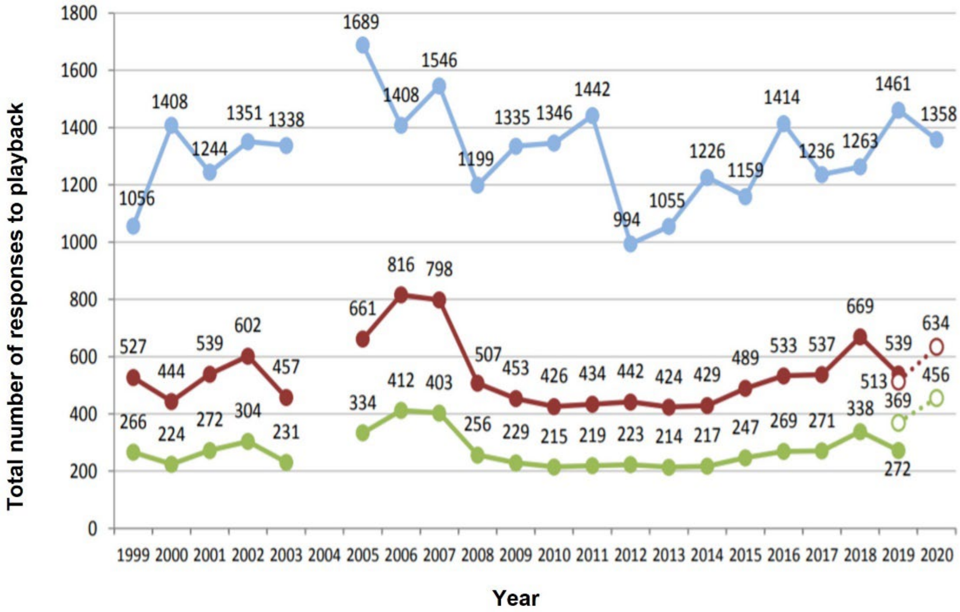

Figure 1. Manx shearwater population estimates from Skokholm Island using responses to playback across representative study plots (1999–2019). Total number of burrows, responses to tape (1999–2019) and to .WAV (2019–2020) and the corrected population estimates for the 7,000 m^2 samples annually since 1999. Solid green dots/lines (bottom line) – Responses (to tape of male song); solid red dots/lines (middle line) – population (using tape corrected to 1.98); solid blue dot/line (top line) – burrows; dashed green line/open dot – responses (to .WAV of duetting pair), dashed red line/open dot – population using .WAV (corrected to 1.39). (From Brown & Eagle (2021), available at: https://www.welshwildlife.org/about-us/reports-and-publications).

3.1.2.2. European storm-petrel

There are very few established annual study plots for European storm-petrel; annual monitoring was identified at two sites, Skokholm Island (Wales) and Priest Island (Scotland) (Brown & Eagle 2021; Insley *et al.* 2014).

Monitoring on Skokholm has been carried out annually since 2010, using tape playback methods and calibration across different habitats around the island. Storm-petrels on Skokholm nest in either stone walls, nest boxes or boulder fields, with the largest colony location in the "quarry", a large scree/boulder field (Brown & Eagle 2021). This monitoring has identified that the population on Skokholm seems to be stable, though there has been some fluctuation between habitats and between years, although this is based on a relatively small sample of accessible sites (Brown & Eagle 2021). This follows on from an apparent decline between 1996 and 2010, which may have been linked to a decline in condition of the wall structures around the island, with crevices becoming filled in with vegetation or soil (Brown & Eagle 2021; Sutcliffe & Vaughan, 2011; Wood *et al.* 2017). It is hoped that further sites will be able to be monitored as occupancy of the specially designed and constructed 'petrel' station (a wall of 119 concrete nest boxes, built in 2016) increases (Brown & Eagle 2021).

Priest Island surveyors use a different method to assess population abundance, after playback surveys in 1999 were considered to be more labour intensive and presented several logistical problems (Insley *et al.* 2014; Mayhew *et al.* 2000). Mist-netting has been carried out annually since 2001, without the use of tape lures to reduce the chances of catching transient non-breeding individuals. Mark-recapture models have suggested that the population has declined from 8,472 birds ± 1,466 (standard error) in 2001 to 3,854 ± 437 in 2012. Playback surveys from 1999, 2004 and 2009 appear to show a similar decline from 9,849 (8,514–11,822) to 5,786 (4,726–7,452), although this decline is treated with caution as it is only over three surveys (Insley *et al.* 2014).

3.1.3. Novel techniques

As previously described, census methods have improved over the years and the methods for data collection using the tape playback technique are probably the optimum way of carrying out this sort of census. However, there are still areas of uncertainty that contribute to wide confidence intervals where novel techniques and new technologies may be able to reduce uncertainty. New techniques can be split into two areas; analytical and field based. Analytical methods seek to apply statistical and modelling techniques before counts are undertaken to direct effort (habitat mapping, species distribution modelling) or analyse existing data to improve accuracy during estimation of key parameters, such as response rate (distance sampling). Field-based methods that may provide improvements to census data collection are acoustic monitoring, taking advantage of the vocal nature of these species to provide a proxy of colony density/counts, remote sensing using cameras, and using dogs to detect the presence of breeding seabirds.

3.1.3.1. Analytical methods

Hierarchical distance sampling

The problem of variable response rate has the potential to be addressed by using modelling techniques. Traditional distance sampling assumes that at a distance of zero, detection is 100%, which we know from response rate calibration is not the case (Buckland *et al.* 2001). Hierarchical Distance Sampling (HDS) uses repeat surveys of the same sites, in this set sampling points rather than a specific AOS, so that population density, detection probability and availability for detection can be modelled independently of each other (Deakin *et al.*

2021; Kéry & Royle 2016; Sillett *et al.* 2012). This method accounts for low response rates by allowing for individuals to be unavailable for detection on some occasions (Deakin *et al.* 2021). HDS also estimates detection rate and probability of a response separately, rather than the traditional playback method that only estimates response rate, which is a product of these two parameters (Deakin *et al.* 2021). An additional advantage of this technique is the ability to model the density of birds with respect to environmental covariates relating to habitat type (Deakin *et al.* 2021). The variation in response rate between habitat types in the traditional method is a source of uncertainty, which would require multiple calibration plots to account for.

This method is particularly useful on uninhabited islands that are both difficult to reach and land on, which leads to a limited amount of survey time (Insley *et al.*, in prep.). For a more detailed description of the techniques and methods see Deakin *et al.* (2021).

Breeding habitat mapping and modelling

Although there are overall challenges in monitoring nocturnal, burrow-nesting seabirds, some issues are specific to a site or number of sites. Skomer is the best studied Manx shearwater colony in the world for a variety of reasons, it is the largest single colony in the UK, but it is also very close to the mainland, has the infrastructure in place to support long-staying researchers and the topography is a lot easier to negotiate than some other sites.

One of the biggest sources of error associated with the census on Rum in 2021 was the uncertainty around colony extent, and this issue was also highlighted for Leach's storm-petrels on St Kilda where survey time is short (Deakin *et al.* 2021; Insley *et al.* in prep). Rum is not an easy island to census because much of the Manx shearwater population is on a mountain, therefore the altitude and terrain make it logistically difficult. In addition to the difficult terrain, the habitat is complex with a variety of different vegetation and topographical types (Bearhop & Sherley, Pers. Comm.). Work conducted as part of the Seabirds Count census in 2021 attempted to use manual Phase 1 vegetation sampling to map potential suitable habitat but this proved to be very time consuming and did not appear to contribute to estimates of population size (Insley *et al.* in prep). However, the use of high-resolution cameras carried by Unmanned Aerial Vehicles (UAVs) has the potential to provide the habitat mapping required to enable accurate prediction of colony extent, which can direct effort, reducing time and resource waste (Insley *et al.*, in prep.). The use of aerial imagery to identify suitable habitat has been undertaken on St Kilda which has a complex matrix of habitats. As not all islands can be surveyed, this technique is vital in making population assessments (Deakin *et al.* 2021).

If habitat mapping in this way were to be employed, ground-truthing would also be required to ensure that interpretation from photographs was possible and accurate. This could be done manually using vegetation surveys, or by surveying the areas predicted to be suitable habitat, but a further option could be the use of dogs, see Section 3.1.3.2 (Scent detection dogs) (Bearhop & Sherley, Pers. Comm.).

Species' Distribution Modelling

Habitat has been proven to be a key predictor of species distribution within an area or island, and certain topographical factors such as elevation, slope and vegetation type can help to identify important areas for seabird species (Arneill 2018). Unlike other procellariforms, storm-petrels and Manx shearwaters showed a preference for habitats with low elevations (< 50 m) and the plant species sea campion (*Silene unifora*). In addition, most shearwaters were found within 200 m of the coast (Arneill 2018). Habitat surveys and digital elevation models can be combined to produce species' distribution models (SDMs) that can predict the distribution of seabird species and identify key areas, which could significantly reduce the effort and time required during surveying (Arneill 2018).

On a wider scale, SDMs can also be used to describe, predict, and project species' entire ranges, which in the past has been applied to one aspect of the species' ecology (Häkkinen *et al.* 2021). However, for seabird species (including shearwaters and petrels) that have multiple ecological niches across the annual cycle (breeding/non-breeding), this approach is limited and may inhibit our ability to accurately model their distributions (Häkkinen *et al.* 2021). The recent study by Häkkinen *et al.* (2021) combined terrestrial and marine variables for three seabird species, including a burrow-nesting, migratory, central-place forager (Atlantic puffin, *Fratercula arctica*), to investigate how the different ecological variables relate to breeding distribution. They found that for puffin the best model combined terrestrial and marine variables, with mean temperature in summer and distance from the sea being the most important terrestrial variables, and winter/spring sea surface temperature (SST) and mean salinity being the most important marine variables. Puffin ranges were equally determined by terrestrial variables as marine variables. This is interesting, as it was expected that marine variables would be more important as puffins have specific foraging requirements, but it draws into question how summer air temperatures may be very significant to burrow nesting species (Häkkinen *et al.* 2021).

Similar results were found during a Marine Protected Areas Management and Monitoring (MarPAMM) project (Davies *et al*. 2021) in which European storm-petrel presence was positively correlated with winter minimum temperature, breeding season SST (quadratic term), coast length and small islands area, but negatively correlated with breeding season maximum temperature (quadratic term) and winter precipitation. Abundance was positively correlated with winter minimum temperature and winter potential energy anomaly, and negatively correlated with winter season SST (quadratic)

3.1.3.2. Field-based methods

Acoustic monitoring

Although some aspects of burrow-nesting seabird ecology present significant challenges for deriving population estimates, birds are very vocal when at the colony, particularly at night and during the early stages of the breeding season (Brooke 1986). Acoustic monitoring is becoming a more prominent and viable option for use in seabird monitoring as technology advances, and is already used around the world, particularly in very challenging habitats (Borker *et al.* 2014; Brownlie *et al.* 2020; Oppel *et al.* 2014).

Work has been carried out in the UK to attempt the estimation of Manx shearwater population density. When carried out in conjunction with playback surveys and GPS tracking, the density of burrows was not correlated with acoustic activity, but there was correlation with in-colony flight activity as birds called whilst flying over the colonies (Arneill *et al.* 2020). However, it was highlighted that there is still a considerable amount of potential using this technique. It may be able to inform on colony size and equipment could easily be deployed in difficult to access locations to confirm presence or absence of a breeding colony (Arneill *et al.* 2020).

Remote camera monitoring

Another remote method of monitoring seabirds is the use of cameras. There are various ways in which this can be done including using satellites, UAVs such as drones, animal borne cameras and fixed-position cameras, the last of which is potentially the most useful method for procellariforms (Edney & Wood 2021). Again, there are a variety of options for using fixed-position monitoring, including time-lapse, motion-triggered and video recording.

Remotely deploying cameras can be extremely beneficial as it allows observation of remote locations, nocturnal monitoring, reduces disturbance, removes observer bias, can be cost-effective (depending on the technology) and can collect vast amounts of data which can be stored and reviewed many times (Edney & Wood 2021). However, there are potentially technological and mechanical problems which may prevent data collection/cause loss of data, quality of data collected depends on the camera deployed which can be very expensive, cameras may need maintenance throughout the season and analysis can be time consuming (Edney & Wood 2021).

UAVs have been used to monitor ground or burrow-nesting birds using photographs and/or thermal imaging to detect occupied burrows and ground-based nests to good levels of accuracy, although there would be limitation at locations with dense vegetation or multiple species of burrow- or ground- nesting birds (Albores-Barajas *et al.* 2018; Israel & Reinhard 2017).

Thermal, infra-red, digital videography has been used to monitor European storm-petrels on Mousa to predict the number of AOS in both natural and wall habitats (Perkins *et al.* 2018). The study found that for the same amount of field effort, the infra-red filming produced slightly more precise results when compared with traditional tape playback. However, image quality was negatively affected by bad weather and darker nights as the season progressed. Enhanced illumination would improve detection, but the large amount of expensive equipment required, and review times mean that this method is currently costly and inefficient compared with playback. This method would be useful at sites where disturbance is likely and where safety is a concern.

Scent detection dogs

It is well known that the olfactory ability of dogs has been deployed across a wide variety of sectors, including in cancer and drug detection, as well as in nature conservation, but the use in seabird monitoring is potentially under-utilised (Bennett *et al.* 2020; Bolton *et al.* 2021). Recent research on UK islands has demonstrated that dogs have the ability to detect Manx shearwaters (Ramsey) and European storm-petrels (Isle of May), including differentiating between the two, in experimental and field conditions (Bolton *et al.* 2021; NatureScot 2021). The application potential of this method is quite varied, it could be used to identify the presence of breeding birds in previously unknown areas or to map the extent of colonies (Bolton *et al.* 2021). Both applications are incredibly valuable and could potentially lead to improvements in our understanding of distribution, both of individual colonies and entire populations. For example, on Rum and as discussed in section 3.1.3.1 (Breeding habitat mapping and modelling), the extent of colonies is an area of uncertainty and source of error, using dogs to identify discrete colony areas would reduce this error and direct effort.

There are limitations and ethical considerations to consider, and all work must be carried out in accordance with UK Animal Welfare Act 2006. Dogs can only work for short periods of time, therefore carrying out large-scale surveys would require a number of dogs and handlers or could take a significant amount of time, consideration for travel would also need to be considered. Other considerations include the possible implications of disturbance to other breeding species.

3.2. Demographic rates

3.2.1. Productivity

3.2.1.1. Manx shearwater

Reproductive success, productivity, is a measure of how many chicks survive to fledging age, expressed as a proportion of chicks fledged per eggs laid. Productivity is the best understood demographic rate for Manx shearwaters, having been monitored across eight sites around the UK: Skomer, Skokholm, Bardsey, Rum, Canna, Sanda, Copeland, and Scilly (see Figure 2, all data collected from SMP database). Studies in England are very limited, four colonies across Scilly have been monitored (St Agnes, Gugh, Bryher, St. Mary's) but the small sample sizes, limited years of study and uncertainty around methods mean they have not been included here. Methods for monitoring productivity of Manx shearwaters have been consistent for decades and are relatively simple. At the end May/early June, at the beginning of the breeding season, occupied burrows are identified by exploring burrows by hand or using a camera such as an endoscope. Following confirmation of occupancy, by the discovery of an incubating adult or a pair of adult birds, the burrow is left alone once the presence of an egg has been confirmed (either by visual confirmation by eye or endoscope or physical check). Checks resume at the end of June/early July to identify hatched chicks, and once a chick has been found the burrow is left alone. Towards the end of the season, early to mid-August, burrows are visited again to assess how many chicks have reached a size/weight where fledging can be assumed.

Figure 2 highlights the high variability in productivity between years at each colony, but also shows that between colonies there is significant variation, which is likely to be influenced by environmental and topographical factors and prey availability/distribution for each location. This annual and geographical variation highlights the importance of suitable geographic representation across the UK. Data from some of these colonies are inconsistent, have small sample sizes or are short in duration, but at least three of the datasets (Skomer, Bardsey and Rum) have been collected consistently over a significant time period (i.e. at least 25 years), so that trends can be analysed.

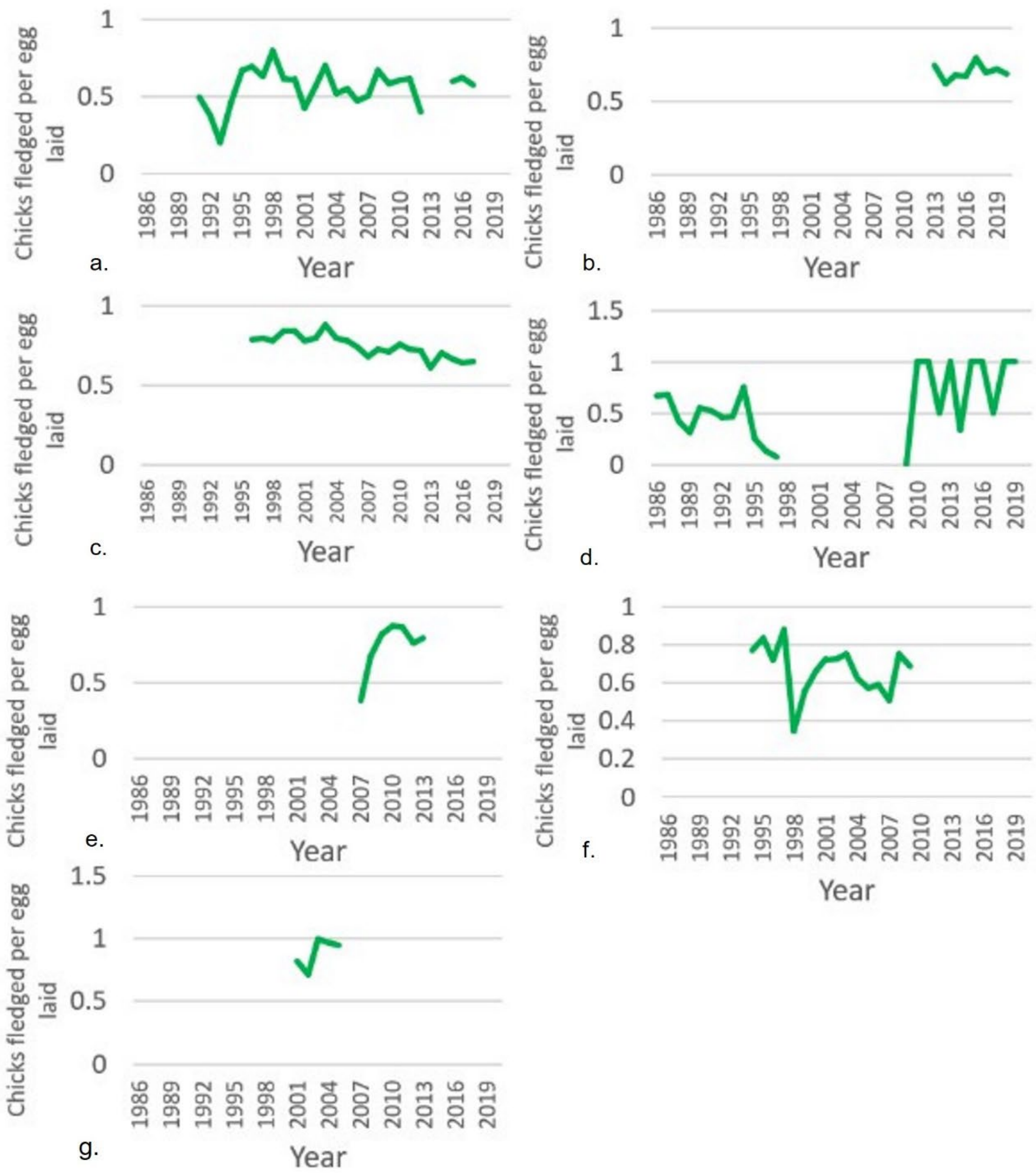

Figure 2. Manx shearwater productivity – chicks fledged per eggs laid – across seven colonies in the UK, between 1986 and 2020. Data for breeding colonies at: a – Skomer, b – Skokholm, c – Bardsey, d – Canna, e – Copeland, f – Rum, g – Sanda. Data from Seabird Monitoring Programme Database.

The most consistent and long-term data available on Manx shearwater productivity are from Skomer, where data have been collected every year since 1991 as part of the SMP (see Figure 3, data collated from Skomer Seabird Reports as not all available in SMP). The long-term productivity average of 0.59 (1995–2021) is very close to the more recent 2012–2021 average (0.56), suggesting that broadly speaking breeding success has remained consistent over time. Some notable years of very low success include 1993 where burrow flooding was suggested to have caused widespread failure (productivity of 0.2). Productivity monitoring has been carried out on Bardsey since 1996, where the long-term average of 0.75 (1996–

2017) is slightly higher than the most recent ten-year average of 0.70 (2008–2017); fifty sites were monitored until 2002, with sample sizes of approximately 100 since then (SMP data).

Rum also provides a long-term and good quality dataset, with excellent sample sizes in most years. Initial visual inspection of the data suggests productivity is broadly consistent over time, and the average productivity over the last 10 years of available data of 0.66 (2000-2009) is the same as the average over the entire dataset, 0.67(1994–2009) (data from SMP).

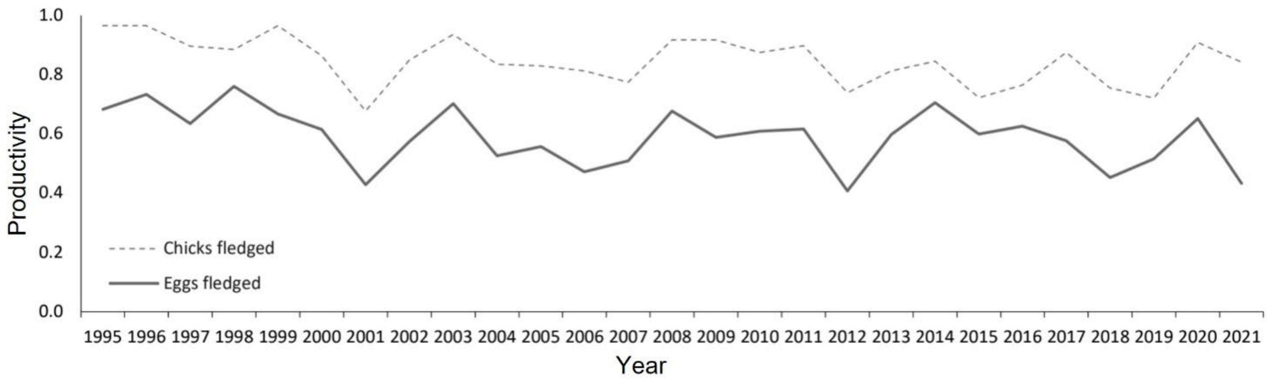

Figure 3. Annual variation in productivity of Manx shearwaters between 1995 and 2020 on Skomer Island, solid line: number of eggs leading to fledged chicks ("eggs fledged"), and dashed line: number of hatched chicks successfully fledged ("chicks fledged") (Figure from Newman *et al.* 2021, available at: https://www.welshwildlife.org/about-us/reports-and-publications.).

3.2.1.2. European storm-petrel

As with Manx shearwaters, monitoring of reproductive success of storm-petrels is logistically difficult and is made even more complex as storm-petrels are more sensitive to disturbance than shearwaters (Carey 2009). Repeat visits, particularly when adults are present have the potential to lead to abandonment. This sensitivity, and the difficulty in finding nest sites that are suitable for monitoring has contributed to the lack of empirical data on productivity. The only data available through the SMP database are from two sites on the Isles of Scilly, where samples sizes were between two and eleven and monitoring lasted either four or five years. The SMP has one record from Skokholm Island 2020, but the Skokholm Bird Observatory annual seabird reports provided further data, showing that a small sample of storm-petrels has been monitored for seven years (see Table 3).

Like shearwaters, storm-petrels display high inter-annual variation in productivity, ranging from 0.45 to 0.74 (Table 3), which highlights the need for systematic, annual monitoring to accurately assess population trends. These data are from one colony and are likely to vary between colonies as shown by shearwater productivity data (Figure 2); therefore, expansion of productivity monitoring will be essential to gain a representative understanding of UK-wide productivity.

Table 3. Reproductive success and sample sizes of European storm-petrels on Skokholm Island (Brown & Eagle 2018, 2021).

Year	2014	2015	2016	2017	2018	2019	2020	2021
Sample size	13	20	12	14	20	19	20	20
Productivity	0.69	0.55	0.58	0.5	0.55	0.74	0.45	0.80

Review of the wider literature-base has shown that monitoring for productivity has been carried out on Mousa Island in Shetland as part of a study to assess the impacts of disturbance on breeding success (Watson *et al.* 2014). In high disturbance areas productivity was 0.44 and 0.38 in 2010 and 2011 respectively, whilst in low disturbance areas it was 0.68 and 0.51, demonstrating an association between productivity and above ground human disturbance.

European storm-petrels, as well as various other petrel species nest in crevices, either natural in boulder fields, or in stone walls (Watson *et al.* 2014). Storm-petrels on Skokholm, and within other colonies in Europe, make use of artificial nest boxes, which have allowed easier access for monitoring of breeding success (de León & Minguez 2003). Stone walls built on Skokholm by farmers in the 18th century have provided a home to storm-petrels, however they have not been maintained and have degraded over the years, reducing possible nesting opportunities (Brown & Eagle 2021; Thompson 2008). In the 1970s wooden boxes were built into the walls around the cottage and other buildings that were originally built in around 1760 and were then replaced in some cases by plastic boxes in the 1990s (WTSWW 2016). Nearly 10% of boxes were occupied in more recent years. Some problems have been identified with the plastic boxes (e.g. condensation), therefore an ambitious project was initiated on Skokholm in 2016 called the “Petrel Station” (WTSWW 2016). This involved construction of a new wall which integrates over 100 nest boxes made of concrete which can be accessed from the back for monitoring purposes, including the ability to use cameras (WTSWW 2016). The wall is a relatively new structure, and uptake has not been significant enough to date so that occupancy rate or reproductive success is assessed to be typical of the island as a whole, but as occupancy increases productivity is likely to become more representative (WTSWW 2016).

3.2.2. Adult and juvenile survival

Adult survival data are collected as part of a variety of different studies, including the Seabird Monitoring Programme and the British Trust for Ornithology’s (BTO) Retrapping Adults for Survival (RAS) network (Horswill *et al.* 2016; Walsh *et al.* 1995). There are also several projects that are carried out independently of the RAS network for a variety of logistical reasons, one being the inability to guarantee annual ringing/resighting (Horswill *et al.* 2016).

Adult survival estimates are difficult to obtain as they require long-term data and relatively large sample sizes. Data are collected using ringing recoveries and resighting from birds re-trapped at the colony, resighted or from dead birds. Metal rings with unique alpha-numeric identifiers, or plastic colour-rings that are either coded, or constitute a unique combination, are placed around the legs of birds by licensed individuals. In nearly all circumstances metal rings can only be read when birds are re-trapped whereas colour rings can be read at a distance. Unless ringed as chicks in the nest it is not possible to exactly age birds ringed as adults as there are no plumage differences in these species once birds are mature.

Both Manx shearwater and European storm-petrels demonstrate philopatry (i.e. they are very site faithful). Most fledglings recruit back to their natal colony and breeding adults often return to the same burrow and partner in consecutive years (e.g. Arneill *et al.* 2019; Brooke

1986; Harris 1966, 1972). This aspect of their breeding ecology is an advantage when monitoring both adult and juvenile survival as ringing and re-capturing at the colony maximises the chances of encountering an individual over its lifetime.

Manx shearwaters can be caught on the nest with a very low risk of egg abandonment; adults can therefore be caught regularly in a discrete area as part of productivity monitoring. This can be easily supplemented by catching birds on the surface of colonies by hand at night (method as defined in Walsh *et al.* 1995). Even though this is still a relatively labour-intensive process and requires licensed ringers, it still appears to be the most cost-effective and reliable way of assessing survival between years.

The same method is not as reliable for storm-petrels as they do not spend time on land, are sensitive to disturbance at the nest and are much more likely to abandon the egg than shearwaters. Ringing therefore needs to occur away from the nest using mist-netting. It is very common for storm-petrel ringing to use tape-luring to maximise the number of birds caught as the opportunity to handle this species is infrequent and ensures as many birds are handled and processed as possible. However, the use of luring can affect the estimates for adult survival, and this is not recommended when conducting these studies (Insley *et al.* 2014).

For Manx shearwaters, age at first breeding is estimated to be 5–6 years old, therefore any breeding adult ringed can be assumed to be at least 5 years old (Harris 1966; Perrins *et al*. 1973; Brooke 1977). Age of first breeding is not as well understood for storm-petrels but recaptures of non-breeding birds in Shetland diminished after two years, suggesting that this was the age they started to breed. In addition, a study in Spain found that captures of first year birds at the breeding colony was unlikely except in extreme years (Okill & Bolton 2005; Zuberogoitia *et al.* 2016). It follows therefore, that European storm-petrels trapped at the breeding colony are likely to be at least in their third year, but this is not proven as ringing recoveries of birds ringed as fledglings are very scarce. All details of ring numbers, ringing time, location and the breeding/age status of each bird are logged and recorded online on the BTO's Demography Online (DemOn) database. When birds are re-encountered the ring number can be read and the minimum age of the bird can be estimated using the online system.

3.2.2.1. Manx shearwater

Adult survival is currently assessed on Sanda, Rum, Skomer, Skokholm, Bardsey and Copeland for Manx shearwaters with the longest dataset dating back to 1953 (Copeland). These studies are conducted as part of the SMP or scientific/RAS studies. The review by Horswill *et al.* (2016) only included studies carried out on Sanda and Rum. The Sanda study, carried out over 5 years, was assessed as "poor" (i.e. not an estimate of survival within 2% of the true mean with 95% confidence). Data collected on Rum over 20 years was assessed as "good" and should therefore provide an estimate of survival within 1% of the true mean with 95% confidence.

Historic studies conducted on Skokholm in 1966 and 1973 produced survival estimates of 93–96% and 80–95% respectively (Harris 1966; Perrins *et al.* 1973).

The best publicly available current dataset on Manx shearwater adult survival comes from Skomer island where data have been collected since 1978. Whilst not the longest dataset, recent analysis has shown that the Skomer dataset is most robust in terms of trend analysis since 1992 (Wood *et al.* 2021; Newman *et al.* 2021). Adults are monitored at a breeding site, and most birds are ringed/encountered in burrows, the long-term average is 0.87 (1977-2020). Survival estimates for this site are low when compared to historic studies from Skokholm and for what may be expected for this species (Newman *et al.* 2021) (Figure 4).

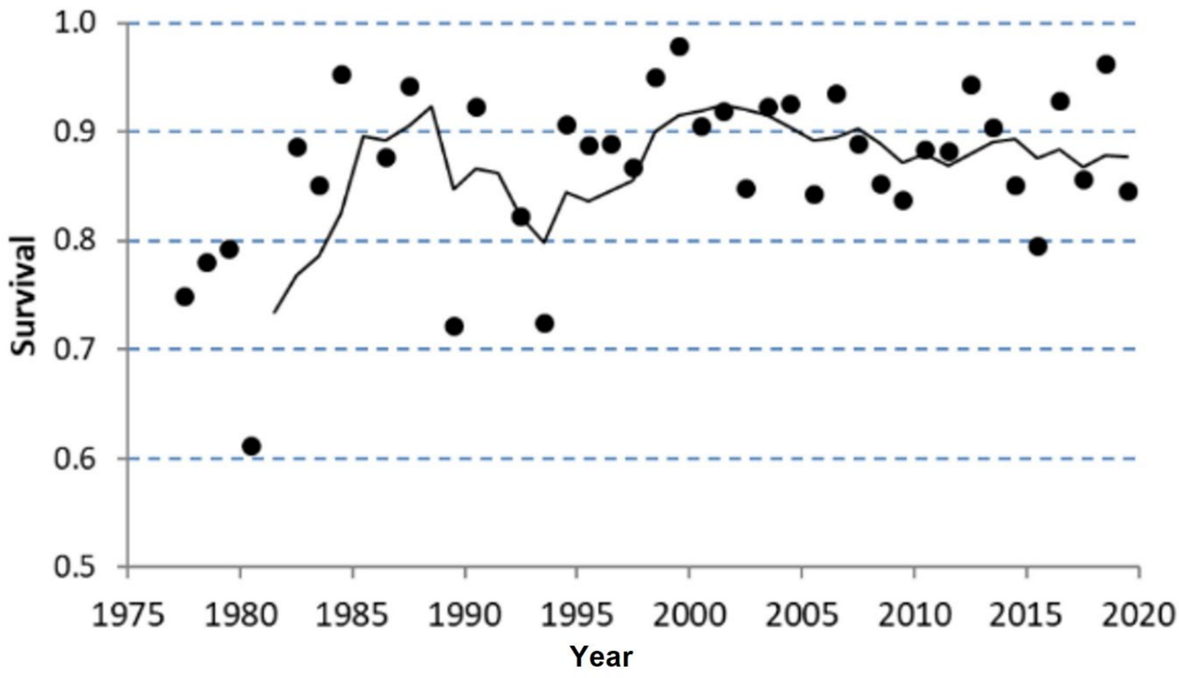

Figure 4. Survival rates of adult breeding Manx shearwaters on Skomer Island between 1978 and 2021 (includes encounter data to 2021) (from Newman *et al*. 2021, available at: https://www.welshwildlife.org/about-us/reports-and-publications).

Recent modelling of survival data from the Isthmus plot on Skomer Island has highlighted the importance of demographic profiles, which differ between individual shearwaters and affect the overall population survival estimate. Wood *et al.* (2021) found that mean survival rate was 10% higher for successful breeders (0.94) when compared with failed breeders and non-breeders (0.86). This finding is not all that surprising as these types of patterns in demographic profiles have been demonstrated in other seabird species. Demographic profiles could be an indication of "quality" or just represent a heterogeneous population where traits vary across a gradient (Wood *et al.* 2021). The fact that the figure for successful breeders is considerably higher for this species highlights a key factor that should be taken into consideration when making survival estimates in the future, including completing survival and productivity monitoring in tandem.

3.2.2.2. European storm-petrel

On review of the literature, there have been very few reported adult survival studies in the UK, and many of the studies in Europe pertain to the Mediterranean sub-species of storm-petrel which are thought to be geographically and demographically isolated (*Hydrobates pelagicus melitensis*) (Cagnon *et al.* 2004). This displays some distinct differences, for example vocalisations and morphometry, as well as in demography (e.g. moult strategy), and therefore any comparisons should be treated with caution (Amengual *et al.* 1999; Sangster *et al.* 2012).

There are current adult survival data available for storm-petrel from four Scottish colonies; Eilean Hoan, Sanda, Priest Island, Lunga and one Welsh colony, Skomer island. A review carried out in 2016 found that of the five studies across the four Scottish islands, only two were assessed to be "good" and provide an estimate of adult survival within 1% of the true mean with 95% confidence: Eilean Hoan and Priest Island (Horswill *et al.* 2016). A study conducted in Spain estimated survival at 0.83 (Oro *et al.* 2005).

The only UK study that was found during this literature search and is not part of the BTO RAS scheme was conducted on Mousa between 2001 and 2012 (Insley *et al.* 2014). On Mousa adult survival was high between 2001 and 2003 (0.92, 0.96), but varied between 0.73 and 0.83 until the end of the study in 2012. Catching was also carried out on neighbouring islands and recaptures showed that only a colony within < 100 m could be considered part of the same population and therefore mark-recapture sites should be at least 100m away from other sites (Insley *et al.* 2014). It is unclear whether other studies considered this when carrying out monitoring.

Adult survival estimates made using BTO ringing recoveries since 1967 show a relatively consistent rate over the years: 0.86 (1967–1996) and 0.9 (2007–2014) (Dagys 2001; Insley *et al.* 2014). Adult survival data have been collected from Skomer since 2006 and is estimated to average 0.88 for breeding adults (2006–2017) (Newman *et al.* 2021).

3.2.3. Juvenile survival

3.2.3.1. Manx shearwater

Juvenile survival has not been formally monitored for Manx shearwater since the 1970s when two studies were conducted on Skokholm Island. Investigations by Perrins (1973) and Brooke (1977) using ring recoveries of birds ringed as chicks estimated juvenile survival to be between 25% and 30% but highlighted the problems of bias as some individuals are successful at evading capture. There are colonies where chicks are ringed annually in relatively large numbers. It may be possible to assess existing data to identify whether enough individuals are encountered to provide estimates of this rate. Horswill and Robinson (2015) do not provide an estimate of juvenile survival rates, citing lower recovery rates than for adult survival estimates, and noted that no recent attempts at estimating juvenile survival had been made.

3.2.3.2. European storm-petrel

There is very limited evidence and data available on storm-petrel juvenile survival. No UK studies or evidence were found during this literature search, and it has been advised that recruitment age of the Mediterranean subspecies is not an appropriate comparison or proxy (Thomas, R. Pers. Comm.).

Ringing of chicks in the nest does occur on Skokholm island, and there have been subsequent recaptures of individuals over the last few years, see Table 4 (Brown & Eagle 2021). A small number of birds have also been controlled at other sites in the UK. Although it is a relatively small sample it does provide important data on recruitment and juvenile survival. As occupancy of the ‘Petrel Station’ continues to increase and ringing continues year on year this site could provide valuable data on juvenile survival.

Storm-petrels are tape-lured annually on Skokholm, and birds ringed as chicks which are returning to the island are caught. A small sample of natural (burrows/crevices) and artificial (boxes) nests are monitored for productivity, and where possible chicks are ringed. Between 2013 and 2019, 78 chicks were ringed and 15 of those have subsequently been re-captured However, this estimate is based on a very small sample size (Brown and Eagle 2021). Previous work on Skokholm estimated that annual mortality between the period of first return to the colony and recruitment into the breeding population may be around 10–15% (Scott 1970).

Table 4. European storm-petrel juvenile survival estimates for Skokholm Island based on chick ringing and subsequent re-capture on the island (Data from Brown & Eagle 2021).

Year	Number of chicks ringed	Encountered in subsequent years on Skokholm	% Re-trapped
2013	4	1	25
2014	11	3	27
2015	17	4	24
2016	6	1	17
2017	7	1	14
2018	10	1	10
2019	13	4	17

3.2.4. Age at first breeding

3.2.4.1. Manx shearwater

Several studies that were carried out on Skokholm to examine breeding behaviour of Manx shearwaters have provided data on the age of first breeding using ringing recoveries. Over the first two studies (1966, 1973), age of first breeding was on average five years old, increasing by one year in the last study (1977) (Brooke 1977; Harris 1966; Perrins 1973). The earliest age a bird attempted breeding was three years old and the oldest was over nine years old, demonstrating that there is considerable variation between individuals (Harris 1966).

More recent observations made on Skokholm, again identified using ringing recoveries of chicks ringed in their burrows on the island, found birds returning to breed between four and seven years old (Brown & Eagle 2021).

In the only tracking study identified for juveniles, Global Location Sensor (GLS) tags were deployed on 54 fledgling Manx shearwaters from Copeland Island, with only three successfully retrieved, highlighting the difficulty in obtaining data from juvenile birds and the necessity for large sample sizes (Wynn *et al.* 2021). The focus of this study was the migratory behaviour of first year birds and demonstrated that birds do not return to the natal colony until at least their third year (Wynn *et al.* 2021).

3.2.4.2. European storm-petrel

The only UK-based estimates of storm-petrel age of first breeding are from the islands of Mousa and Skokholm (Brown & Eagle 2021; Okill & Bolton 2005). To gain a better understanding of the age structure of the Mousa population, a total of 799 chicks were ringed between 1990 and 2004 (Okill & Bolton 2005). Of these birds, 39 have been recaptured using tape lures away from the breeding colonies. Most of these birds were in their second year while one was in its first year (Okill & Bolton 2005). This study suggests that by the fifth year the majority have become breeding individuals and that between 40% and 45% of individuals recruit into the breeding population in their third year (Okill & Bolton 2005).

3.2.5. Sabbaticals

Long-lived species, such as seabirds, can skip breeding in certain years where they may not be in optimum condition and breeding might have a significant impact on their survival and subsequent breeding attempts (Giudici *et al.* 2010). These “sabbaticals” are only possible because long-lived species will have many more chances to reproduce and therefore can prioritise their own condition.

Although this demographic rate was not included in our initial discussions and searches, consultation with experts at the workshop highlighted the importance of this parameter. Sabbatical rate is not included in PVA but is an important demographic rate when considering apportioning. While only breeding birds associated with a colony are considered within HRA processes, the proportion of birds seen at-sea during surveys that are breeding, non-breeding adults (sabbatical) and immature birds is unknown. This could mean impacts to breeding adults are not accurately captured in assessment.

Not accounting for non-breeding birds in population assessments can have implications for estimating population growth rates. For example, when comparing models that did and did not include non-breeders, models without non-breeders showed upwardly biased estimates of demographic variance and can mask low population growth rates (Lee *et al.* 2017). This could be particularly important when considering the potential impacts of OW developments on a population and influence the requirements for compensatory measures or mitigation.

3.2.5.1. Manx shearwater

Our literature search did not find any studies that have specifically looked at the proportion of individuals taking sabbaticals. This appears to be currently unknown. Sabbaticals are inherently linked with breeding success, and the recent work by Wood *et al.* (2021) has highlighted those individuals breeding in one year are significantly more likely to breed the following year, whereas individuals that skip breeding are less likely to attempt breeding in subsequent years. Conversely, Shoji *et al.* (2015a) found that individuals that skipped breeding had shown higher activity levels in the preceding winter, more time flying and foraging and less time resting. This link suggests that birds going into the breeding season in poor condition prioritise their own fitness and can instead invest more into the next season’s breeding attempt. In addition, these birds were found to have an increased likelihood of success in the season following a sabbatical (Shoji *et al.* 2015a). The differences in findings between these studies could have been caused by multiple factors, including demographic differences between the individuals sampled, or extrinsic reasons such as inter-specific competition (Wood *et al.* 2021).

3.2.5.2. European storm-petrel

As with Manx shearwater, no studies in the UK found during the literature search cite sabbatical rates for storm-petrels. This species is better studied in northern France (e.g. Cadiou 2001; Cadiou *et al.* 2010). Three studies have identified potential factors influencing the likelihood of skipped breeding; food scarcity (Hémery *et al.* 1987, cited in Franco *et al.* 2004; Soldatini *et al.* 2016) and habitat change (Cadiou *et al.* 2010). The first two studies have made estimates of sabbatical rates as a result of these influences (31–60%), but no baseline estimate of sabbatical rate is available. The limited literature suggests that sabbatical rates in European storm-petrel are likely to be highly variable between colonies and in response to environmental variables.

3.3. At-sea distribution and behaviour

For Procellariiformes, assessing distribution at sea presents some key challenges. Both Manx shearwater and European storm-petrel are central-placed foragers during the breeding season as they are tied to a colony during incubation and chick rearing, but unlike a lot of other seabird species they have extensive foraging ranges (Bolton 2021; Fayet *et al.* 2015). Manx shearwaters in particular can regularly travel hundreds of kilometres to exploit certain key food resources which is a significant advantage if prey distribution or abundance changes (Guilford *et al.* 2008). However longer journeys incur greater energetic costs in an already costly period of the year and may increase interactions with other species, marine infrastructures, or fisheries (Humphreys *et al.* 2015).

3.3.1. At-sea survey data

Surveys at sea can be carried out in two main ways, by boat and by air. Boat-based surveys were the original method of data collection, but increasingly digital aerial surveys are becoming the most common way of collecting large-scale at-sea distribution data. Aerial surveys are however less likely to capture more fine-scale behavioural data and surveys capturing imagery in the visual spectrum, as is currently the norm, including boat-based surveys, cannot collect data at night or during adverse weather conditions. These limitations are important when attempting to understand and assess the risk and magnitude of impact from, for example OWF for species that are active at night and may change their behaviour in high winds (flight height for example).

3.3.1.1. Boat-based

Opportunistic boat-based data have been collected for centuries but a more rigorous methodology was developed and implemented through the European Seabirds At Sea (ESAS) surveys (Camphuysen *et al.* 2004; Tasker *et al*. 1984). The ESAS database is the longest running dataset in North-West European waters; data collection began in 1991 and the database contains over two million records (Kober *et al.* 2012). ESAS surveys involve counting all birds on the water within a 200 m or 300 m wide line transect (split into three or four distance bands: 0–50 m, 50–100 m, 100–200 m and 200–300 m) running parallel to the track line of the boat, as described in Webb and Durinck (1992).

Boat-based surveys allow for accurate detection and identification of most species but given their small size storm-petrels can be very difficult to detect unless the conditions are very calm, hence density estimates obtained from transect-based surveys are generally low and likely subject to bias (Critchley *et al.* 2020; Kober *et al.* 2010).

Data collected from 1979 to 1993 by ESAS surveys was used by Stone *et al.* (1994) to assess the distributions of Manx shearwaters. During the breeding season, Manx shearwater distribution was centred around Rum, Skomer and Skokholm, with the highest densities observed in the Irish Sea, south-west Wales, south-west Ireland, and the inshore waters of west Scotland during chick rearing (Stone *et al.* 1994). The Irish Sea Front and the surrounding stratified waters were important, particularly in autumn, where feeding occurred in preference to other areas of the Irish Sea (Stone *et al.* 1994). Low densities of birds were observed in the North Sea with birds mainly restricted to waters off the east coast of Scotland and northeast coast of England, particularly Moray Firth, Firth of Forth and Flamborough Head, likely driven by river outfalls where tidal mixing occurs (Hall *et al.* 1987; Stone *et al.* 1994).

Specific investigation into the relationship between distribution and water depth identified contrasting patterns for Manx shearwater and European storm-petrel, although distribution of both was negatively associated with SST (Skov *et al.* 1994; Stone *et al.* 1995). Densities of shearwaters was highest in waters less than 100 m deep and were particularly low over the shelf edge and deep sea (Stone *et al.* 1995). Their distribution was correlated with depth, and they were only found further afield over banks less than 200 m deep (Stone *et al.* 1995). Storm-petrels were mostly distributed beyond the 50 m isobath with substantial numbers over the shelf edge and deep sea (Stone *et al.* 1995). The correlation between Manx shearwater distribution and frontal zones has been highlighted in multiple other studies (Begg & Reid 1997; Durazo *et al.* 1998; Scales *et al.* 2014).

Studies reported that European storm-petrels were most common in the areas surrounding their colonies, often within 400 km of land, particularly to the northwest at the continental shelf edge (Hall *et al.* 1987; Skov *et al.* 1994; Stone *et al.* 1995). It has been suggested that distribution was driven by prey resources and oceanographical characteristics (Hall *et al.* 1987; Skov *et al.* 1994).

3.3.2. Marine Ecosystems Research Programme

The most comprehensive assessment of seabird at-sea distributions comes from the Marine Ecosystems Research Programme (MERP). A total of 1.36 million km of seabird surveys (aircraft, small and large boats) from various methods (line and strip transects) were collated, compiled, and analysed, which represents the most comprehensive estimation of seabird at-sea distribution in the North-east Atlantic, see Figure 5 (Waggitt *et al.* 2020).

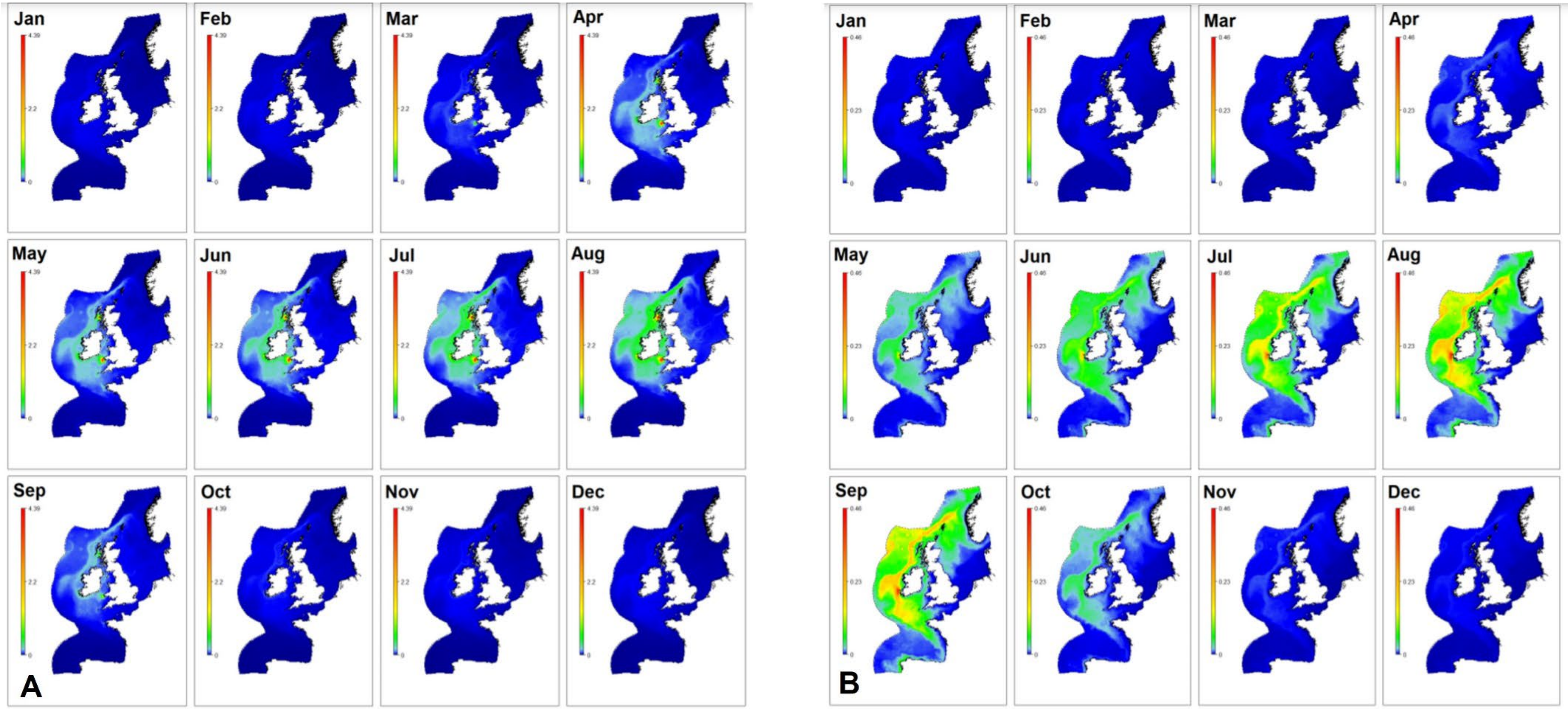

Figure 5. Monthly distribution maps produced by the Marine Ecosystems Research Programme for: A – Manx shearwater; and B – European storm-petrel (from Waggitt *et al*. 2020, distribution maps available via https://doi.org/10.1111/1365-2664.13525).

3.3.3. Aerial survey (digital and visual)

Aerial surveys were originally carried out visually, with an observer making the observations from the plane, typically flown at altitudes of around 76 m (Žydelis *et al.* 2019). This is increasingly uncommon as advances in technology have led to the introduction of digital surveying, either taking photographs or videos from planes flown at higher altitudes to reduce risk of disturbance to the birds. However, there is a lack of systematic evidence with respect to detection rates of birds on the sea surface and there may be challenges for species such as storm-petrels, given small size and dark plumage. Novel methods such as LiDAR can potentially enhance detection of smaller objects but cannot be used to identify species.

Digital aerial survey is now the dominant method used in OW impact assessment to gain data on at-sea seabird distribution and abundance. It has several advantages, including reduced disturbance and ability to fly OWF post-construction surveys through increased flight heights, more species and individuals can be observed, and higher densities of all bird species/groups can be estimated (Žydelis *et al*. 2019). Surveys prior to consent provide baseline data to inform impact assessments, and post-consent surveys can be used to assess any changes in abundance, distribution, and behaviour. However, although developers are encouraged to share data on the Marine Data Exchange this does not always happen, which was an issue raised at the procellariforms expert workshop in January 2022. Most aerial survey data for UK waters are gathered as part of OW development, and therefore is currently limited to coastal waters, where the distribution of shearwaters and storm-petrels is patchy. However, as the development of floating wind farms is increasing more data will become available further offshore (Kober *et al.* 2012). Data are also limited to daylight hours and to weather conditions in which it is safe to fly aircraft.

3.3.4. Tracking

Tracking of seabirds at sea significantly improves the ability to understand seabird behaviours, including variations between different sectors of the population or between individuals, in addition to at-sea distributions associated with known colonies. Surveys can give a good representation of where seabirds are foraging or travelling but they cannot provide information on foraging trip length, differences between age classes or the origin and breeding status of the birds seen. However, in terms of distribution much of the tracking data gathered have corroborated findings from other methods such as ESAS. Sites of existing UK tracking data for Manx shearwaters and European storm-petrels are shown in Figure 6.

As described previously one of the disadvantages of traditional methods is the inability to conduct surveys at night and in adverse weather conditions. Tracking can be carried out continuously and studies have shown that Manx shearwaters spend daylight hours foraging and flying, with flight behaviour affected by wind speed (Dean *et al.* 2013; Gibb *et al.* 2017). European storm-petrels have a more pelagic distribution during the day (Bolton 2021).

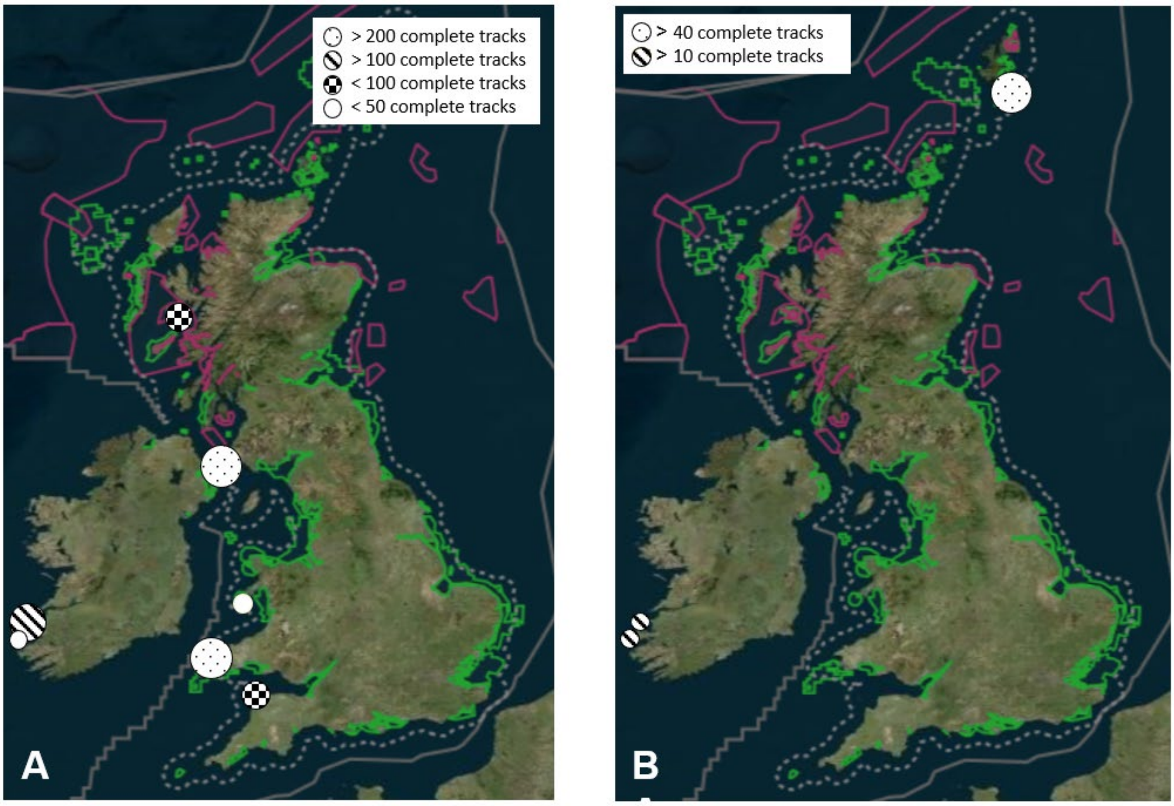

Figure 6. Tracking data collection for: A – Manx shearwaters; and B – European storm-petrels in the UK shown on a scale of intensity. Data collated from variety of articles and provide an estimate of collected data (it is possible that there are more data that were not identified or available).

3.3.4.1. Manx shearwater

Tracking of Manx shearwaters has been undertaken in the UK for several decades. Given their medium size (% body weight in comparison to tag weight) and tolerance to handling they are an excellent study species (Guilford *et al.* 2008). Much of the focus of tracking studies in the UK has been in the Irish Sea region, particularly on Skomer, Copeland and Bardsey, but there has also been data collected from Skokholm, Rum, Lundy, High Island and Great Blasket which gives a broad overview of distributions in waters around Britain and Ireland (Critchley *et al.* 2020; Dean *et al.* 2015; Fayet *et al.* 2015; Freeman *et al.* 2012; Gibb *et al.* 2017; Guilford *et al.* 2008; Kane *et al.* 2020; Shoji *et al.* 2015b; Wilson *et al.* 2009; Wischnewski *et al.* 2019). Some of the data collected are available through the BirdLife Seabird Tracking database, or as described in various research publications.

Tracking work has improved our understanding of at-sea distribution but has also led to significant advances in understanding of at-sea behaviour, including diving, resting/rafting, and flight patterns, foraging strategies, and the navigational abilities of Manx shearwaters (Fayet *et al.* 2015; Guilford *et al.* 2008; Richards *et al.* 2019; Shoji *et al.* 2015b). Skomer, where tracking has been carried out annually for almost two decades, provides an extensive dataset from which fine-scale behaviour can be extracted.

Manx shearwaters from colonies in the vicinity of the Irish/Celtic seas often remain within this area when they are tied to the colonies during incubation and chick rearing periods, although there are some exceptions with some individuals foraging as far as the north-western Atlantic and almost as far north as Iceland, they display considerable variation between years (Dean *et al.* 2015; Guilford *et al.* 2008). Manx shearwaters tracked from the west coast of Ireland, High Island and Great Blasket, largely stayed to the west of Ireland, making some extensive foraging trips into the North Atlantic, see Figure 7 (Critchley *et al.* 2020; Wischnewski *et al.* 2019).

Simultaneous tracking has been carried out across four colonies which has highlighted key foraging locations for birds from geographically distant colonies (Dean *et al.* 2015). It is well known that Manx shearwaters have extensive foraging ranges, but the use of key shared foraging areas demonstrates that local foraging areas are vital even when other more distant food resources are available (Dean *et al.* 2015).

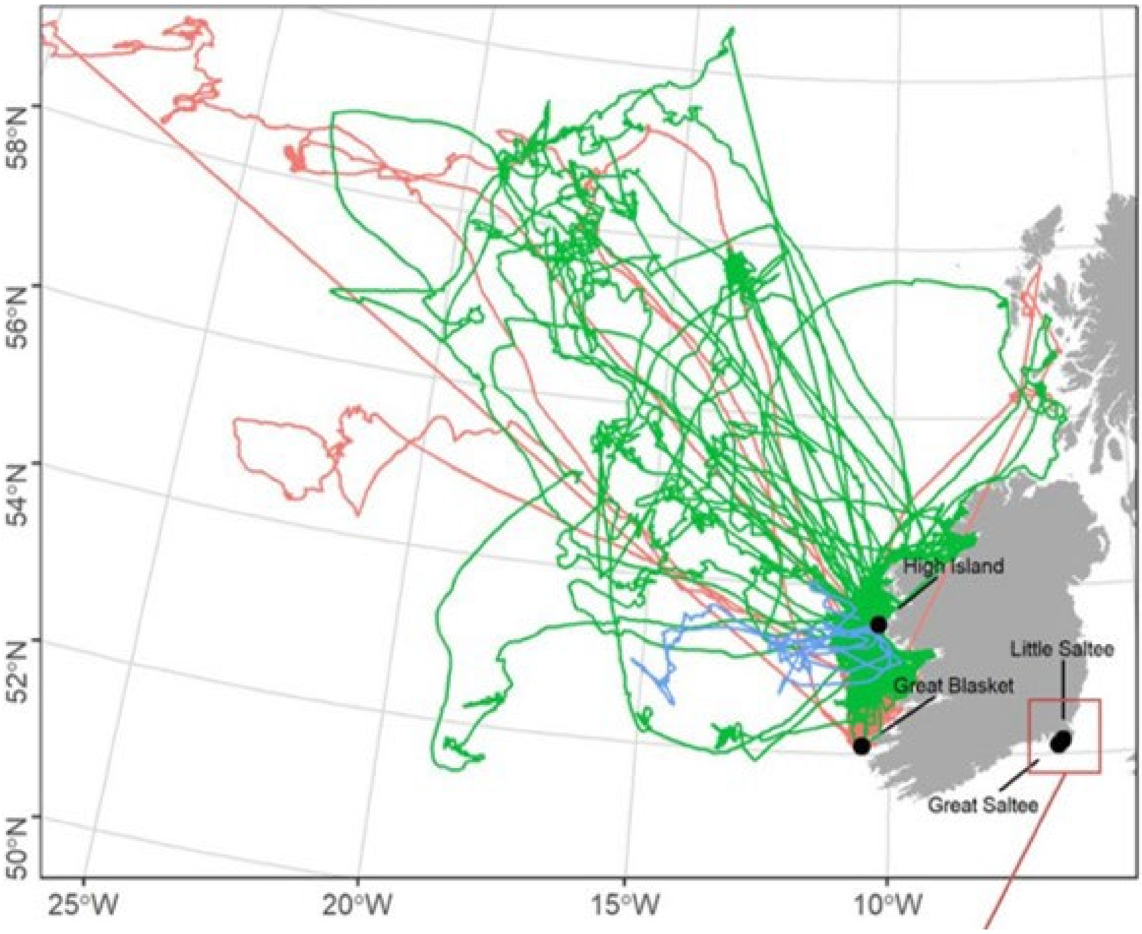

Figure 7. GPS tracks from Manx shearwaters on Great Blasket (red) and High Island (green), and European storm-petrels on High Island (blue) (figure from Critchley *et al*. 2020, open access via https://doi.org/10.1111/ecog.04653 and data available from the [Seabird Tracking Database](#)).

There was very little evidence from our literature review for tracking of juveniles or fledglings. In the only study identified, GLS (Global Location System) tags were deployed on 54 fledgling Manx shearwaters from Copeland Island, with only three successfully retrieved, highlighting the difficulty in obtaining data from juvenile birds and the necessity for large sample sizes (Wynn *et al.* 2021). The focus of this study was the migratory behaviour of first year birds and demonstrated that birds do not return to the natal colony until at least their third year (Wynn *et al.* 2021).

3.3.4.2. European storm-petrel

When compared with Manx shearwaters there are very limited data available on storm-petrel tracking in the UK. Ethical guidelines set out that devices, tags, etc., should only be deployed if they weigh no more than between 3% and 5% of the body mass of the bird, which for a species that weighs on average less than 50 g has presented a technological challenge (Bolton 2021). Of the tracking that has occurred, most studies have used low resolution tags which cannot provide enough detail to analyse the foraging trips of such a small species (Bolton 2021). Three UK studies were identified where European storm-petrels have been tracked using high resolution GPS tags and these have provided a variety of data that have improved our understanding of these species (see Figure 7 (Critchley *et al.* 2020; Wilkinson 2021)). Our literature review provided no evidence of any tracking of fledgling/juvenile storm-petrels.

The most extensive dataset comes from the largest breeding site for storm-petrels in the UK, Mousa, Shetland (Bolton 2021). Data were collected over four years and across all stages of the breeding season allowing comparison between key parts of the breeding cycle (Bolton 2021). This study drew several key conclusions, including:

- Storm-petrels showed a high degree of consistency in foraging range and bearing across all years, which is in contrast to Manx shearwaters that show very different foraging strategies between years.
- During incubation, trip length varied between 1 and 3 days.
- Median trip length, 159 km, far exceeded the previous estimate of 65 km (Thaxter *et al.* 2012), and birds regularly travelled up to 300 km from the colony.

Further data presented by Critchley *et al.* (2020) from High Island on the west coast of Ireland (Figure 7) show storm-petrels foraging to the south and west of the colony with one trip in particular heading out into the Atlantic. It should be noted that only eight tracks were collected during the chick-rearing period for this study which may not be representative of the colony as a whole (Critchley *et al.* 2020; Soanes *et al.* 2013).

The third known tracking dataset comes from Illauntannig, which is one of the Magharee Islands in Ireland. During this study five of six deployed tags were retrieved, but due to data restrictions analysis was only carried out on four tracks from three individuals. This study suggested that foraging distribution is likely to be influenced by environmental and biological factors, but any results should be treated with caution given the very small sample size (Wilkinson 2021)

3.3.5. Ethical considerations and limitations of tracking studies

Whilst the contributions that tracking and tagging can make can be significant, they need to be balanced with the potential negative effects on the birds themselves. Ethical considerations are always part of the planning process for any tagging study, and assessing the potential impacts are usually considered when designing methods (Bolton 2021; Carey *et al.* 2009). Most studies only consider the short-term, immediate effects on phenology and fitness, such as breeding success and weight of tagged bird, but the impacts on behaviour and longer-term fitness should also be considered (Bolton 2021; Carey *et al.* 2009; Gillies *et al.* 2020). For example, Gillies *et al.* (2020) found that there was no effect on Manx shearwater breeding success during the study and subsequent year, but that tagged incubating birds altered their foraging behaviour, doubled their time away from the nest, spent less time flying and experienced reduced foraging gains compared with untagged birds. Hence, in addition to any concerns for animal welfare, it is also worth considering the representativeness of the data collected by tags as it has been shown that they have an impact on a variety of foraging parameters.

While at-sea and aerial surveys can observe very high numbers of individuals, the expense, logistical and ethical considerations involved in tracking studies usually lead to small numbers of tracks recorded (per individual, per year), which should be taken into consideration before extrapolating observed behaviours and distributions to the whole population.

3.3.6. Foraging radius models

Wakefield *et al.* (2017) demonstrated a methodology for deriving at-sea distributions from tracking data. In this instance, tracking data for four species were collected for analysis. There may be sufficient existing tracking data for Manx shearwater (e.g. Celtic/Irish Seas) for such a model to be run for part of the UK range of this species, but there are likely to be gaps (e.g. with respect to the major population on Rum). Crucially, some of these gaps potentially intersect with ScotWind lease areas and both current, Celtic Seas, and future floating wind proposals. For European storm-petrel, as highlighted above, there are very limited tracking data, and these birds may also be under recorded in boat or aerial surveys. While sufficient data could be collected for gaps to be filled, at-sea survey data collection and conducting tracking campaigns are extremely time-consuming and expensive. An alternative method for assessing at-sea distribution is the use of weighted foraging radius models that can allow the rapid projection of distribution for entire colonies during the breeding season (Critchley *et al.* 2018; 2020). This method uses data on colony location, population size and maximum foraging range to estimate distribution and identify hotspots. This approach allows the prediction of at-sea distribution for colonies where very little data are available or for species where tracking is particularly difficult or display complex foraging strategies (Critchley *et al.* 2018; 2020). The model predicts the occurrence of breeding birds (central-place foragers) within the at-sea area surrounding a colony up to a set colony-centred radius (Critchley *et al.* 2018; 2020). The foraging range can be set using any method but should represent the best available data for that species, either direct (GPS), indirect (data loggers such as accelerometers) or survey data (Critchley *et al.* 2018).

This method was applied to both Manx shearwater and European storm-petrel in the work undertaken by Critchley *et al.* (2020) where they compared the effectiveness of the models to aerial survey and GPS tracking data. Foraging range distributions were not significantly positively correlated with tracking data or aerial survey data for Manx shearwater, although this may have been affected by the dual-foraging strategy of Manx shearwaters (i.e. breeding adults alternate between long trips for self-maintenance and short trips for offspring care) (Critchley *et al* 2020). There was a positive and significant correlation between tracking data and modelled foraging range distributions, but no correlation with aerial survey data (Critchley *et al* 2020). For storm-petrels, this method may be a good alternative to tracking, although tracking sample size was smaller than recommended, and results should be treated with caution (Critchley *et al.* 2020; Soanes *et al.* 2013).

Therefore, foraging radius models may provide an interim method for determining at-sea distributions while strategic tracking is established, or where insufficient data are collected.

4. Gaps in understanding

4.1. Population abundance and trend estimates

Estimating the total population of burrow-nesting seabirds is always going to be incredibly difficult to do accurately, and even as methods improve and provide more robust and precise results the confidence intervals are likely to be wide. This uncertainty means that when using census data to assess population trends, sensitivity is low and is only likely to detect very large changes in population numbers, even as much as 10%. It is recommended whole-island surveys are carried out every five years (Arneill *et al.* 2019; Hatch 2003). Ability for timely detection of change at a population level and identification of the causes of change are therefore restricted. However, because of the increase in precision of recent surveys, such as those for Seabirds Count, the estimates are likely to be far closer to actual numbers than they have in the past and for the first time two census results will be able to be compared to provide trend estimation.

Cook *et al.* (2019) noted that they were unable to identify any colonies within SPAs for which likely significant effects (LSE) could not be ruled out as a result of predicted impacts by proposed OWFs: "*at which regular abundance monitoring may enable baseline population estimates to be established against which any impacts arising as a consequence of the development of offshore wind farms could be assessed."* European storm-petrel was not examined as at the time LSE could be ruled out for SPAs classified for this species, but given the limited monitoring for this species, a similar conclusion would likely be drawn. The study made several recommendations, including with regards to abundance monitoring:

> "I. It is vital that the current national seabird census 'Seabirds Count' is supported. This will provide vital baseline information about the population status of the UK's seabirds. Amongst other uses, this will provide robust baseline population estimates for species and sites at which LSEs in relation to offshore wind farms cannot be ruled out by the HRA screening process.
>
> II. Existing monitoring of abundance by the SMP should be expanded so that abundance of all species within SPAs where LSEs could not be ruled out by the HRA screening process is monitored at least once every two years."

Gaps in our knowledge and understanding of population abundance estimates fall into three broad categories:

- numbers at any given time;
- temporal variation/trends, and
- regional variation.

A robust estimate of current population is important as a baseline against which to assess any predicted impact (i.e. what is the conservation objective of the site for population abundance, is the site currently meeting that conservation objective, and what is the magnitude of predicted impact against that conservation objective?). It is also a key parameter in population modelling that may be used for a more detailed assessment, and to understand the potential magnitude of impact.

Similarly, an understanding of population trends is important context when assessing the impact, as it will be a factor in the conservation objective for a site (maintain or restore) and will be a factor in determining the population consequence of an impact (i.e. a declining population is more likely to be vulnerable to additional pressures than a stable or increasing one).

Section 3.1 above has highlighted that there is information on population abundance and trends estimates for some sites, but that this is limited. Whilst most of the UK population of Manx shearwater breeding in Welsh colonies may be better understood, there are several colonies in Scotland for example that are either monitored infrequently or not at all. Our baseline for assessment for potential impact of projects coming forward, for example through ScotWind, is therefore limited.

For robust impact assessments to be made, detection of change within a population is vital, therefore continuing the census efforts is essential to ensure trends can be identified. For this reason, the use of small sample plots to assess annual fluctuations in abundance seems vital, and if done in a strategic and efficient way, could provide a very valuable alternative that can be managed on a smaller scale (Arneill *et al.* 2019). Work carried out on Manx shearwaters has suggested that by being selective about the areas and plots that are surveyed, census effort can be reduced by as much as 80% but still provide a sufficient representation of population trends and allow us to make regular assessments on the status of our seabird populations (Arneill *et al.* 2019). Nevertheless, it is essential to know what is happening at a UK-wide scale to inform impact assessment.

It is certain, that whether future work focusses on prioritising smaller sample plots or expanding the census programme to occur more frequently, we do need to improve our understanding of population size, distribution around the UK and trends over time to make accurate assessments of the potential impacts of Offshore Wind and contribute to HRAs. The current knowledge we do have is generally quite localised and changes to methods over time or the use of different methods between sites have rendered estimates largely incomparable. The standardisation of data collection, potentially using simplified methods, the expanded use of new approaches to modelling and/or data collection should help reduce uncertainty and will be particularly important when considering the continuing expansion of OW.

Given the range of breeding sites of both species between south-west England and Ireland to the Northern Isles of Scotland, there is the potential that they face different pressures, and trends may not be extrapolatable from one region to another.

4.2. Demographic rates

As noted in Section 3.2, it is currently unknown whether there is sufficient statistical power to detect changes in demographic rates in response to the effects associated with offshore wind farms (Cook *et al.* 2019). Cook *et al.* (2019) made several recommendations about monitoring for demographic rates (particularly productivity and adult survival) for seabirds. This study did not examine European storm-petrel but highlighted for Manx shearwater that realistic mark-recapture studies of the sort possible for individual OWF projects are likely to be able to detect a reduction in adult survival of no more than 0.03 and a population could decline by nearly 40% over 25 years before the decline would be detected (Cook *et al.* 2019). It is questionable whether five-year mark-recapture studies could be carried out at all key sites for either species potentially impacted by future OWF development.

There is, therefore, a need to improve our understanding of demographic rates for both Manx shearwaters and European storm-petrels across multiple colonies and in different parts of the UK. Evidence from other species, such as kittiwake, show that demographic rates can vary widely between colonies and therefore basing all modelling or assessments on data from single colonies may not be appropriate. Improving estimates of these vital rates would allow better parameterisation of models such as PVA, which would allow more robust assessment of the possible impacts of OW developments in the UK. There are current datasets and projects that are collecting relevant data, but it is limited to a handful of colonies and most of the study sites fall within a relatively small area (Irish Sea).

As previously mentioned, uncertainty can be either stochastic or systematic. Both can be improved by collecting or analysing more data, reducing uncertainty, and improving our understanding of natural variation in population dynamics. Improving our knowledge of natural fluctuations in certain parameters, such as productivity, for specific colonies/populations will better enable us to assess the potential impacts of OWFs and therefore inform consent.

As the number and distribution of OWFs increases, the potential impacts on shearwaters and petrels, particularly where they are features of a protected site, will have to be considered before consent is given. We currently have very little information on some aspects of the ecology of these species which may make assessment conservative and therefore consent difficult to achieve.

Research projects that will provide data allowing us to improve precision of the most influential input parameters can be designed. Those that provide information that will improve empirical estimates and provide data for key (most influential or most uncertain) input parameters are likely to represent best value for money.

Cook *et al.* (2019) highlights the increased power to detect change where multiple parameters are monitored at the same site. Consideration is given in this report to how that may be best achieved.

4.3. At-sea distribution and behaviour

Improving our understanding of at-sea distribution and the spatial/temporal use of certain areas for key behaviours (foraging, commuting, and resting) will make significant improvements in understanding of the potential interaction (spatial and temporal) between OWFs and these two species. The behaviour of Manx shearwaters and European storm-petrels at a given OWF location will have a large influence over how they might be impacted (e.g. flight patterns/behaviour influencing collision risk, the relative importance of an area should displacement be a concern, etc.), and such understanding will be vital going forward during the screening and assessment stages of HRAs. Understanding of the spatial and temporal distribution of these species, and their broad-scale behaviours will also inform any mitigation/compensation strategies, should they be required, potentially at both project and strategic scales.

The most notable gap in understanding we have in this area for European storm-petrel is at-sea distribution and behaviour. Although the distribution of this species has been observed over decades of boat-based surveys, their small size and dark colouring makes them difficult to see, especially when weather is anything but very calm (Kober *et al.* 2010). In addition, although advances are being achieved very rapidly with digital camera systems the detectability of storm-petrels has not been possible until relatively recently, which was highlighted as a potential issue by Critchley *et al.* (2020). Detectability has not been investigated systematically, so the changes in detection rate across weather conditions, varying camera systems and with different Ground Sampling Distance (GSD) are not well understood. These surveys have been used to produce the distribution maps discussed in 3.3 but it should be noted that these distributions do not contain information such as distributions during darkness, or the linkage between birds using particular marine areas and breeding colonies. Such information would be helpful in assessing the potential impact of OWF developments.

The storm-petrel tracking studies have so far highlighted the importance of foraging areas near the colony but also consistent use of shelf areas (Critchley *et al.* 2020; Bolton 2021; Wilkinson 2021). However, it is important to recognise that these studies only focus on three of the 62 storm-petrel colonies in the UK, and the sample size of two of the studies was smaller than recommended (Critchley *et al.* 2020; Soanes *et al.* 2013; Wilkinson 2021). Small sample sizes increase the risk that the individual selected may not be representative of the wider colony, other colonies in the region or other regions (Soanes *et al.* 2013).

The current lack of data for storm-petrels is a consequence of a lack of appropriate tagging technology, although recent advances mean that this tagging can now be applied at various colonies around the UK to improve our understanding of at-sea distribution and behaviour across the entirety of their UK range. More detailed behavioural and spatial analysis will only be possible at a UK level once more data are available.

For Manx shearwater there is a quite considerable evidence base of tracking data that covers at least eight colonies across all countries of the UK, which can inform on distribution and has already led to advances in behavioural understanding (Brown & Eagle 2015; Critchley *et al.* 2020; Dean *et al.* 2015; Guilford *et al.* 2008; Wilson *et al.* 2009). Although many questions have been answered with the existing data, there may be further areas of uncertainty that can be addressed by applying the same data to new questions. For example, understanding changes in distribution and behaviour over time may be possible, which is particularly pertinent when considering the impacts of climate change. If for example foraging ranges are changing, then it may be necessary to take this into account within project and plan-level assessments to reduce the potential of cumulative effects and may inform the location of mitigation/compensation measures, should these be required.

An area of investigation that may be possible for both species, currently for Manx shearwater and in the future for storm-petrel, is the relationship between distribution (foraging) and environmental variables. From existing data, it is understood that these species have associations with frontal systems and shelf areas, but it may be possible to analyse in more detail the potential relationships with more specific environmental variables, such as SST or chlorophyll-α and key nutrients (Begg & Reid 1997; Bolton 2021; Kane *et al*. 2020; Stone *et al*. 1994, 1995; Wilkinson 2021). Such an understanding may in turn present a more nuanced and finer-scale understanding of the drivers of distribution of these two species and may inform sensitivity/risk-based spatial planning in the future. An additional gap for both species is the lack of data on non-breeding and immature birds. Spatial segregation between breeding adults and other age classes has already been demonstrated for Manx shearwaters from Skomer island, and if this is the case for European storm-petrels and for shearwaters from other colonies, this may have implications for apportioning and future planning/consent (Fayet *et al.* 2015).

5. Potential research opportunities to improve understanding

This section is a result of collaboration with, and input from, a consortium of key scientific expertise from species and industry experts. Discussions focussed primarily on improving or refining current methods of data collection and analysis, making assessments of current knowledge/data with a view to undertaking gap analyses, which will then inform the expansion of monitoring to new sites or scaling up of existing studies (Figure 8). The expansion of monitoring will be most valuable and will contribute the most to reducing uncertainty at colonies in the vicinity of existing or planned OWFs.

Although these ROs have been developed with Manx shearwaters and European storm-petrels in mind it is likely they could be extended or applied to other Procellariiformes. These actions will make it easier to conduct PVA and are vital for the undertaking of HRAs and impact assessments and will direct future effort and resources to where they are needed most. Improving our understanding of these populations, rates and distributions would directly contribute to planning and consenting decisions.

The ROs that have been developed below will firstly seek to make it easier to gain a broad understanding of the research that has been undertaken, the data that exist and where more research is required. The ROs will explore the potential methodological developments that may reduce the effort and resource-requirements of monitoring studies/programmes, particularly for population estimates and demographic rates, seek to identify key areas of uncertainty and work towards reducing confidence limits and improve our overall understanding of these species by directing research effort and expanding monitoring/tracking programmes.

This section provides information on research opportunities that the authors, consortium, and Statutory Nature Conservation Bodies (SNCBs) thought were of the most direct benefit to reducing uncertainty in estimates of population abundance, demographic rates and at-sea distribution and behaviour of Manx shearwaters and European storm-petrels.

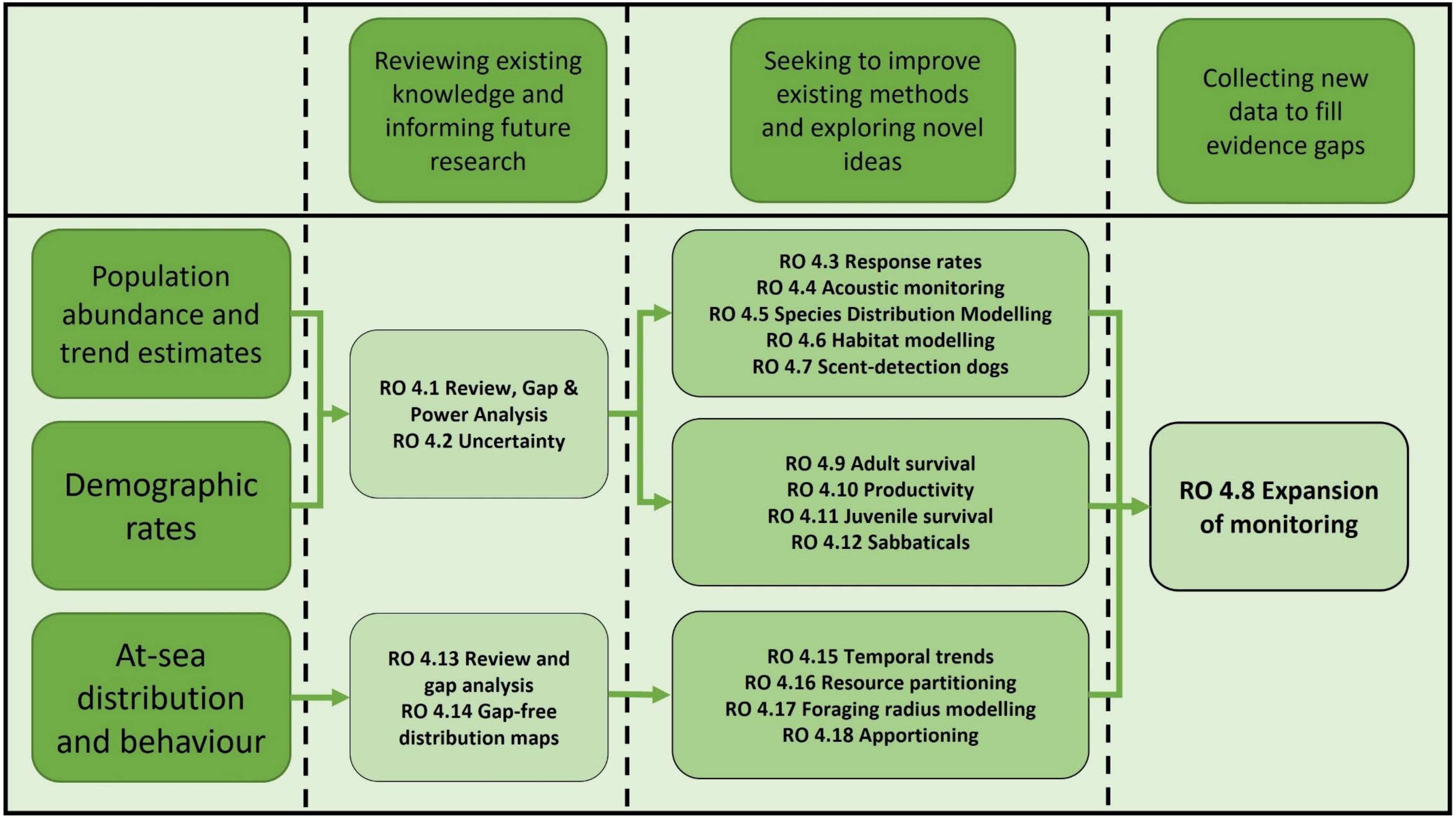

Figure 8. Summary of Research Opportunities identified through the OWSMRF process.

5.1. RO 4.1 Strategic review and gap analysis of existing data and ongoing projects covering population estimates and demographic rates

5.1.1. Evidence needs/rationale

One of the overarching issues identified during the workshop is the availability of data. Most monitoring of vital rates occurs as part of the SMP but not all data are available on this platform (e.g. adult survival data). Some research projects are published as journal articles (with data used often published as supplemental information) but searching for and collating this data is time consuming and some data are not published or available. Data collection in the field is time consuming and often expensive, entering it into an online database can also be a lengthy process, so it is understandable that data holders would not necessarily want their data to be freely or widely available. However, to help future research and direct monitoring effort, having a review of what data has been collected, the methods used, the location, time frame, sample size etc may be useful in providing a record of input parameters for EIAs so that the most accurate or geographically appropriate data can be used.

Once a review is carried out a gap analysis and power analysis can be conducted to establish how frequently monitoring needs to be carried out, how many sites should be sampled, and the sample sizes required for rates sampling such as number of birds ringed/burrows monitored.

5.1.2. Work already underway

There is not currently one location/website/database where a comprehensive collation of existing demographic data is available. The SMP Database holds data that are publicly available, but it relies upon data holders to upload and does not include data collected under different programmes.

5.1.3. Work required

5.1.3.1. RO 4.1a Strategic review of historic and ongoing population and demographic rate monitoring

This RO would consist of a series of strategic UK-wide reviews, carried out by experts, that would include all completed, ongoing and planned projects carrying out monitoring of shearwaters and petrels. The focus of the review would be collating data on rates that are vital to the running of PVA and that would contribute HRAs. As well as reviewing what we know and what data collection is ongoing, it could also identify the spatial and temporal gaps in data, therefore informing future work and working alongside other ROs identified in this report (RO 4.8).

A schedule for reviews would need to be agreed on, and it is likely that the regularity of the reviews would depend on the rate of new data collection being carried out. This RO should not necessarily need to be restricted to Manx shearwaters and storm-petrels but could incorporate other/all seabirds.

5.1.3.2. RO 4.1b Gap analysis

Following the review, a gap analysis will assess the number of sites and/or colonies that should be monitored to provide a representative sample of the population and rates across the UK. An appraisal of known sites should be carried out so that “key” sites can be identified, taking into consideration the proximity and connectivity between colonies and OW developments (particularly Round 4, ScotWind, Celtic Seas and floating wind). Consideration should also be given to geographical representation, size of colony and ideally representation of different types of colonies (proximity to the coast, topography, potential interactions with other seabird species (i.e. predators or competitors for nesting sites)).

5.1.3.3. RO 4.1c Power analysis

To detect change in a population at a scale that will allow action to be taken in the event of population decline it is vital that population estimates are carried out regularly enough for even small population changes to be identified. Work by Hatch (2003) on seabird populations in North America identified the required frequency of surveys to identify percentage changes over a set period. This sort of analysis could be carried out for UK populations to establish a survey program that would be able to detect change at the desired sensitivity.

This stage would aim to improve standardisation of data collection across colonies and potentially reduce effort by conducting statistical analysis to identify the optimum sample size for productivity monitoring. It would aim to provide a sampling strategy whereby individual sites can plan and carry out monitoring to improve confidence in demographic rate estimates across colonies where monitoring is currently occurring or is planned in the future. This may have to occur on a colony-specific basis as there are significant differences between colonies

5.1.4. Benefits/key outcomes

As this RO would cover all aspects of shearwater/petrel ecology there would be close links to ROs on population estimates and at-sea distribution and behaviour. Regular stock takes of what is known would improve our ability to conduct accurate and precise risk modelling and contribute to consenting processes.

This RO would provide an opportunity to carry out an assessment of existing knowledge, including the methods used, as well as signposting to sources of both publicly and privately held data. Its output will highlight in more detail the areas of uncertainty and gaps in knowledge. This will serve to inform other ROs identified here, as well as providing a single source identifying where current uncertainties in demographic rates lie and hence allow more informed incorporation of these uncertainties in assessment and decision-making for OWF

5.1.5. Risks/Inter-dependencies

The extent and completeness of such reviews would depend on the availability of information and access to published works. As this resource is a review and would not require the submission of data or significant time input from data holders it is hoped that this would not be a barrier to the work.

5.1.6. Predicted resources to deliver this RO

5.1.6.1. RO 4.1a Strategic review of historic and ongoing population and demographic rate monitoring

As this is desk based the resource requirements will be:
LOW resource requirements per review, with reviews repeating every few years (less than one year and less than £100,000).

5.1.6.2. RO 4.1b Gap analysis

As this is desk based the resource requirements will be:
LOW resource requirements per review, with reviews repeating every few years (less than one year and less than £100,000).

5.1.6.3. RO 4.1c Power analysis

As this is desk based the resource requirements will be:
LOW resource requirements per review, with reviews repeating every few years (less than one year and less than £100,000).

5.2. RO 4.2 Identifying key variables generating uncertainty in abundance estimates from census data

5.2.1. Evidence needs/rationale

It is accepted that there will always be a certain level of uncertainty around population estimates for these difficult to count species. The methods that have been developed and refined over the years have improved the precision of the estimates, but the confidence limits are still wide for both European storm-petrels and Manx shearwaters, up to 38% in some cases (Skomer estimates for Manx shearwaters in 2018 were 349,663 ± 93,340) (Perrins *et al.* 2020). There are certain aspects of survey for both Manx shearwater and European storm-petrel that still have the possibility to be improved upon, with different colonies conveying different challenges. Although there is a degree of understanding of the sources of error in abundance estimates for both species, there is a need to systematically identify all potential sources of error, and to assess the relative contribution of each to the overall uncertainty in abundance estimates.

5.2.2. Work already underway

The methodology for census has already been developed considerably since the first national census in 1969/70. The improvements have led to a more accurate estimate of population abundance, and consistency between the most recent two national censuses will allow the first estimate of temporal change in UK population to be assessed. Analytical developments include the use of a calibration curve to calculate response rate and an App to automate the process of data analysis. Over the course of censuses and through the development of new techniques, sources of uncertainty, which have translated into wide confidence intervals, have been identified but more work is required to pinpoint the specific areas that can be improved upon.

5.2.3. Work required

Work for this RO would be broken down into four steps:

5.2.3.1. RO 4.2a Assessment of current understanding, collation of available data and "best" approaches of data analysis

Systematic review of current available population abundance estimates data and methods, including data collection and analysis, to identify the factors potentially introducing uncertainty in population abundance estimates. The challenges and sources of error are likely be colony specific as each colony has different accessibility, habitat, and topography, etc. For example, on Rum, burrow flooding and therefore burrow characteristics are likely to be an important source of error. This review would include comparison of approaches under different circumstances, such as the time/resources available for surveys and the type of colony. Outputs if this sub-RO could include best practice recommendations

5.2.3.2. RO 4.2b Focussed analysis of existing data to fully understand the sources of uncertainty

Assessment of the relative contribution of variables identified in RO 4.2a to error/uncertainty in population abundance estimates, through for example sensitivity analysis of abundance estimates to those identified sources of error. Where datasets exist, this analysis could be conducted on data collected from a colony or several colonies that are in proximity to OWFs, and with which seabirds may interact. This will allow the opportunity for hypotheses to be tested.

5.2.3.3. RO4.2c Modelling

Once the main variables contributing uncertainty have been identified through a literature review, consultation with experts and analysis of existing data (sub-ROs a & b), they need to be captured in models estimating population size. Modelling will allow the relative importance in driving population size estimates to be quantified, and recommendations could be made to improve population estimates. For example, this could include targeting collection of data on the most relevant variables that drive uncertainty so that it is captured in future modelling.

5.2.3.4. RO 4.2d Review of field techniques for burrow monitoring and development of best practice guidelines

This final stage would build on the recommendations made under sub-RO 4.2c. One of the most important features of population abundance data in the future should be uniformity across populations. This would require data collection to be standardised so that new analytical methods, such as the Shiny App, can be used for all surveys and results can be compared between all colonies around the UK, which will be vital for trend analysis on a broader scale. Given the complex nature of data collection for these species, consideration should be given to colonies where only short visits are possible. Identifying a method for these scenarios, which provides robust detection and response rates, would also be very beneficial, especially if they can be compared in some way with more extensive surveys.

This review should include:

- Information gathering from fieldworkers on use of and applications of endoscopes
- Best use of endoscope, survey, calibration of detection/response rate
- Recommendations on equipment specifications for each species, different colonies
- Best practice guidelines to minimise injury risk/disturbance

5.2.4. Benefits/key outcomes

This RO will allow the specific sources of uncertainty to be identified and the validity and level of representation that sample plots provide as an alternative to whole island counts. Once the sources of uncertainty are identified, work can be initiated to identify solutions to the problems so that eventually the confidence limits of population estimates can be narrowed. Reducing the confidence intervals around abundance estimates will go some way to improving the confidence of predictions of the relative magnitude and the population consequences of impact from OWFs.

This RO will work alongside RO 4.3 and 4.6 to improve the current methodology and reduce uncertainty around population estimates of these difficult to monitor species.

5.2.5. Risks/inter-dependencies

There is a possibility that sources of error/uncertainty may be site-specific. These ultimately may be addressed with site-specific correction factors (e.g. if response rates at different sites are different), but there remains a risk that a generic 'fix' is not possible. Site-specific adjustments could be made to survey/analysis methods, but this would risk the ability to compare results from sites, or to reliably derive wider population abundances and trends. There may not be the ability therefore to reduce uncertainty without unintended consequences. However, even if this were the case, there would still be a better understanding of the influence and source of uncertainty, and these caveats could be considered in a more evidenced way when assessing the impact of OWFs.

5.2.6. Predicted resources required to deliver this RO

5.2.6.1. RO 4.2a Assessment of current understanding, collation of available data and "best" approaches of data analysis

As this is desk based the resource requirements will be:
LOW resource requirements (less than one year and less than £100,000).

5.2.6.2. RO 4.2b Focussed analysis of existing data to fully understand the sources of uncertainty

As this is desk based the resource requirements will be:
LOW resource requirements (less than one year and less than £100,000).

5.2.6.3. RO4.2c Field study to compare sample plots to a census of an area

This RO would require field work although this would not necessarily need to be a long-term study:
MEDIUM (2 or more years and up to £500,000, potentially more depending on the number of colonies and individuals sampled).

5.2.6.4. RO 4.2d Review of field techniques for burrow monitoring and development of best practice guidelines

LOW resource requirements (less than one year and less than £100,000).

5.3. RO 4.3 Improving estimates of response rate in playback surveys

5.3.1. Evidence needs/rationale

A standard technique for determining adult nest occupancy and hence estimating abundance for European storm-petrels and Manx shearwaters is the use of call playback. An accurate estimate of response rate is vital when conducting tape playback surveys to apply an appropriate correction when estimating total abundance. Other methods of confirming occupancy (e.g. using a burrow scope), are available but are expensive, can be temperamental and will not always reach the end of deep burrows. Their use in validating survey results is therefore limited but may provide a way of verifying results of tape playback as part of response rate/calibration. Evidence has shown that there are a variety of factors that influence whether birds respond or not and there will always be some birds that do not respond. Whilst current methods employ several improvements to attempt to reduce uncertainty and improve estimates (increased scale of calibration surveys, number of visits increased, visiting multiple habitat types, improving tape quality, and using dual-call tape) response rate is still a source of error contributing to the uncertainty around abundance estimates.

5.3.2. Work already underway

Response rates have been identified as a key contributor to wide confidence limits in multiple studies as it is highly variable, there are multiple factors which contribute to this, including detection rate, stimulus used and observer error (Lavers *et al.* 2019; Ratcliffe *et al.* 1998; Soanes *et al.* 2012). This has been the case for some time and has been addressed to some extent with the development of dual-call playback, using habitat specific response rates and the use of modelling approaches such as HDS. HDS, as described by Deakin *et al.* (2021), allows the estimation of response rate, detection rate and population abundance at the same time, which can then be related to environmental variables and allow the prediction of abundance in other areas. This method appears to be significantly less labour intensive than the current methods which involve separate sampling to establish response rate and calibrate for individuals that do not respond to tape playback.

5.3.3. Work required

This RO would be broken down into two work packages:

5.3.3.1. RO 4.3a Review and analysis of existing data on response rate including alternative methods

This RO would initially seek to identify the key sources of error when undertaking tape playback calibration work, including the consideration of habitat type, topographical features, observer error and the possible effect of the individual. It would go on to review the alternative methods for estimating response rate, such as hierarchical modelling techniques as used by Deakin *et al.* (2021) with storm-petrels on Mousa.

5.3.3.2. RO 4.3b Investigate hierarchical modelling techniques

Deakin *et al.* (2021) suggest that hierarchical modelling techniques have good potential but that more work would be beneficial to ensure that the assumptions made in the complex model are met, however it would lead to more precise population estimates. The authors make several recommendations on how the method could be validated/improved. In terms of survey design, they highlighted the importance of accurate assessment of colony extent and how to define a sampling strategy. They also suggested that using simulated datasets with known population sizes, response rates and detection rates would be useful to assess directionality effects. This step would aim carry out these suggestions and help refine/improve the method.

5.3.4. Benefits/key outcomes

The current method for calibration combines the probability of detection and likelihood to respond to playback as one value, response rate. Using hierarchical modelling allows these parameters to be estimated separately which should allow for more accurate identification of uncertainty. Identifying the drivers of this uncertainty will potentially allow it to be reduced in the future. As for RO 4.2, reducing the confidence intervals around abundance estimates could improve the confidence of predictions of the relative magnitude and the population consequences of impact from OW.

This RO will work alongside RO 4.2 and 4.6 to improve the current methodology and reduce uncertainty around population estimates of these difficult to monitor species.

5.3.5. Risks/inter-dependencies

This source of error is likely to be identified by RO 4.2a. However, it has already been highlighted as a major contribution to uncertainties in population abundance estimates throughout the literature and by stakeholders, and RO 4.3 is therefore not reliant on the outputs of RO 4.2.

Hierarchical modelling is already tested for this species (e.g. Deakin *et al.* 2021) and therefore there is limited risk of it not being of value at other colonies.

5.3.6. Predicted resources required to deliver this RO

5.3.6.1. RO 4.3a Review and analysis of existing data on response rate including alternative methods

This work package will be desk-based:
LOW resource requirements (less than one year and less than £100,000).

5.3.6.2. RO 4.3b Investigate hierarchical modelling techniques

This work package will be desk-based:
LOW resource requirements (less than one year and less than £100,000).

5.4. RO 4.4 Investigation into the suitability and applications of acoustic techniques to monitor Procellariiformes

5.4.1. Evidence needs/rationale

Monitoring of nocturnal, burrow-nesting birds in its current form is unavoidably a labour-intensive process that requires significant effort and resources, particularly when surveys are conducted on remote, difficult to access islands. In some cases, it is simply not possible to deploy fieldworkers to some islands or specific colonies, so remote methods are required either to confirm presence or absence, or potentially make assessments of population numbers or colony extent. Increasingly, new technologies are being explored and utilised to increase the efficiency of data collection whilst gathering high-quality data to the same standards. Acoustic monitoring is such a technology that can be applicable to these seabirds as they have distinctive calls and call frequently at the colony.

The technology to carry out acoustic monitoring exists and is relatively inexpensive (e.g. AudioMoths), therefore this is the primary focus of this RO, however there are other potential methods that may be beneficial or may present a suitable alternative which will be investigated under stage one of this RO. There are several potential applications for these devices; to determine presence/absence at previously un-surveyed locations, to gain a better understanding of colony extent or distribution across a large area or to estimate colony size/density.

5.4.2. Work already underway

Identifying and testing alternatives to traditional monitoring techniques is increasing in seabird ecology in an attempt to find cheaper and less labour-intensive methods of making population assessments. For vocal species, including Procellariiformes, acoustic monitoring has been investigated for several species around the world, including Manx shearwaters and Leach's storm-petrels (Arneill *et al.* 2020; Borker *et al.* 2014; Buxton and Jones 2012; Oppel *et al.* 2014; Orben *et al.* 2019). Acoustic monitoring is not widely used in the UK but has been attempted for Manx shearwaters, using vocal activity at the colony as a proxy for population density (Arneill *et al.* 2020). This study found that although there is potential for use of this sort of method, there was no correlation between acoustic activity and population density (Arneill *et al.* 2019). Acoustic monitoring has been proven to estimate population size of other shearwater species, such as the Cory's shearwater (*Calonectris borealis*), and other seabirds such as Forster's terns (*Sterna forsteri*) to an equivalent level of accuracy as other methods (Borker *et al.* 2014; Oppel *et al*. *2014).*

5.4.3. Work required

This RO would be broken down into four work packages:

5.4.3.1. RO 4.4a Conduct a literature review of studies using acoustic monitoring for seabirds

A review to examine the utility and limitations of acoustic monitoring for seabirds, to identify the priorities and identify the areas where we can gain the best returns and value from using this sort of technology. This would include the need for and use of correction factors, review methods, assess protocols and practicalities for remote deployment/retrieval, device upkeep and data cleaning. The scope of this RO should also include the review of potential complementary technology or methods that might aid data processing and analysis and help to account for uncertainty or improve confidence in the results. Finally, alternative remote monitoring techniques, including but not limited to camera traps, should also be investigated, and compared with acoustic monitoring to establish the benefits and limitations of the different methods.

5.4.3.2. RO 4.4b Establish a methodology

This project would in part be dependent on the outcome of part RO 4.4a. If this technology is only appropriate for colony identification and assessment of colony extent, then an exercise would be required to identify where and how devices could be deployed and the time scales of deployment. If this technology could be used to assess colony density and/or be used as a proxy to estimate abundance then a sampling strategy would need to be established (e.g. array vs. transect approach), in addition to where it would be conducted. This step would also need to consider what form the data will take, the limitations of that data and what sort of analyses could be conducted, for example, how an index of call density/intensity can be used to estimate actual abundance.

5.4.3.3. RO 4.4c Field test

This work package would put into practice the work carried out under RO 4.4b, to assess the ability to deploy in remote locations and investigate the limitations of the technology (e.g. data download, battery life, weather proofing). It would allow the collection of data in a controlled environment where the efficacy of the technology can be regularly monitored, and any failures can be promptly resolved. A field test should also act as a calibration alongside other monitoring methods, as described in Arneill *et al.* (2020).

5.4.3.4. RO 4.4d Roll-out

Based on the outcome of 4.4b and 4.4c, acoustic monitoring would be deployed to remote colonies where traditional monitoring is very difficult or not possible.

5.4.4. Benefits/key outcomes

The benefits will be defined by the potential application of this technology. Colony identification is a very valuable use of this technology as it reduces the resource requirements of a team going out to remote locations, and offsets the logistical challenges around field work on islands. This would allow just two visits to be made, one to deploy the devices and another to retrieve them. In this case the analysis would be very simple. If presence of breeding birds was identified then survey effort/resources could be deployed at a later stage, and if colony extent could be estimated by presence/absence of calls then resources and time can be more accurately directed.

The application of this technology to answer more complex questions around population density and/or abundance would require significantly more investment in terms of time and resources but would return significantly greater benefits. It has the potential to produce estimates of abundance without the significant input of time and resources that more traditional methods require (although the requirements of deployment of sensors, retrieval of data, etc., should not be underestimated). It also has the potential to aid (through identification of colony extent) or provide more complete estimates of colony abundance, which would provide a more robust baseline upon which to base impact assessment.

5.4.5. Risks/inter-dependencies

Experience thus far with AudioMoths is that they are relatively reliable and low maintenance. There is however a risk that deployment of technological solutions brings its own issues of data recovery, reliability, etc., and are not always the solution to resource-intensive methods involving extensive fieldwork. This would be mitigated by the review and testing of technology proposed in RO 4.4a and 4.4c. Robust field testing, particularly if several technologies are identified as having potential, may be resource intensive, even if done only at one/few locations.

There is risk that the review and testing would demonstrate that such technologies could not be deployed at large scale, and there may not be the ability to monitor more remote/inaccessible colonies as hoped.

5.4.6. Predicted resources required to deliver this RO

5.4.6.1. RO 4.4a Conduct a literature review of studies using acoustic monitoring for seabirds

This work package will be desk-based:
LOW resource requirements (less than one year and less than £100,000).

5.4.6.2. RO 4.4b Establish a methodology

This work package will be desk-based:
LOW resource requirements (less than one year and less than £100,000).

5.4.6.3. RO 4.4c Field test

The work package would require fieldwork and investment in technology:
MEDIUM (two or more years and up to £500,000, potentially more depending on the number of colonies and individuals sampled).

5.4.6.4. RO 4.4d Roll-out

The work package would require fieldwork and investment in technology across multiple sites and years:
MEDIUM (two or more years and up to £500,000, potentially more depending on the number of colonies and individuals sampled).

5.5. RO 4.5 Development of Species Distribution Models to predict suitable colony locations

5.5.1. Evidence needs/rationale

SDMs are a vital method used to describe, predict, and project species ranges and their use has increasing in studies predicting present and future distribution of species (Robinson *et al.* 2017). Recent advances have led to the development of models that combine terrestrial and marine variables, which is vital when considering species such as seabirds that require both habitats during their annual cycle (Häkkinen *et al.* 2021). This method can act as an important tool and can incorporate information from both terrestrial and marine habitats to construct models that can accurately predict species ranges and how they may change in the future, which will be vital when considering planning for OWF going forward (Häkkinen *et al.* 2021).

5.5.2. Work underway

Recent advances to modelling at a broad scale have incorporated both marine and terrestrial variables which better represents the two niches that seabirds occupy, their land-based breeding sites and the marine environment for foraging (Critchley *et al.* 2020; Häkkinen *et al.* 2021). The inclusion of both terrestrial and marine variables into SDMs improved the accuracy of the models both in terms of specificity and sensitivity (Häkkinen *et al.* 2021).

5.5.3. Work required

This RO would be broken down into four work packages:

5.5.3.1. RO 4.5a Review of terrestrial and marine variables that may predict Manx shearwater and European storm-petrel distribution

Literature review to identify the key factors influencing the breeding locations of these species, including marine and terrestrial environmental and geographical variables, prey distribution and ecological variables such as the proximity to other colonies.

5.5.3.2. RO 4.5b Apply "Häkkinen model" to Manx shearwater and European storm-petrel to test the ability of the model to predict the location of known colonies

Using outputs of RO 4.5a to apply the "Häkkinen model" to Manx shearwater and European storm-petrel to assess whether we have sufficient data and understanding of species ecology to predict the location of known colonies.

5.5.3.3. RO 4.5c Apply Species Distribution Models, using terrestrial and marine variables, to Manx shearwater and European storm-petrel to predict currently unidentified colonies

Based on the outputs of RO 4.5b, if successful, apply the model to predict the location of currently unidentified colonies suitable for breeding Manx shearwater and European storm-petrel.

5.5.3.4. RO 4.5d Validation of model predictions

This final stage will examine the predictions made under 4.5c to ensure that the evidence is robust and can contribute effectively to impact assessments.

5.5.4. Benefits/key outcomes

This RO would provide a more complete understanding of the breeding (colony) distribution of both species. This has several benefits with regards to assessment of OWF impacts. It will provide information on potential linkage between individual breeding colonies and current/future offshore wind areas. This will aid in defining which SPAs should be included in HRA considerations. It will also provide a more robust basis on which to base impact apportioning, by providing information on the potential origin and proportion of birds using a marine area.

In addition, it could direct census effort, RO 4.8, to ensure better UK-wide coverage and understanding, potentially focusing on those colonies with demonstrated linkage to OWF areas. This could be facilitated using the outcomes of RO 4.4, once potential new colony locations have been identified using the models, acoustic monitoring devices could be deployed to confirm presence/absence of birds.

5.5.5. Risks/inter-dependencies

There may be insufficient understanding of relevant factors, or insufficient data to extrapolate beyond known colonies. There is also the potential that statistical models may not be able to predict with sufficient spatial resolution to inform census strategies.

5.5.6. Predicted resources required to deliver this RO

5.5.6.1. RO 4.5a Review of terrestrial and marine variables that may predict Manx shearwater and European storm-petrel distribution

This work package will be desk-based:
LOW resource requirements (less than one year and less than £100,000).

5.5.6.2. RO 4.5b Apply "Häkkinen model" to Manx shearwater and European storm-petrel to test the ability of the model to predict potential colonies

This work package will be desk-based:
LOW resource requirements (less than one year and less than £100,000).

5.5.6.3. RO 4.5c Apply Species Distribution Models, using terrestrial and marine variables, to Manx shearwater and European storm-petrel to predict currently unidentified colonies

This work package will be desk-based:
LOW resource requirements (less than one year and less than £100,000).

5.5.6.4. RO 4.5d Validation of model predictions

This work package will be desk-based:
LOW resource requirements (less than one year and less than £100,000).

5.6. RO 4.6 Apply habitat models to assess extent and distribution of suitable habitat to focus future effort

5.6.1. Evidence needs/rationale

A key part of Manx shearwater and storm-petrel ecology is their propensity to nest on islands, driven by lower predation pressure, particularly from land-based predators such as rats. The UK has a vast array of islands and the size, topography and accessibility vary widely. Some islands such as Skomer and Skokholm are relatively small, close to the mainland and are easily accessible to researchers. They are also less complex in terms of their topography; they are largely flat, and the terrain is more manageable. For these reasons among others, the seabird populations there are some of the most well understood in the UK. This cannot be said for other colonies. For example, Rum, is 50 times larger than Skomer and at the highest point is at 10 times the altitude. As part of a MarPAMM study (which has contributed to Seabirds Count) a team from Exeter University completed a census of Manx shearwaters on Rum and during the survey climbed the equivalent of Mount Everest to complete their work. In addition to the mountainous terrain the habitat is also considerably more heterogeneous than some other islands, and the researchers identified that colony extent was one of the most significant sources of uncertainty during the census.

Poor accessibility to islands, difficult terrain and the length of time needed to carry out surveys are part of the reason that counting these species is so difficult. Being able to accurately identify suitable habitat and define colony extent would allow effort to be focussed to key areas, reducing the time needed at a site and the manpower required. Arneill *et al.* found that if monitoring effort can be focussed to sample plots that have high burrow densities, then fewer plots could be monitored, requiring less effort than a full census, whilst providing more statistical power to detect modest population changes. Identifying "key" representative plots at each colony through a combination of habitat modelling and density assessments, may lead to a significant reduction in resources and time required for surveys whilst generating results that provide more power to detect population level change (Arneill *et al.* 2019). Arneill's method is not an alternative to a comprehensive whole-island survey to establish total population size but could be employed on a more regular basis at selected sites to detect population trends (2019).

5.6.2. Work underway

In addition to predicting distribution across a broad scale (RO 4.5), SDMs have been applied to specific habitat types within individual areas/islands, to predict the specific breeding habitat distribution (Arneill 2018). Arneill (2018) found that both Manx shearwater and European storm-petrel distribution across six UK colonies was able to be accurately predicted using key topographical and vegetation type variables. The study suggested that models should be transferable across different sites but recognised that the same predictive variables from one colony may not be applicable to all colonies, as for example, shearwaters on Rum nest at considerably higher altitudes than the colonies sampled for the models (Arneill 2018). But the use of these models, with some additional variables such as soil characteristics and with some ground-truthing work could further improve predictive power and allow extrapolation to other sites (Arneill 2018). Further work by Arneill *et al.* (2019) found that current sampling strategies may not have statistical power to detect change, and that by strategically selecting sample plots with high burrow densities this power increases, while reducing effort. Combining the modelling approaches from both studies could allow the prediction of high-density areas of both storm-petrels and Manx shearwaters using habitat as a predictor, then focussing monitoring efforts here to provide robust results with the power to detect population change (Arneill 2018; Arneill *et al.* 2019).

5.6.3. Work required

This RO would be split into three work packages:

5.6.3.1. RO 4.6a Carry out habitat mapping using high resolution imagery, ground-truthed using habitat surveys/dogs

High resolution habitat/topographical mapping would be required for key colonies of interest. Habitat mapping of sufficient quality may already be available where this has been undertaken for, for example designated habitat condition assessment, but may need to be carried out. Care should be taken to ensure that mapping accounts for conditions during the breeding season, for example surveys completed during the winter would not be able to account for vegetation that dies back (e.g. bracken), which could have a significant impact on species distribution.

5.6.3.2. RO 4.6b Apply models to islands where access is very difficult

This work package would allow prediction of whether suitable habitat is present, assess extent of habitat, potentially predict population through extrapolation of survey results to the extent of suitable habitat within a colony, and allow direction of survey effort to reduce time required/staff needed for surveys

5.6.3.3. RO 4.6c Validation of models

Once models have been applied to any islands/colonies it is essential to carry out validation, which would require the undertaking of a survey using traditional playback methods. This would highlight any inaccuracies with the method.

5.6.4. Benefits/key outcomes

As outlined by Arneill (2018; *et al.* 2019), current survey methods have the potential to be streamlined and better directed whilst still achieving the same results. Carrying out full censuses requires surveys of a vast area in most cases. If suitable habitat can be identified before surveys are carried out then survey effort can be deployed to maximise the outputs whilst being strategic about the use of resources, with the results of surveys more robustly extrapolated to un-surveyed areas of suitable habitat. This in turn would provide more robust abundance estimates upon which to base impact assessment.

The use of habitat mapping for carrying out census of Manx shearwaters has already been used on Rum, although ground-truthing of the method is still required. Therefore, this site, and the results/methods might be a good fit for this RO, to build on the work already completed and potentially reduce the confidence intervals for population estimates at a key site for Manx shearwaters.

Efficiency savings would potentially reduce the resource requirements of abundance monitoring at individual sites. This freed resource could be used in other endeavours, for example in expanding monitoring or more intensive/frequent survey effort at key sites.

5.6.5. Risks/inter-dependencies

A risk of this RO is the fact that there are significant differences in topography and vegetation diversity/composition between UK islands, models trialled and developed, for example, on Rum, may not be appropriate or applicable for other islands which may have very different habitat characteristics. If a bespoke model must be developed for each island it will be much more expensive and time consuming to apply than a model that could be used across the board.

This RO has synergies and potential efficiencies with RO 4.5, where use of habitat mapping, and identification of key sites are proposed. There are therefore clear efficiencies where this work could be combined, but this RO is not reliant on other ROs proceeding. A key risk to this project is the availability, or ability to collect, interpret and ground-truth high resolution mapping to inform the modelling proposed in RO 4.6b. This would need a different skill set than that of traditional census fieldwork.

5.6.6. Predicted resources required to deliver this RO

5.6.6.1. RO 4.6a Carry out habitat mapping using high resolution imagery, ground-truthed using habitat surveys/dogs

This would require the use of specialist equipment and expertise:
MEDIUM (two or more years and up to £500,000, potentially more depending on the cost of equipment, access to colonies and analysis).

5.6.6.2. RO 4.6b Apply models to islands where access is very difficult

This would require the use of specialist equipment and expertise:
MEDIUM (two or more years and up to £500,000, potentially more depending on the cost of equipment, access to colonies and analysis).

5.6.6.3. RO 4.6c Validation of models

This work package will be desk-based:
LOW resource requirements (less than one year and less than £100,000).

5.7. RO 4.7 Use of scent-detection dogs to explore/characterise new colonies

5.7.1. Evidence needs/rationale

A lot of work has been carried out over many years to make improvements to the current methods of monitoring for burrow-nesting seabirds. The methods have been refined and we currently have the best available estimates of these populations but carrying out surveys using traditional methods is incredibly time consuming and resource heavy, particularly if the populations are small, dispersed and in challenging terrain. Consequently, monitoring on a UK-scale only occurs every 15–20 years. Carrying out accurate surveys more regularly would make significant improvements to our understanding of population trends. The use of scent detection dogs to carry out population estimates is a technique that has been used around the world for different species and is thought to be underutilised for seabirds (Bolton *et al.* 2021). There are several ways in which trained dogs could improve our understanding: they could carry out exploratory surveys on islands where breeding has not been proven and they could help to define the extent of colonies in complex, heterogenous habitats where colonies are sparse and could carry out systematic surveys. The use of dogs in one of these scenarios has already been proven to be successful in a colony where breeding of storm-petrels has been suspected but never proven using traditional techniques (NatureScot 2021).

There are several islands around the UK that have never been surveyed for burrow-nesting seabirds such as storm-petrels and Manx shearwaters, which may be appropriate for colonies of these species to exist (such locations could be identified as part of RO 4.5). Once potential locations for unknown colonies have been established, using scent-detection dogs may be the most cost- and time-effective method of undertaking surveys as current evidence suggests that in the same time period a dog can cover up to six times as many burrows than playback sampling (Bolton *et al.* 2021).

5.7.2. Work already underway

Scent-detection dogs are widely used around the world for a variety of purposes but are potentially underutilised in seabird conservation in the UK. There are a couple of recent examples of dogs being trained and used for seabird monitoring, with European storm-petrel breeding confirmed on the Isle of May, Manx shearwater burrows being identified on Ramsey and the ability of dogs to distinguish between the two species being proven, but there is certainly potential for expansion (Bolton *et al.* 2021; NatureScot 2021).

5.7.3. Work required

This RO would be split into three work packages:

5.7.3.1. RO 4.7a Training of scent-detection dogs

Dog training and trials would need to be carried out. The training period for a dog is initially 3-4 months and would require samples for each species to be collected (either feather or faecal samples), and this would include Manx shearwater, European storm-petrel and Leach’s storm-petrel. Depending on the islands that will be sampled it may be necessary to also use puffin samples to ensure that the dogs can differentiate between puffins and shearwaters. Dogs would also require some training to ensure they can safely travel to the islands, in addition to familiarisation and desensitisation to boats (possibly helicopters depending on the location).

5.7.3.2. RO 4.7b Trial stage

Once dogs have been trained, trials would be carried out at a site to evaluate the precision and efficiency of the dogs, as well as to assess the logistical issues and potential for disturbance to seabirds during/after surveys. This would need to be done where burrows can be sampled by endoscope or manually to confirm occupancy and species present and potentially where behaviour of birds can be monitored before/during/after the dogs have been present to investigate any impacts.

As part of this trial a comparison between traditional methods, tape playback, and the use of scent detection dogs to carry out a population estimate should be carried out to assess the precision of the method and the level of survey effort required. This comparison will allow the evaluation of the relative effectiveness of using detection dogs vs. traditional methods.

5.7.3.3. RO 4.7c Use of dogs to identify new colonies or survey existing colonies

This stage is reliant on stages a and b, if the use of dogs is found to be time- and cost-efficient and is not deemed to cause disturbance to seabirds, then this method could be deployed in multiple scenarios. Dogs could be used on islands where breeding of shearwaters and/or petrels is suspected but has not been confirmed (using outputs of RO 4.5), or to assess extent of difficult to access colonies or simply carry out population surveys if this method is shown to be more efficient than traditional methods.

5.7.4. Benefits/key outcomes

The use of a scent-detection dog to conduct exploratory surveys has the potential to reduce the effort and resource requirements of identifying new colonies. Dogs can cover a considerable area in a short period of time, even with the requirement for breaks. This method has been proven to work on the Isle of May where storm-petrel breeding was thought to occur but was never confirmed before dog surveys were carried out.

This has the potential to be a cost-effective way of identifying new colonies as once the dog has been trained the costs are estimated to be ~£90 per day (in addition to travel and accommodation costs). The costs of sending fieldworkers to carry out surveys would likely be much higher and take longer.

This method could work alongside RO 4.6 to help with ground-truthing of habitat mapping completed using drones. Dogs could also be used to help define colony extent in complex habitats. Habitat and vegetation types have been shown to be accurate predictors of burrowing seabird distribution; therefore, habitat mapping could be a useful tool to assess population distribution. This method is still relatively new and will in some areas need ground truthing (e.g. Rum). Dogs could be deployed alongside drone surveys to confirm colony extent and verify the predictions made based on habitat, but this would only occur once the accuracy and efficiency of using dogs has been fully assessed.

5.7.5. Risks/inter-dependencies

Training a dog for this specific purpose, to the scent of these seabirds is time-consuming and would only be done if there was a guarantee of enough work to justify the time and cost, therefore there would need be a certain level of commitment to this method from the outset.

This method has already been proven to work, including the ability of a dog to differentiate between storm-petrels and Manx shearwaters, so their ability to be trained for this purpose does not appear to be a significant risk. There is risk in the application of dogs to carry out these surveys, although they can cover ground much more quickly than humans these are complex habitats, often very dense colonies and there is a risk associated with potential disturbance of breeding birds. The trials, and comparison between dogs and traditional methods may show that dogs are not accurate enough over an entire survey and that any reduction in survey time is at the expense of precision.

5.7.6. Predicted resources required to deliver this RO

5.7.6.1. RO 4.7a Training of scent-detection dogs

LOW (training would take 3–4 months and could be done remotely with an estimated cost of £10–15,000).

5.7.6.2. RO 4.7b Trial stage

LOW resource requirements (less than one year and less than £100,000).

5.7.6.3. RO 4.7c Use of dogs to identify new colonies or survey existing colonies

LOW resource requirements (less than one year and less than £100,000).

5.8. RO 4.8 Expansion of annual monitoring for Manx shearwaters and European storm-petrels

5.8.1. Evidence needs/rationale

This RO will be informed by the work carried out on census methods/techniques, demographic rate and tracking ROs and can work either alongside these or be a subsequent exercise, but should ideally follow the review and gap analyses (RO 4.1 & 4.13). This can be a dynamic process whereby future data collection can be conducted in the more efficient, robust, and comparable way both geographically and temporally. The work packages below will first establish the requirements for any expansion of existing survey and tracking programs or for monitoring at new sites, priority will be given to colonies that have links to the sites of proposed developments that are part of Round 4 in England, ScotWind, Celtic Seas and floating wind developments. Colonies that already have existing/ongoing monitoring should also take precedence, particularly if they have long-term datasets.

For conciseness, this RO is assigned to both species, however it does not necessarily mean that this RO cannot be divided by species if taken forward to the scope of work stage. It is understood that there are differences in the ways in which monitoring and tracking are carried out for each species, that both species are not necessarily found at the same locations and priority sites for each species may differ.

5.8.2. Work already underway

Monitoring currently occurs either annually or periodically, see Section 3 (Existing Evidence and Understanding) for a detailed summary. Work is carried out either as part of national monitoring schemes, such as the SMP and RAS network, or by academic institutions conducting research.

5.8.3. Work required

This RO will be made up of two work packages:

5.8.3.1. RO 4.8a Feasibility review

This stage will be informed by RO 4.1 and 4.13 which will undertake gap analyses to identify the number of potential sites required, either for expansion of existing monitoring or establishment of new sites. Outcomes of other ROs should also be taken into consideration when undertaking new monitoring, such as the application of new techniques or the identification of specific data needs (for example RO 4.4, 4.5 & 4.6) and/or development of best practice guidelines (RO 4.2). Efforts should be concentrated to sites that already have data but need support or development and sites where annual monitoring could be established rather than one-off counts.

Once sites have been identified a feasibility review will be necessary to estimate the resources required to establish new sites or enhance existing ones. The review should identify possible project partners, potentially run workshops with stakeholders at existing monitoring sites to collaborate on future directions, resource requirements and logistics.

5.8.3.2. RO 4.8b Roll out

This project would see the roll out of census, demographic rate monitoring and tracking to multiple colonies and over multiple years. The specific locations, frequency and methods would be determined by the previous steps in this RO.

5.8.4. Benefits/key outcomes

This work would significantly improve our understanding of population dynamics, trends and at-sea distributions for these species. This is particularly important in the context of rapid OW expansion and would go some way to action the recommendations in Cook *et al.* (2019) in support of the national census and expansion (geographic and temporal) of monitoring to additional key sites. This will be particularly important with a large focus on expansion of OWF through Round 4 and ScotWind being on the west and north coasts of the UK, and the relatively little monitoring of colonies that is currently undertaken at those colonies closest to this expansion and potentially most directly affected.

Roll out of a more strategic and geographically complete abundance monitoring campaign is important in relation to OWF impact assessments for all the reasons highlighted in RO 4.1–4.7:

- Robust colony, regional and national abundance estimates
- Robust trends
- Understanding of linkage between breeding colonies and individual marine areas (e.g. OWF arrays)
- Ability to apportion impacts at an OWF array to breeding colonies in a more evidenced way than assumptions about foraging range.

5.8.5. Risks/inter-dependencies

This RO builds on the culmination of work carried out under ROs 4.1 and 4.13 and is therefore dependent upon the outcomes of them. It should consider the outcomes and/or recommendations of both demographic rates and abundance ROs together, so that effort across the season is efficient in terms of field work and statistical power can be maximised.

This RO should work synergistically alongside ROs 4.3 to 4.12, the development of demographic rate monitoring and methods for estimating abundance. It is likely that these ROs should be undertaken, at least in part together to make the most efficient use of resources and produce the most robust and complete data to feed into assessments. As has been demonstrated by Wood *et al.* (2021), collecting varied demographic data alongside population data can provide the best understanding of what is happening in a population. Although the work itself, including the methodologies, for collecting demographic and population data are different, they would both require significant investment of resources if undertaken separately, therefore conducting them alongside each other would not only provide more robust data, but be a more efficient use of resources. Given that all three areas of focus will require building on current knowledge, it is likely that the same islands/colonies will be candidates for all aspects of monitoring.

5.8.6. Predicted resources required to deliver this RO

5.8.6.1. RO 4.8a Feasibility review

This work package will be desk-based:
LOW resource requirements (less than one year and less than £100,000).

5.8.6.2. RO 4.8b Roll out

HIGH (several years and over £500,000), best achieved through collaborative approach.

5.9. RO 4.9 Improving estimates of Manx shearwater and European storm-petrel adult survival

5.9.1. Evidence needs/rationale

Sensitivity analysis (Cook & Robinson 2016) has shown that although all demographic parameters are important to PVA, adult survival can have the greatest influence over the results, particularly as both species are long-lived, have low fecundity and improve their reproductive success as they get older. This was also reflected in the advice received during workshop discussions as being the most important parameter of PVA to improve.

5.9.2. Work already underway

There are established adult survival projects ongoing around the UK, specifically as part of the SMP and studies as part of RAS. For storm-petrel, of the known studies that were assessed by Horswill *et al.* (2016) only two were evaluated as “good” and therefore improving these existing studies in addition to establishing new studies should be considered. Establishing a ringing protocol to ensure that tape-lures are not used as part of RAS ringing studies could be useful to reduce bias/error in current estimates.

The recent publication by Wood *et al.* (2021) highlights the need to consider the impact of individual quality, or demographic profile, of birds within a population. The work carried out on Skomer Island demonstrated that what was previously thought to be a colony (Isthmus plot) with a lower-than-expected adult survival is made up of individuals that display different survival rates. This study suggests that more detailed modelling and analysis of existing data could provide more precise adult survival estimates, although it is uncertain how many datasets exist in the UK that are comprehensive enough to conduct such analysis.

The aim of this RO is to use available data to improve current estimates of adult survival, to ensure that data collection is standardised and to expand data collection to key colonies.

Evidence has demonstrated that adult survival varies between individuals, and there is the potential for variation between colonies

5.9.3. Work required

This RO would be split into five work packages:

5.9.3.1. RO 4.9a Review of existing data

The present literature review and workshop highlighted that there is potentially more data on mark-recapture available that just than just from Skomer (e.g. Copeland; Reid, N. Pers. Comm.), and that this could be a source for increasing confidence in demographic rate estimations. Wood *et al.* (2021) demonstrates how such data could be analysed. A first step therefore is to identify colonies where data are available to assess the demographic influences on survival and recapture probability. This would be a desk-based exercise.

5.9.3.2. RO 4.9b Carry out modelling of existing data to improve understanding of adult survival at the colony

Following on from RO 4.9a, use modelling methods as set out by Wood *et al.* (2021) to undertake modelling of available data. This analysis may demonstrate that adult survival rates do not vary significantly across colonies, in which case a generic adult survival rate could be applied within population modelling. Alternatively, it may demonstrate that there is variation between colonies, and would provide site-specific rates for those colonies where there are sufficient data. In addition, where variation is found, but a generic survival rate needs to be applied to colonies with insufficient data for analysis, there would be an understanding of inter-colony variance and the survival rates for the nearest similar colonies.

5.9.3.3. RO 4.9c Feasibility review of adding adult survival monitoring to existing monitoring programs

Building on the analysis in 4.9a (empirical or expert opinion), which will show gaps in knowledge, this activity would be a review of where adult survival monitoring could be added to sites already conducting productivity monitoring, a review of the feasibility of addition, and for which sites this addition could be advantageous for improving adult survival estimates, particularly with regard to sufficient geographic coverage of areas/colonies where there is potential for interaction with current and future OWF development. This would include estimation of expected re-capture rate and hence sample size required at each site.

5.9.3.4. RO 4.9d Designing a protocol, based on SMP methods, for data collection

One of the potential issues with the current system is that data are not all collected in the same way and therefore comparison is not always possible or has to be caveated. Standardising this and coordinating adult survival and productivity monitoring would ensure all data are comparable and would ensure that methods, analysis, and inferences made are robust.

5.9.3.5. RO 4.9e Roll out of adult survival monitoring at appropriate colonies

Based on the outputs from 4.9d, UK roll-out, over multiple colonies and years as informed by the outcomes of the RO 4.1 gap and power analyses. Discussions during the workshop yielded several suggestions for possible sites for future monitoring, including Lundy for Manx shearwaters and Mousa/St Kilda for European storm-petrel.

5.9.4. Benefits/key outcomes

RO 4.9 a and b will allow the best use of data that are already available to improve our understanding of adult survival and productivity, in addition to the demographic profiles within each colony. ROs 4.9 c, d and e will allow the strategic expansion of adult survival monitoring to locations that already carry out monitoring and where the infrastructure is in place to support such work. Using additional monitoring at such sites will be more efficient than establishing new sites by building on existing knowledge and expertise. As Wood *et al.* (2021) have shown, adult survival, productivity and sabbaticals are all interlinked, therefore conducting this sort of modelling, and collecting data in such a way to enable future modelling, will provide good value for money and enable multiple areas of uncertainty to be addressed.

This RO will therefore allow the parameterisation of population models (e.g. NE PVA Tool which currently is not parameterised for Manx shearwater). In the shorter term, it will provide a generic adult survival rate, information on inter-colony variance in adult survival rates, and site-specific adult survival rates for colonies where there is currently sufficient data for analysis. In the longer term, this RO will standardise the methodology of data collection for adult survival rates and expand collection of this data from a more geographically representative selection of key sites. This expansion would be particularly important where inter-colony variation is likely to lead to a lack of confidence around the predictions of population modelling for colonies potentially impacted by proposed OWF (e.g. particularly those associated with ScotWind) with currently insufficient data to provide site-specific estimates.

5.9.5. Risks/inter-dependencies

Both species nest on offshore rocky islands, and as such for sub-RO 4.9e there will be some health and safety considerations for personnel involved in capturing and tagging the birds, particularly nocturnal work. Thus, ensuring staff have appropriate training prior to undertaking this work (e.g. working at heights and rope-access) will be required. This is to some extent mitigated by focusing on colonies where monitoring is already undertaken, and access and safety requirements are well understood. Additional handling/tagging effort will inevitably increase resource requirements, and there may be logistical bottlenecks (e.g. accommodation limitations, recruitment of additional fieldworkers, etc.).

The aim of this project is to collect data on a more strategic basis, with improved geographic coverage to account for any regional variation. There does remain a risk of lack of adequate geographic coverage due to lack of existing data and, for example, accessibility and logistics of collecting data from additional sites. Minimising this risk should be part of the planning stages and of RO 4.9d

5.9.6. Predicted resources required to deliver this RO

5.9.6.1. RO 4.9a Review of existing data

As this is a desk-based study, it is likely to be of restricted duration and cost.
LOW resource requirements (less than one year and less than £100,000).

5.9.6.2. RO 4.9b Carry out modelling of existing data to improve understanding of adult survival at the colony

As this is a desk-based study in the first instance, it is likely to be of restricted duration and cost. Familiarity with data of various types and format is required and experience of extracting, manipulating, and combining data from disparate sources and in various formats

is required. Experience of advanced population modelling techniques is required.
LOW resource requirements (less than one year and less than £100,000).

5.9.6.3. RO 4.9c Feasibility review of adding adult survival monitoring to existing monitoring programs

As this is a desk-based study, it is likely to be of restricted duration and cost.
LOW resource requirements (less than one year and less than £100,000).

5.9.6.4. RO 4.9d Designing a protocol, based on SMP methods, for data collection

As this is a desk-based study, it is likely to be of restricted duration and cost.
LOW resource requirements (less than one year and less than £100,000).

5.9.6.5. RO 4.9e Roll out of adult survival monitoring at appropriate colonies

Monitoring will need to be carried out for many years to provide reliable, accurate and robust estimates of adult survival; however, some initial results will be available from year two onwards. The outcome of RO 4.9c and how labour-intensive monitoring will be is a key factor in the cost of this RO. The initial set up of the monitoring plots will be the most labour-intensive part of the project, but materials (i.e. rings), are not expensive.
MEDIUM (two or more years and up to £500,000, potentially more depending on the number of colonies and individuals sampled).

5.10. RO 4.10 Improving confidence in Manx shearwater productivity

5.10.1. Evidence needs/rationale

Discussions with experts at the workshop suggested that the methodology for collection of productivity data is currently very efficient, and that there would be little value in attempting to improve the current methodology or to introduce the use of novel technology. The advice from experts during the workshop was that for both Manx shearwater and European storm-petrel, the incubation period is the time where most failures occur, and once chicks hatch, they are likely to go on to fledge, especially once they are a few days old. Once chicks reach a certain size fledging is assumed. Although there is a very small chance of predation at this stage the extra effort required to confirm fledging would not significantly improve estimates and therefore the current method of assessment is considered appropriate. The method could be streamlined even further by timing two visits at the peak incubation and chick rearing times which would reduce effort and may mean that monitoring is more feasible at remote colonies.

Productivity data collection is conducted via study plots. There is currently some uncertainty as to the representativeness of productivity in these plots in comparison to the site as a whole. As highlighted in Section 3.2.1, productivity data are available from only a limited number of the known breeding colonies. Therefore, the most important developments to improve understanding of this demographic rate would be to understand the influence of habitats and allow investigation of factors influencing productivity (e.g. human disturbance, competition, or weather). This would allow inferences to be made about whether current productivity estimates are representative of their colony and inform decisions on expanded monitoring to further sites to gain a broader geographical spread of data.

This RO would need to be carried out at a colony that is well-understood and provides opportunities to examine different aspects of breeding ecology, initially it seems logical for this to be at one colony (e.g. Skomer), to identify if the outcomes will make a difference to how monitoring could be carried out in the future. If there are significant differences identified in productivity between for example habitats or other geographic or topographic variables then this could then be carried out at other sites such as Lundy, Rum and Copeland.

This RO would be informed by work carried out under RO 4.1 which will carry out a power analysis to identify the number of sites, years and study burrows required to produce robust and reliable results that can be compared between sites/islands

5.10.2. Work underway

Productivity data are currently collected annually at several sites around the UK, see section 3.2, which provide a relatively broad geographic spread of information. These data are collected and submitted online as part of the SMP. As far as could be identified through a literature search there are no sites that have multiple study plots to assess the variation in productivity between plots/habitats. Feedback from the workshop highlighted that the current methodology is good and does not need to be improved as part of the OWSMRF work.

5.10.3. Work required

This RO would be split into four work packages:

5.10.3.1. RO4.10a Identifying potential new sites for Manx shearwater productivity monitoring using habitat mapping

There are currently many gaps in our understanding of the most important factors affecting productivity, including topographical factors, competition, and climate change. The first step of this RO would be to conduct a review of the factors that most significantly impact productivity and identify the habitat features that may influence success. Using a site where Manx shearwaters are well monitored, in this example Skomer (but could be another site), it could use existing or undertake new high-resolution habitat/topography mapping to identify potential areas for new study plots to allow comparison of productivity across different habitat types. Habitat mapping from imagery would potentially need ground-truthing.

5.10.3.2. RO 4.10b Establish new study plots across the island

Using the outcome of RO 4.1c (power analysis), design a sampling strategy and establish new study plots in a variety of different habitat types across a study site. For example, coastal/inland, flat/sloping, with/without competition, highly disturbed/undisturbed and different vegetation types.

5.10.3.3. RO 4.10c Analysis of productivity between plots

Analysis of differences between plots to identify whether the original plot, on Skomer (i.e. the Isthmus plot) is representative of the island as a whole. Where possible, when modelling and analysis of productivity between different sites are carried out, other factors should be taken account of, for example plot location, competition, and human disturbance. One variable that is likely to be influential is individual experience, but without years of ringing data on individual birds, capturing this information will not be feasible. However, this is a variable that should be considered when planning future study locations for adult survival monitoring, as the results of studies with both productivity and survival data will be significantly more robust.

5.10.3.4. RO 4.10d Roll-out of additional study plots to other sites

Depending on the outcome of RO 4.10 b and c, and if monitoring is logistically and practically feasible, then this RO can be carried out at other sites, which might have similar topographical profiles (Skokholm/Lundy) or very different habitat types (Rum). If analysis reveals differences in productivity with habitat/other factors then this may be able to inform the locations of monitoring plots at other sites, for example if the biggest differences were found between coastal and inland plots).

5.10.4. Benefits/key outcomes

Productivity is a key parameter for population modelling. However, we currently have a limited understanding of how productivity varies across a population, particularly between habitats. The results from one site within a population may vary widely to that of other even very nearby sites. There is therefore uncertainty over the accuracy of current productivity estimates and hence the error they may introduce into population modelling. This RO would establish this for Skomer island and inform on whether one plot per population can give an accurate representation of the productivity of the population as a whole. Where this is not the case, additional study plots may be needed at other sites where productivity is currently estimated to ensure the accuracy of data.

This RO will therefore improve confidence in productivity estimates and allow the parameterisation of population models with site-specific rates for those sites where there are available data (e.g. NE PVA Tool which currently is not parameterised for Manx shearwater). As for RO 4.9 (adult survival), this RO will provide information on within-colony variance in productivity rates. This novel evidence would allow a more informed assessment of confidence around population modelling outputs derived from a generic or nearby site productivity rate when predicting the consequences of impact from OWF.

If this RO is successful, then similar work could be applied to European storm-petrels to allow accurate productivity data collection.

5.10.5. Risks/inter-dependencies

It is not currently known the extent to which high-resolution habitat mapping is available at key Manx shearwater colonies. Where these sites are designated for habitats (Site of Special Scientific Interest (SSSI)/Special Area of Conservation (SAC)), such photography or detailed mapping may already exist. Where it does not, then it would need to be conducted. This may be via use of SNCB/stakeholder UAVs but may also need to be contracted out. In addition, as with any field-based project, there are likely to be health and safety implications associated with mapping work, and it may need to be repeated on a relatively regular basis (every few years) to ensure accurate up-to-date mapping. Habitat mapping is likely to require ground-truthing by experienced fieldworkers, but the use of UAVs and interpretation of aerial photography to produce habitat maps would need different skill sets than traditional seabird data collection methods.

5.10.6. Predicted resources required to deliver this RO

5.10.6.1. RO4.10a Identifying potential new sites for Manx shearwater productivity monitoring using habitat mapping

As this is a desk-based study, it is likely to be of restricted duration and cost.
LOW resource requirements (less than one year and less than £100,000).

5.10.6.2. RO 4.10b Establish new study plots across the site

Monitoring will need to be carried for a number of years to allow accurate and reliable comparison between plots and allow for annual variation in extrinsic factors such as weather. The initial set up of the monitoring plots will be the most labour-intensive part of the project.

MEDIUM (two or more years and up to £500,000, potentially more depending on the number of colonies and individuals sampled).

5.10.6.3. RO 4.10c Analysis of productivity between sites

As this is a desk-based study, it is likely to be of restricted duration and cost.
LOW resource requirements (less than one year and less than £100,000).

5.10.6.4. RO 4.10d Roll-out of additional study plots to other sites

The resource requirement for this RO is dependent on need. Should RO 4.10a–c conclude that existing study plots likely provide a reasonable representation of site productivity, then there would be no requirement for this RO. However, should that prove not to be the case, then there may be a need for a repeat of RO 4.10 a–d across the six sites where productivity data are regularly collected, with the consequent resource requirement.
HIGH resource requirements (more than two years and greater than £500,000).

5.11. RO 4.11 Juvenile survival of Manx shearwaters

5.11.1. Evidence needs/rationale

This parameter is arguably the demographic rate we know the least about, but which could have a significant impact on the outputs of a PVA. The best estimate we currently have is from data collected decades ago by Brooke and Perrins (1973; 1977). Despite the age of these studies, the method would be repeatable if sufficient ringing data are available and therefore current assessments could be made of juvenile survival. Given that across several island colonies, chicks are ringed annually, there may be sufficient data to carry out analysis such as that described by Thomson *et al.* (1999). The most suitable colony for this type of work may be Lighthouse Island, Copeland. Fledglings have been ringed here since 1954, with considerable effort being put in annually, particularly since 1973, with at least 191 individuals ringed annually since then (https://www.thecbo.org.uk/birds/manx-shearwaters/).

This RO is currently only applicable to Manx shearwater as there are not enough data for European storm-petrels. Ringing more fledgling storm-petrels should be included as part of expanded monitoring so that this sort of work can be carried out in the future.

5.11.2. Work already underway

The most recent estimates of juvenile survival are decades old and there is not any current work going on in this area. In one tracking study that tagged fledglings, 54 from Copeland Island, only three were successfully retrieved, highlighting the difficulty in obtaining data from juvenile birds and the necessity for large sample sizes (Wynn *et al.* 2021). The study demonstrated that birds do not return to the natal colony until at least their third year (Wynn *et al*. 2021).

5.11.3. Work required

This RO would be split into two work packages:

5.11.3.1. RO 4.11a Collation of existing data and feasibility review of methods

This step would use the output of RO 4.1 to identify sources of juvenile survival data. A feasibility review would then assess the potential methods for analysis to estimate juvenile survival, such as demographic modelling, which will likely be based on ringing data. This would include ensuring enough data are available and that the outputs of each method would provide sufficiently reasonable and robust estimates. Consideration of other rates and behavioural characteristics will be required. For example, recruitment rates to the natal colony and, with the potential for individuals to recruit to other colonies within the same island or to nearby colonies, emigration rates.

5.11.3.2. RO 4.11b Analysis of juvenile survival

Modelling of existing juvenile survival data using method selected in RO 4.11a.

5.11.4. Benefits/key outcomes

Juvenile survival is a vital population modelling parameter, but confidence in current estimated rates is low (it was not estimated by Horswill and Robinson (2015), with our best estimate being based on historic data (1970s) and only two short-term studies). If the survival rate is even a few percentage points different than the rate currently used, this could have a significant impact on population modelling outputs.

This RO aims to identify the “best” method of analysis using more recent data to provide a more up-to-date estimate, and to explore alternative methods to estimate this demographic rate. This will allow parameterisation of population models (e.g. NE PVA Tool which currently is not parameterised for Manx shearwater), potentially with site-specific rates if there are sufficient data. It is likely that this would be a small piece of work that would go a long way to improving our understanding of the population dynamics of Manx shearwaters.

5.11.5. Risks/inter-dependencies

This RO is in part based on the review carried out as part of RO 4.1, if sufficient data does not exist then analysis will not be possible. This RO uses an established analysis methodology, and therefore the only risk is that there is an insufficient dataset to provide statistical power. Ideally this would also be from a range of geographic locations to account for any regional/site variation.

5.11.6. Predicted resources required to deliver this RO

5.11.6.1. RO 4.11a Collation of existing data and feasibility review of methods

As this is a desk-based study, it is likely to be of restricted duration and cost.
LOW resource requirements (less than one year and less than £100,000).

5.11.6.2. RO 4.11b Analysis of juvenile survival

As this is a desk-based study, it is likely to be of restricted duration and cost:
LOW resource requirements (less than one year and less than £100,000).

5.12. RO 4.12 Assessment of rate of sabbaticals

5.12.1. Evidence needs/rationale

Although sabbatical rate is not included in PVA analysis it is an important factor to consider for OWF as it will have an impact on the number of individuals that are apportioned to any given colony and may mitigate for a decrease in adult survival. Evidence also shows that not taking non-breeding birds into consideration when carrying out population analyses can obscure low population growth rates and therefore potentially have an important effect on impact assessments (Lee *et al.* 2017). Using common techniques such as digital aerial survey it is not possible to differentiate between breeding adults that are linked to a colony and those non-breeding and immature individuals.

5.12.2. Work already underway

During our literature search we did not find any ongoing or previous work on sabbaticals for Manx shearwaters or European storm-petrels.

5.12.3. Work required

Initially a feasibility analysis would be carried out to establish what sort of data would be required to perform analysis of sabbatical rates among shearwaters and storm-petrels. This would include assessing what data are already available, how many years of data would be needed and how many individuals would need to be sampled. It may be possible to derive sabbatical rates from existing and ongoing adult survival studies using ringing data, but what sort of analysis/modelling would be required would need to be established as part of this RO.

5.12.4. Benefits/key outcomes

Gaining a proper understanding of the proportion of adult birds that are skipping breeding in any given year will improve estimates on the potential colony impacts of OWF and feed into PVA studies.

5.12.5. Risks/inter-dependencies

This is likely to be largely a data exploration and collation exercise with potential for analysis and modelling and therefore there are unlikely to be any risks associated with it. The outcomes may contribute to future monitoring effort by directing data collection where empirical evidence is unavailable.

5.12.6. Predicted resources required to deliver this RO

As this is a desk-based study, it is likely to be of restricted duration and cost:
LOW resource requirements (less than one year and less than £100,000).

5.13. RO 4.13 Review of existing at-sea distribution data and gap analysis to identify research needs

5.13.1. Evidence needs/rationale

At-sea distribution of seabirds is a particularly important issue when it comes to marine spatial planning, including for offshore and floating wind developments. Improving our understanding of this issue for Manx shearwaters and European storm-petrels is likely to be highly beneficial when it comes to current and future consent as development expands to the west coast of the UK and further offshore. There is not currently a centralised programme for collecting or collating at-sea survey data, but there is a series of projects and studies which use different methods, tracking/visual survey, which are carried out by different organisations. Some collation of tracking data is done as part of the BirdLife Seabird Tracking Database, but not all data are available here, and the recently published MERP maps are based on at-sea survey data but there has not been an overall review of what at-sea distribution data are available.

Conducting a review of all known studies and data will give an overview of what is known from all of the different data collection methods, improving our understanding of the key foraging areas for these species as well as changes in distribution over the course of the breeding season. A stock-take of this sort will also improve our understanding of the metadata that is available, such as the number of studies, number of birds tracked, spatial coverage, links with OWF. It may also provide an opportunity to compare the data collected by at-sea surveys and tracking to identify whether there is agreement between the distributions derived from each method.

As well as improving our understanding of current data this review would be able to highlight the gaps in knowledge. Once the review is completed a gap analysis can be carried out so that the future resources and effort can be directed to the areas and colonies where less is known. This will feed into other ROs (RO 4.8) which will seek to collect more data.

5.13.2. Work already underway

The recent MERP maps were produced using the most comprehensive collation of at-sea survey data to date, so the review stage of this work is likely to only be necessary for tracking data. Some tracking data are available on the BirdLife Seabird Tracking database but there is a large amount that is not on this platform.

The data integration of tracking and at-sea survey data (InTaS) project led by Offshore Renewables Joint Industry Programme (ORJIP) is working towards solving the problem of appropriate apportioning of seabirds seen at sea. Currently at-sea survey data, whether aerial or boat-based, cannot distinguish between breeding adults, which are subject to impact assessments, and immature/non-breeding birds which are not. As discussed in the demographic rates section of this report, the rates of sabbaticals and juvenile survival are not well understood for Manx shearwater and storm-petrel. This means that it is not possible to establish how birds seen during surveys should most appropriately be considered in impact assessments. While improvements in the tracking of both species is already providing valuable insights into the at-sea distribution of breeding adult birds, the ORJIP project will seek to integrate data collected by both visual survey (boat/aerial) and tracking to improve our estimates of apportioning to individual colonies.

5.13.3. Work required

5.13.3.1. RO4.13a Review of tracking data and SPA colonies within foraging range of OWF

A review of all tracking studies that have been carried out for each species will be needed, including collating metadata such as sample size, length of study, breeding stages tracked, tag type and data available (e.g. nocturnal as well as diurnal; coincident immersion/depth logger data, coincident altimeter data, coincident diet data, etc.). This would involve a review of existing databases to assess to what extent they contain seabird tracking data (e.g. BirdLife International Seabird Tracking Database, Marine Data Exchange, MarLIN) and engagement with relevant research groups to ascertain whether further data are available. Rather than collating existing evidence the purpose of this step is to assess what studies have been done and the metadata associated with them, to understand the data availability in order to improve estimates of at-sea distribution identified in this report. This step may already have been carried out as part of ORJIP project InTas, although the exact scope of that project has not yet been established.

5.13.3.2. RO4.13b Gap analysis to determine geographic expansion required

Using data reviewed in RO 4.13a, analysis would be carried out to establish where the gaps are in at-sea distribution data, tracking/survey, to ensure that future tracking campaigns can be planned to fill gaps and ensure a thorough UK-wide coverage can be achieved. A review of colonies that are within foraging ranges of any existing or planned OW developments would be needed to allow recommendations to be made regarding expansion of existing tracking programmes. While the focus of the review will be on SPAs, there may be an opportunity to expand to non-SPA colonies, depending on project scope. Gap analysis would establish the minimum/maximum distance recommended between study colonies.

5.13.4. Benefits/key outcomes

Collation and synthesis of currently available data will have immediate benefit to OWF developers, advisers, and regulators in potentially accessing data for site (and area) characterisation and inclusion in more detailed assessment of risk.

5.13.5. Risks/inter-dependencies

This RO would rely on cooperation from stakeholders, individuals, and organisations to supply information on their studies, as this would not include providing the actual data/tracks etc it is hoped that this would not be a significant barrier to this RO. There is some potential overlap with other established studies, particularly InTaS as it is likely that a review of current data would be part of the project, although this is to collate data rather than complete a review and the purpose of this project is purely around apportioning whereas the purpose of this RO is to improve understanding of distribution. If this RO was to be taken forward more discussions should be undertaken with ORJIP and/or the successful contractor.

5.13.6. Predicted resources required to deliver this RO

5.13.6.1. RO4.13a Review of tracking data and SPA colonies within foraging range of OWF

As this is a desk-based study, it is likely to be of restricted duration and cost: **LOW** resource requirements (less than one year and less than £100,000).

5.13.6.2. RO4.13b Gap analysis to determine geographic expansion required

As this is a desk-based study, it is likely to be of restricted duration and cost: **LOW** resource requirements (less than one year and less than £100,000).

5.14. RO 4.14 Produce gap-free at-sea distribution maps for Manx shearwater and European storm-petrel

5.14.1. Evidence needs/rationale

Distribution mapping of Manx shearwaters and European storm-petrels has been carried out in various ways for decades, including the recent MERP maps based on at-sea survey data, but there is no one place where distributions derived from tracking data are collated and can be easily accessed. Although mapping using at-sea survey data is incredibly valuable and can provide excellent evidence on distribution, tracking data can deliver more detailed information on distribution, behaviour and connectivity between key foraging areas and breeding colonies, and it can be particularly useful for collecting data when traditional surveys are not possible such as at night or in adverse weather. However, evidence from comparative studies on auks has shown that single colony tracking data are most valuable around colonies but not where there are numerous and/or large colonies nearby and that at-sea surveys or multi-colony tracking are better suited for aggregated colonies (Carroll *et al.* 2019). From studies like these it is apparent that both at-sea survey data and tracking data are important for assessing distribution, but which technique is required will depend on the questions being asked.

Collating all existing tracking evidence in one place that is readily available would have benefits for developers, advisers, and regulators as it will inform on where effort is required to fill gaps, and where birds undertake the majority of their foraging, commuting, and resting which is vital for planning and impact assessment.

Distribution mapping as per Wakefield *et al.* (2017) for Manx shearwaters from colonies in the Celtic/Irish Seas may be possible using existing tracking data and would usefully establish spatial and temporal linkage between those colonies and current and future OWF. It could also establish the location of broad-scale behaviours and hence inform relative risk at specific locations. Filling the current gaps in tracking data for both species would allow the production of gap-free at-sea distribution maps, establishing the extent and intensity of usage of marine areas, and the linkage specific between marine areas (e.g. OWF arrays) and SPA colonies. This in turn would better inform spatial risk planning.

Existing at-sea surveys and tracking data have indicated that both Manx shearwater and storm-petrel distribution is linked to some key features within the environment, for example frontal zones and continental shelf regions (Begg & Reid 1997; Stone *et al.* 1994, 1995). In addition to these more physical environmental features, Manx shearwater and European storm-petrel distribution has been shown to be significantly correlated with chlorophyll-α concentration (Kane *et al*. 2020; Wilkinson 2021). If strong correlations such as these exist throughout the UK, it may be possible to predict seabird distribution at given times of year with environmental data which would be complementary for foraging radius models.

The ultimate aim of this RO is to create a mapping tool that can provide the most up-to-date and detailed distributions of shearwaters and petrels at-sea based on spatial data, this would be the primary and "simplest" output. Where data are available, the secondary aim to be to also produce maps that highlight nocturnal distributions, behavioural maps, environmental predictors and identify the key foraging locations for individual colonies. Where data are not available modelling based on tracking data will provide the next best prediction of distribution until new tracking data are available.

This RO could also be extended to other Procellariiformes; fulmar, Leach's storm-petrel, Balearic shearwater and sooty shearwater.

5.14.2. Work already underway

As described above, the InTaS project is currently out to tender (closed 12/06/22) and one of the outputs of this project will be mapping at-sea distribution based on integrated tracking and at-sea survey data. At this stage it is unclear exactly what form these maps will take, what species will be included, and how this will be done but it may be that there is significant overlap which may mean parts of this RO may not be required.

POSEIDON (Planning Offshore Wind Strategic Environmental Impact Decisions) is a project lead by Natural England and funded through The Crown Estate's OWEC programme. Initiated in January 2022, it is a four-year project to improve knowledge of environmental risks across UK waters and provide tools for future OW planning. The project remit is to produce risk and opportunities mapping for seabirds, marine mammals, and benthic habitat. It will do this across the UK with existing data and collect new data within English and Welsh waters. Manx shearwater and European storm-petrel are included in the initial long list of seabird species of interest. It is therefore possible that POSEIDON may do some of the work envisaged in RO 4.14a, b, and c, and provide a mechanism by which distribution mapping could be updated as more data becomes available. However, it is not yet determined to what extent tracking data will be used in distribution mapping in this project (the focus may be to use ESAS and digital aerial survey data).

Climate change is currently one of the most important and studied aspects of seabird ecology and conservation and there is likely to be work ongoing in this area. As outlined in RO 4.15, work has been planned to look at the long-term trends in distribution for existing long-term data collected by OxNav. Although this is not targeting towards the relationship between distribution and environmental variables, it is possible that this work will highlight this (e.g. changes in distribution linked to climate change). The importance of accounting for the effects of certain key environmental variables when predicting seabird occurrence has been shown in various studies, including in the UK, through the use of species distribution models (SDMs).

5.14.3. Work required

This RO would require a series of steps, three in total:

5.14.3.1. RO 4.14a Feasibility review and RO outcomes

Once a review of available data has been conducted a feasibility review will allow the assessment of data to establish what is possible and where the limitations in the data lie. Thus far, mapping of tracking data has focussed on diurnal distribution, but it is likely that data are available to also produce nocturnal distribution maps and locations of broad-scale behaviours (e.g. differentiating between foraging, loafing, and commuting behaviours). Nearly all Procellariiformes demonstrate contrasting strategies during different stages of the breeding season, a pre-laying exodus (particularly for females), foraging during incubation to maintain condition, and dual foraging during the chick rearing period to provide food for themselves and the chick, as observed in Manx shearwaters (Warham 1990; 1996). Mapping these different stages may provide vital information on resource/habitat requirements across the entire breeding season.

This review would also aim to identify any sources of evidence for associations between Manx shearwater and European storm-petrel distributions with measurable environmental variables.

This step would likely involve extensive engagement with stakeholders to establish exactly what sort of product is required and the data requirements to achieve it. For example, distribution mapping could be static (e.g. MERP density maps) or interactive (e.g. BirdLife International seabird tracking database, Department for Environment, Food and Rural Affairs (Defra) MAGIC website). It may also be beneficial that the outputs are complementary with other similar outputs, such as the ORJIP project InTas, so that they can be used together.

This step would also include an assessment of the requirements for a potential hosting platform, which will have to meet a set of criteria (e.g. being easily accessible, secure, and future proof). Examples of host platforms are The Marine Data Exchange or the Defra MAGIC websites. This project would examine the ability to host distribution maps on existing platforms, or the need for a bespoke platform (including maintenance).

5.14.3.2. RO 4.14b Produce behavioural distribution maps

Based on the outcomes of RO 4.14a, this stage will produce a series of maps that show densities and distributions of birds at-sea from given colonies.

Where there is sufficient tracking data from a colony and at a good enough resolution, this stage would involve extracting each of the behavioural states (foraging, commuting, and resting) from tracking data, as was done by Dean *et al.* (2015). This would allow for the distinction between discrete areas that are important for different behaviours. For example, isolating direct flight between the colony and foraging locations will identify key routes that allow birds direct access to important foraging areas. Displacement from these routes may inhibit birds from reaching that resource or may incur an increased energetic cost from an excursion.

Where there is insufficient tracking data from an individual colony that is within foraging range of windfarms, or of too poor resolution to infer behavioural states, modelling techniques used in Wakefield *et al.* (2017) could be applied to estimate at-sea distribution based on colony size, intra-specific competition, and environmental covariates. This, in addition to the outputs of RO 4.17, would allow the creation of distribution maps for areas where tracking data is not currently available and provide an interim output that would provide valuable information for developers and regulators. The modelled distributions could then be phased out when sufficient tracking data for these colonies becomes available (see RO 4.14c). Where possible, maps should be developed for both nocturnal and diurnal distributions and behaviours.

5.14.3.3. RO4.14c Longer-term incorporation of additional colonies as data become available

This work package would be an ongoing process, a schedule for updates would need to be established and applied to the collection of available data, and update to the maps. The methodology applied in RO 4.14b would be followed for each update.

5.14.4. Benefits/key outcomes

The resulting mapping outputs have the potential to be a very useful tool for a variety of users. Currently there is a lot of data and information available, but it is spread across different platforms and within published articles. Collation and synthesis of currently available data will have immediate benefit to OWF developers, advisers, and regulators in potentially accessing data for site (and area) characterisation and inclusion in more detailed assessment of risk.

Understanding and mapping where information is currently lacking would highlight where resources should be directed and aid in reducing the likelihood of duplication of effort.

The RO would also establish a single location where tracking-based distribution mapping for these species (and potentially additional procellariform species as tracking data become available) would be located and accessed. In a relatively short period of time, it would produce distribution mapping from currently available data and establish a mechanism by which this mapping could be updated and extended as additional data are gathered.

If strong correlations exist between environmental variables and the distribution of Manx shearwaters and storm-petrels, this may present a less expensive method of predicting distribution for key colonies where limited data are available and tracking work is not practical or affordable. It may also provide an interim alternative method for predicting at-sea distributions whilst additional tracking data are being collected.

Distribution mapping would be useful in understanding potential spatial and temporal interactions between current and planned OWF and relative risk based on density and broad-scale behaviours. In addition, the underlying tracking data would evidence the linkage between marine areas and specific breeding colonies.

5.14.5. Risks/inter-dependencies

There are three key risks: overlap or duplication with existing projects, establishing a suitable host for distribution mapping products, and the ability to produce gap-free distribution maps for both species.

It may be that existing sites/platforms could host the required mapping products, but this would first need agreement from stakeholders on what those requirements are and the safeguards around data access. Static mapping products could be published as a report (or reports), but interactive mapping would likely need a host platform (e.g. like Defra MAGIC website or a platform produced through the POSEIDON project). Where interactive mapping was desired, incorporation into an existing well used platform may represent the best option. Development of a bespoke platform would need significant investment in platform architecture and promotion of its existence and use. It would also need the mechanisms and funding for maintenance and update as new data became available.

The mapping products themselves would need data sharing agreements for the tracking data to be used in distribution mapping, and the current ability to produce distribution maps from tracking data alone is limited to Manx shearwater in only part of their range. Producing gap-free distribution mapping for both species is likely to be a long-term aim, and interim measures such as incorporation of predicted distributions from other means (e.g. foraging radius models) will be needed, in which case the realisation of this RO at least in the medium term will be reliant on other ROs.

5.14.6. Predicted resources required to deliver this RO

5.14.6.1. RO 4.14a Feasibility review and RO outcomes

As this is a desk-based study, it is likely to be of restricted duration and cost: **LOW** resource requirements (less than one year and less than £100,000).

5.14.6.2. RO 4.14b Produce behavioural distribution maps

As this is a desk-based study, it is likely to be of restricted duration and cost: **LOW** resource requirements (less than one year and less than £100,000).

5.14.6.3. RO4.14c Longer-term incorporation of additional colonies as data becomes available

LOW resource requirements (less than £100,000, timescale over which complete gap-free mapping would be produced would be over several years as additional data becomes available).

5.15. RO 4.15 Assess temporal changes in distribution at regional scales

5.15.1. Evidence needs/rationale

Climate change is affecting seabirds throughout the UK directly and indirectly, changes in SST will have implications throughout the food web and influence abundance and distribution of prey which will in turn impact seabird distribution (Jenouvrier 2013; Lynam *et al.* 2017). Those changes over time have the potential to change the nature and timing of interactions between these species and both current and future OWFs. Given the lifetime of OWF projects (>30 years), these changes may have implications for the magnitude of impacts over that timescale and will need to be incorporated into impact assessments. An understanding of likely future distributions will also aid in spatial planning.

This RO would build on the work carried out under RO 4.14 and therefore should be carried out subsequently if possible. Temporal trends are likely to be driven by a number of environmental factors and identifying them is a logical first step for this RO.

5.15.2. Work already underway

During the workshop it was brought to our attention that analysis of this sort is planned for the long-term tracking dataset on Manx shearwaters gathered by the OxNav group at Oxford University. The majority of the tracking data collected comes from Skomer, but data are also available for other colonies around the Irish/Celtic Sea regions. The work done on Skomer will provide a working example of how this can be done to test relevant hypotheses and the amount/type of data that would be required for future studies. Building on the analysis underway, this RO will help build a UK wide picture of temporal changes in distributions.

5.15.3. Work required

This RO is currently only applicable to Manx shearwater as there are insufficient tracking data for European storm-petrel. This work would build on RO 4.13, using the review of existing tracking data, to assess whether a temporal analysis would be possible. In order to assess the dataset length and number of tracks required to conduct such a statistical analysis a power analysis may be required, once the data requirements are known this could direct future tracking effort. Once any datasets that are of sufficient length and quality are identified, spatial analysis can be carried out and modelled against various environmental variables.

5.15.4. Benefits/key outcomes

This RO would allow the changes over time to be analysed with the aim of identifying the extent to which Manx shearwaters are being affected by climate change. This could be incorporated into project and plan level assessments to determine the potential for changes to the nature and magnitude of impact over the lifetime of projects and plans. It could also provide information on future risk and hence aid in future spatial planning and/or inform strategic compensation measures should they be required.

5.15.5. Risks/inter-dependencies

A significant risk is the sufficiency of suitable data. It is reliant on datasets being of sufficient length in order to have the statistical power to detect changes in abundance and distribution. There may be sufficient data from colonies such as Skomer, but the current ability to identify changes in distribution across the UK is limited. The project is therefore partially reliant on additional data collection proposed in RO 4.8.

5.15.6. Predicted resources required to deliver this RO

As this is a desk-based study, it is likely to be of restricted duration and cost:
LOW resource requirements (less than one year and less than £100,000).

5.16. RO 4.16 Better understanding of resource partitioning between breeding adults/non-breeding adults/immatures

5.16.1. Evidence needs/rationale

In a long-lived species where population persistence is driven by adult survival, identifying the sites that are more important to breeding adults may be a more strategic conservation option and will allow for more accurate apportioning of impacts to breeding colonies, which is vital when conducting impact assessments. There has been limited tracking of juvenile Manx shearwaters and no tracking of immature European storm-petrels in the UK.

Another possible area to explore in this RO is the influence of demographic traits. Research by Wood *et al.* (2021) demonstrated that there are distinct differences between individual Manx shearwaters that define their propensity to breed, their breeding success and survival. Given that these birds demonstrate such diverse demographic traits it might follow that they demonstrate opposing foraging abilities or strategies.

Understanding the differences in foraging strategies and particularly which foraging areas are vital for adults as opposed to immature birds is important for impact assessment and understanding the population consequences of impacts. As highlighted in the demographic rates section of this report we currently have a very limited understanding of key rates that will influence population age structure as a result of delayed onset breeding and unknown juvenile survival rates. PVA has been shown to be most sensitive to adult survival, and any OWF impacting this demographic rate are likely to have a greater impact on populations (Cook & Robinson 2016). It is therefore important to understand age-class partitioning for both project level assessments, and to inform spatial planning.

5.16.2. Work underway

Current evidence shows that breeding adult Manx shearwaters and immature birds demonstrate spatial segregation at feeding grounds, immature birds forage at less productive sites than adults, they also gain less weight per unit time spent foraging, which would suggest lower foraging efficiency (Fayet *et al.* 2015).

A first stage would be to establish whether existing datasets include both adult and immature birds. This project would build on and would benefit from the review conducted under RO 4.13a. If data are not available to a sufficient extent, which includes coverage of the different ages/stages required this could then direct effort as part of RO 4.8 to collect data so that this analysis is possible in the future.

5.16.3. Work required

5.16.3.1. RO 4.16 Analyse existing data

Based on RO 4.13a if datasets are available that can provide adult and immature tracking data from the same colony and time, analysis based on the techniques used by Fayet *et al.* (2015) would be carried out. In this work GPS tags were deployed on immature and breeding birds and at-sea data were analysed to assess the different behaviours and distributions of individuals. This is a relatively simple statistical technique which can highlight the importance of different foraging areas for individuals at different life stages and across the breeding season.

5.16.4. Benefits/key outcomes

This work would enable the identification of foraging areas that are important for different age classes of birds. This would aid in the assessment of population consequence of impact, particularly where proposed OWF interacted with adult rather than juvenile/immature birds. It would also aid in avoiding areas of higher risk (i.e. those areas important for adult resource use and hence survival) in spatial planning.

5.16.5. Risks/inter-dependencies

As with other ROs reliant on tracking data, a significant risk is the sufficiency of suitable data. It is reliant on datasets particularly of sufficient size, in terms of total number of tracks and data from both age groups, in order to have the statistical power to detect changes in abundance and distribution. There may be sufficient data from colonies such as Skomer, but the current ability to identify changes in distribution across the UK is limited. The project is therefore reliant on additional data collection proposed in RO 4.8.

5.16.6. Predicted resources required to deliver this RO

5.16.6.1. RO 4.16 Analyse existing data

As this is a desk-based study, it is likely to be of restricted duration and cost:
LOW resource requirements (less than one year and less than £100,000).

5.17. RO 4.17 Explore the use of foraging radius models as an alternative to tracking data to predict at-sea distribution

5.17.1. Evidence needs/rationale

Our understanding of the foraging ranges of all seabirds has improved with the development of tracking technology, and this is particularly the case for Manx shearwater and storm-petrel in recent years (Thaxter *et al.* 2012; Woodward *et al.* 2020). Foraging radius models use foraging ranges to estimate the distribution of seabirds from colonies, with a probability of occurrences calculated for each grid square within a study area using a distance-weighted approach (Critchley *et al.* 2020). The benefits of using this type of modelling include estimating distribution for colonies where tracking data are not available (e.g. hard-to-access colonies). This is particularly useful for storm-petrels, for which the tracking technology has only recently become available. However, with small sample sizes and new technology, validation may be challenging and should be considered when undertaking any work. This RO will initially focus on Manx shearwater with the potential to expand to storm-petrels when more data are available.

Although tracking data may provide the “best” evidence of at-sea distribution and foraging ranges, filling gaps in tracking for Manx shearwater and receiving sufficient data to carry out this type of analysis would be a long-term project. In the interim, alternative methods of predicting distribution such as foraging radius models (e.g. Critchley *et al.* 2018; 2020) could be examined and applied. Understanding the drivers of distribution, and particularly establishing the locations of marine areas that are used by multiple colonies will aid in the production of apportioning tools.

5.17.2. Work underway

Foraging range models have already been applied to Manx shearwaters on two colonies on the west coast of Ireland and compared to kernel-estimated utilisation distributions from GPS tracking data. No correlation was found between model predictions and either tracking/aerial survey data for Manx shearwaters (Critchley *et al.* 2020). An absence of correlation for shearwaters could be the result of their dual-foraging strategy, a combination of short and long foraging trips. Therefore, part of this RO will be to identify if splitting the GPS tracks between long and short trips would perform better when predicting at-sea distribution using foraging range models (Critchley *et al.* 2020).

5.17.3. Work required

5.17.3.1. RO 4.17a Identify colonies for analysis of dual-foraging strategy tracks

This stage would require the identification of candidate colonies to test the modelling approach used by Critchley *et al.* (2018; 2020). Such colonies would need to have sufficient sample sizes of both trip lengths.

5.17.3.2. RO 4.17b Carry out assessment of foraging radius models

This work package is dependent on outcomes of part a. If sufficient data for both trip lengths for Manx shearwater are available at UK colonies, foraging radius models would be run for these colonies and compared with tracking data to assess how well they correlate.

5.17.3.3. RO 4.17c Expand modelling approach to data-poor colonies/regions

If the models perform well and correlation is high, this approach could be rolled out to islands where data are sparse, and tracking is not possible.

5.17.4. Benefits/key outcomes

This RO would build on the work done by Critchley *et al.* (2020). As the models did not work well for Manx shearwaters, breaking down the foraging patterns for this species has the potential to improve the model performance. If it is found that foraging radius models correlate well with existing tracking data then this method could be considered as a viable, cheap, and quick alternative to carrying out extensive tracking studies at new colonies.

5.17.5. Risks/inter-dependencies

Existing use of foraging radius models have not been successful for Manx shearwaters, with their dual-foraging strategy potentially being the cause, this stage of the RO will establish whether it is possible to establish two foraging ranges for Manx shearwater.

5.17.6. Predicted resources required to deliver this RO

5.17.6.1. RO 4.17a Identify colonies with sufficient dual-foraging strategy tracks for Manx shearwater

As this is a desk-based study, it is likely to be of restricted duration and cost:
LOW resource requirements (less than one year and less than £100,000).

5.17.6.2. RO 4.17b Carry out assessment of foraging radius models

As this is a desk-based study, it is likely to be of restricted duration and cost.:
LOW resource requirements (less than one year and less than £100,000).

5.17.6.3. RO 4.17c Expand modelling approach to data-poor colonies/regions

As this is a desk-based study, it is likely to be of restricted duration and cost:
LOW resource requirements (less than one year and less than £100,000).

5.18. RO 4.18 Apportioning of seabirds-at sea to colonies using tracking data

5.18.1. Evidence needs/rationale

Current methods for apportioning are based on foraging radius models, which can provide estimates for impact assessments but are not always appropriate or accurate. This is particularly important when considering the use of shared foraging areas of high importance to seabirds from multiple colonies (e.g. the Irish Sea Front). In addition, these tools cannot account for the presence of non-breeding or immature birds. For Manx shearwaters and storm-petrels that have extensive foraging ranges and display dual-foraging strategies, methods based on foraging ranges may be underestimating their abundance at key sites. Improving the apportioning of birds to specific colonies, and also accounting for non-breeding birds would improve our ability to accurately apportion impacts to specific colonies, potentially reducing consent risk.

Marine Scotland funded a research project to investigate potential apportioning methodologies, including the use of tracking data alongside survey data to account for both breeding and non-breeding birds. This method has been implemented for common guillemot (*Uria aalge*), kittiwake, and razorbill (*Alca torda*), but is not yet applicable to shearwaters and petrels (Butler *et al.* 2017). This method would require further investigation, but with more data it may be able to achieve apportioning of different life stages.

NatureScot produced an apportioning tool, which is based on distance from colony and takes into account species foraging ranges. This tool may be problematic for Procellariiformes as they have dual-foraging strategies and extensive foraging ranges.

5.18.2. Work underway

There are two relevant ORJIP projects: AppSaS, Apportioning Seabirds at-Sea, due to be completed in August 2022, aims to reduce uncertainty by reviewing approaches and enabling more robust pre-consent impact assessments, and will suggest improvements or develop new approaches to apportioning. Petrels are included to some degree in this project but not as part of the full analysis, and therefore this RO might be well placed to build on this work. As described in RO 4.14, the second project, InTaS, will be working on integrating tracking data with at-sea survey data to improve differentiation between breeding and non-breeding birds seen at sea; it is planned to start in summer 2022 but it is unclear if petrels will be included.

5.18.3. Work required

This RO would be split into two work packages:

5.18.3.1. RO 4.18a Review of apportioning methodologies

Building on Butler *et al*. (2017), review the ability/limitations of current methods to apportion species where there are birds from multiple colonies using a shared resource (particularly Manx shearwater and European storm-petrel). This will likely build on what is completed under AppSaS and/or InTaS but may have already been completed under these projects and may therefore not be required.

5.18.3.2. RO 4.18b Amend/develop new apportioning methodology for Manx shearwater and European storm-petrel

Amendment of current methodology if and where appropriate (e.g. Marine Scotland Apportioning Tool), and development of a bespoke tool where current approaches cannot be adapted.

5.18.4. Benefits/key outcomes

Current apportioning methods cannot account for non-breeding or immature birds and given that estimates suggest that around 25% of the population of Manx shearwaters could be immature and that in a given year up to half of the population could be non-breeders, the number of birds apportioned to breeding colonies could be vastly overestimated (Guilford *et al.* 2008; Skov *et al.* 1994). Use of tracking data collected from adults, non-breeders, and immatures (see RO 4.16) would allow more precise apportioning of the potential impacts of OWF.

5.18.5. Risks/inter-dependencies

There are already projects underway that are working to address the issues around apportioning, with tools for other species already developed (Marine Scotland, NatureScot), in progress (AppSaS) and planned (InTaS). This RO might best be considered once other work has completed.

As one of the key issues around apportioning is to differentiate between the distribution of adults, non-breeders and immature birds, this RO would benefit from the outcomes of RO 4.16. This RO would also benefit from opportunities identified as part of the demographic rates ROs, particularly ROs 4.9 and 4.11 on adult and juvenile survival and RO 4.12 on sabbatical rates.

5.18.6. Resources required to deliver this RO

5.18.6.1. RO 4.18a Review of apportioning methodologies

As this is a desk-based study, it is likely to be of restricted duration and cost:
LOW resource requirements (less than one year and less than £100,000).

5.18.6.2. RO 4.18b Amended/new apportioning methodology for Manx shearwater and European storm-petrel

As this is a desk-based study, it is likely to be of restricted duration and cost:
LOW resource requirements (less than one year and less than £100,000).

6. Conclusions

This report sets out a series of eighteen potential research opportunities (ROs) which were suggested and discussed amongst a consortium of experts in Manx shearwater and European storm-petrel vital rates estimation and tracking. These projects are seen as part of a dynamic process to improve understanding, either working synergistically or undertaken in sequence to contribute to subsequent ROs. Although these ROs work together and inform each other, they could in theory be approached as separate pieces of work, but some could not be delivered without the outputs of previous ROs. By and large, however, each of the ROs presented in this report represent a single coherent piece of work of varying resource requirements. Many are entirely desk-based (e.g. analysis of existing of data), but there are several which involve further data collection. This represents an appropriate balance between making the most of any data that are collected or already available, and where required, collecting additional data to answer the questions that are unable to be fully addressed with existing data.

There are extensive synergies between the ROs, both within each of the three main “topic” areas, but also between them. Particularly for European storm-petrels, there is a significant lack of understanding of all aspects of their ecology and distribution, so it makes sense that where effort is being put into monitoring of these species both aspects are completed at the same time. Not only will this provide the best use of resources and time, but it has also been demonstrated that the best understanding of vital rates and population dynamics comes when all aspects of demographic rates and population estimates are known.

Given the overriding lack of understanding over a variety of the aspects of shearwater and petrel ecology, the highest priority ROs will be the collection of new data, either at new sites or by expanding existing work. The natural first steps would be ROs 4.1 and 4.13; literature and data reviews, gap analysis and power analysis, which will be vital steps in informing how frequently work needs to be carried out, how many sites need to be monitored and where those sites should be. If well-rounded, good-quality and geographically diverse data can be collected this will contribute to all of the other stated ROs that aim to improve specific aspects of population abundance, demographic rates and at-sea distribution and behaviour.

The intention is that this report provides a signpost towards research which can contribute to reducing uncertainty around the population abundance and demographic rate estimates, and at-sea distributions and broad-scale behaviour. These will contribute to overall reduced uncertainty in offshore windfarm environmental impact assessments. Incremental reductions in uncertainty will become more important as the wind sector is expanded, 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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