A review to inform the assessment of the risk of collision and displacement in petrels and shearwaters from offshore wind developments in Scotland

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A review to inform the assessment of the risk of collision and displacement in petrels and shearwaters from offshore wind developments in Scotland

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1 Executive summary

- Scottish Government published the Sectoral Marine Plan for Offshore Wind in 2020, setting out sustainable plan options for the continued development of commercial-scale offshore wind energy in Scotland, as a key contribution to achieving the target of net-zero greenhouse gas emissions by 2045. In January 2022, Crown Estate Scotland announced the lease option agreements for 17 new projects within 14 Plan Option Areas, principally on the eastern and northern coasts.

- Scotland's seas and coastlines are home to a rich diversity of marine life, including internationally important colonies of seabirds, many protected under Scottish, UK and international designations. The need to ensure that future offshore developments do not adversely impact on protected sites and species is embedded within the Scottish Government's National Marine Plan, and potential impacts to marine life and other users of the sea are required to be assessed as part of planning, consenting and licencing processes.

- Several frameworks, methods and tools have been developed in recent years to facilitate the assessment of the likely impacts of offshore wind farm developments on seabirds, and these require data inputs on a variety of parameters relating to species morphology, ecology, behaviour and distribution.

- This key information has not been collated for a group of seabird species for which Scotland holds some of the largest colonies in UK, Europe and globally; namely the Manx Shearwater *Puffinus puffinus*, Leach's Storm-petrel *Hydrobates leucorhous*, and the European Storm-petrel *Hydrobates pelagicus*. These species are active nocturnally, and there is evidence to suggest they are sensitive to light attraction ("phototaxis"), which could render them especially vulnerable to negative impacts from offshore windfarms, for example, if attracted to the rotor-swept area by lights on the turbines that are required for navigation purposes. We also consider, in less detail, two further species from the same taxonomic group, namely Northern Fulmar *Fulmarus glacialis* and Sooty Shearwater *Ardenna grisea*.

- Low fecundity rates and a relatively protracted time to reach maturity (3–6 years) for these species, means seemingly small impacts on survival rates can have large impacts on population viability, making them particularly vulnerable to lethal impacts of wind farm development.

- We reviewed the published peer-reviewed and grey literature for information on the 24 key parameters/data groups required to assess the vulnerability of these species to potential impacts of offshore wind farms and associated structures and activities.

- We compiled a library of more than 1000 scientific papers, reports and other publications, from which we extracted all relevant information to assist in the implementation of methods and tools to quantify the likely population-level impacts of sites leased in the Sectoral Marine Plan Option areas. We highlight critical data gaps that currently prevent a reliable assessment of population-level impacts on protected colonies of these three species.

- Good quality data from within Scotland exist for ten of the key parameters/data groups for all three main species (Manx Shearwater and the two storm-petrel species), and for just three parameters for the other two species. Data collected from elsewhere, or from closely related species, are available for 21 key parameters for all three main species. Less information is available for Leach's Storm-petrel in Scotland than for the Manx Shearwater or European Storm-petrel.

- The evidence needs that were highlighted as being most important for the three focal species were to improve understanding of: (i) biases in detectability of birds at sea; (ii) flight height and speed (and their variation); (iii) avoidance behaviour; (iv) light attraction and (v) foraging ranges from breeding colonies.

- There is a need for experimental validation of potential biases in aerial survey methods, including detectability, identification and diel variation. Detectability could be tested by carrying out targeted digital aerial surveys or vessel-based surveys with an experimental approach, using either tagged model "decoys" or tagged free-roaming birds, though achieving adequate sample sizes of the latter may be challenging.

- Estimates of flight parameters such as speed and height can be gained from tracking data, but acquiring accurate estimates is difficult, even with high resolution data. Where possible, "instantaneous" flight speeds from GPS tags, based on Doppler-shift information derived from the movement of the tag relative to the movement of the satellites, will be more accurate than that derived from distance covered between successive fixes. Constraints on device size/weight suitable for use on storm-petrels limit the range of tracking devices that can be deployed on these species.

- Assessment of macro-avoidance of windfarm development can be achieved by comparing marine distributions of seabird pre- and post-construction. In light of the limited tracking of the three focal species in Scotland to date, we recommend further tracking studies from key colonies to better understand the pre-construction movements and distribution of these species. Such tracking studies should continue as construction occurs and after it is completed, to inform understanding of avoidance behaviour. Such work will also increase understanding of drivers of marine distribution and foraging ranges.

- Crucially, we found that there is currently a lack of evidence on which to judge the existence and strength of light attraction in these species. It is clear from the evidence base that all three focal species may become disorientated by powerful light. This typically occurs in foggy conditions and particularly affects recently fledged young, who may still have under-developed visual capabilities. Under such circumstances, birds may circle a light source for many hours, until succumbing to dehydration or exhaustion. In the context of assessment of the likelihood of collision with turbine blades, the probability of collision is vastly increased, since a bird may pass through the rotor swept area many times. Attraction to or disorientation by light can also be considered a form of displacement, for example if birds are drawn away from foraging areas or behaviours.

- A further compounding factor is the extent to which birds are drawn from a distance to the lights on turbine towers, or whether such attraction is very local (i.e. "micro-scale attraction"). Whilst there are many documented cases in the literature of seabirds dazzled by lighthouses, ships' lights, gas flares from oil platforms, etc., the distances from which birds may be attracted are unknown. This is a critical distinction. If birds are attracted to bright light sources from considerable distance (i.e. hundreds of metres to kilometres) the potential for adverse impacts from collision is greatly increased, as the number of birds attracted scales as the square of the range from which they are drawn. Taken together, the effect of disorientation, causing birds to circle for many hours and increasing the number of passes through the rotor-swept area, and the potential for birds to be attracted from an area covering tens of square km, would render current methodologies of assessing impacts unreliable.

- We recommend urgent studies to quantify the distance over which flight paths of these species may be influenced by bright light sources, to examine the age class of individuals most likely to be affected, and to assess whether the wavelength and pattern of illumination (flashing vs constant) may affect the level of attraction or disorientation. Such studies will require the novel application of tracking technology (e.g. use of thermal video imaging, radar, VHF and/or GPS tags). The most appropriate approach for each species will depend on device size/weight constraints and logistic constraints of particular breeding locations. We make recommendations as to how such studies may be conducted, suggest suitable locations, and highlight potential challenges.

- We detail several options for mitigation of potential impacts, such as altering the wavelength or pattern of illumination of navigation lights on turbines and associated structures. We discuss the current technical and legislative constraints to such modifications.

2 Introduction

Scottish Government's Energy Strategy (Dec 2017) set a 2030 target for 50% of the energy for Scotland's heat, transport, and electricity consumption to be supplied by renewable sources, and the Climate Change (Emissions Reduction Targets) (Scotland) Act 2019 sets a target of net-zero greenhouse gas emissions by 2045. These targets will require the development of extensive areas for marine renewable energy extraction. In October 2020, the Scottish Government published the Sectoral Marine Plan for Offshore Wind (SMP; Scottish Government, 2020), which identified the most sustainable plan options for the future development of commercial-scale offshore wind energy in Scotland. With six operational offshore wind farms in Scotland, and a further eight having received consent, in January 2022 the Crown Estate Scotland announced the results of a further leasing round ('ScotWind'). Seventeen proposed projects within 14 of the 15 Plan Options now have lease option agreements, covering over 7,000 km^2 of seabed in Scotland, with a total generating capacity of nearly 25 GW. These projects are predominantly off the north and east coasts of mainland Scotland, in waters beyond the 12 nm territorial limit (Figure 1; Crown Estate Scotland, 2022).Unleased areas, including Plan Option NE1, underwent a Clearing process which closed on 10 May 2022, and resulting Option Agreements from the Clearing process will be signed in Autumn 2022. In February 2022, Marine Scotland published an Initial Plan Framework for a Sectoral Marine Plan for Innovation and Targeted Oil and Gas Decarbonisation (INTOG; Scottish Government, 2022). This provides potential areas for future seabed leasing for small scale innovation and offshore wind farms specifically for the purpose of providing low carbon electricity to power oil and gas installations and help to decarbonise the sector. These areas are all in the north and east of Scotland, therefore potential new offshore wind farm projects could come forward in these locations in the future.

The need to ensure that future offshore developments do not adversely impact Scotland's internationally important marine environment is embedded in the aims of both the National Marine Plan (NMP; Scottish Government, 2015) and SMP. In addition, Habitat Regulation Appraisals and Strategic Environmental Assessments require evaluation of potential impacts of proposed marine developments on marine biodiversity, and on other marine users. The SMP, which assessed for up to 10 GW maximum installed capacity at a national level, identified the key risk factors of development in all Plan Option regions include "risks to bird species, including collision risk and displacement, as well as potential impacts to birds on migratory pathways".

A number of frameworks and tools have been developed to assess the vulnerability and sensitivity of seabird species to marine pressures (e.g. Williams et al., 1995, Furness and Wade, 2012, Furness et al., 2013, Bradbury et al., 2014, Certain et al., 2015, Rogerson et al., 2021), to quantify risk of collision with offshore turbines (Band et al., 2007, McGregor et al., 2018), to apportion impacts of marine development to particular breeding populations (NatureScot, 2018) and to estimate survival consequences for seabirds of displacement from former foraging areas (Searle et al., 2018, Searle et al., 2019). Implementing these frameworks and tools requires key information about the distribution, ecology, morphology, behaviour, and population status of the species of interest. For example, knowledge of species' population sizes and marine distributions is required to assess overlap with licensing areas for offshore wind farms, and the density of birds within these areas of overlap; factors such as flight height and levels of nocturnal activity will influence a species' vulnerability to collision, and an understanding of a species' behaviour is important for determining the probability and scale of avoidance of an offshore development, and therefore the levels of displacement or barrier effects. In addition, seabird species that are nocturnally active, such as Manx Shearwaters, European and Leach's Storm-petrels are potentially vulnerable to attraction to artificial lighting (Rodríguez et al., 2019) such as that associated with offshore wind structures and related shipping. Structures associated with offshore wind farms in UK waters are required to display illumination to meet the lighting requirements of the Air Navigation Order 2009 (CAA, 2016), the Northern Lighthouse Board, and the Maritime and Coastguard Agency. Attraction to illumination associated with offshore wind farms may affect the risk of collision for these nocturnally active procellariiform seabird species. This key information is not currently synthesised for Procellariiformes in Scotland and, given the rapidly increasing activity relating to offshore wind farms in the country, there is a clear and urgent need to do so. The current ScotWind leasing round, and potential future rounds, are likely to include areas to the north and west of Scotland not previously developed, and in closer proximity to the breeding colonies and foraging areas of procellariform seabirds.

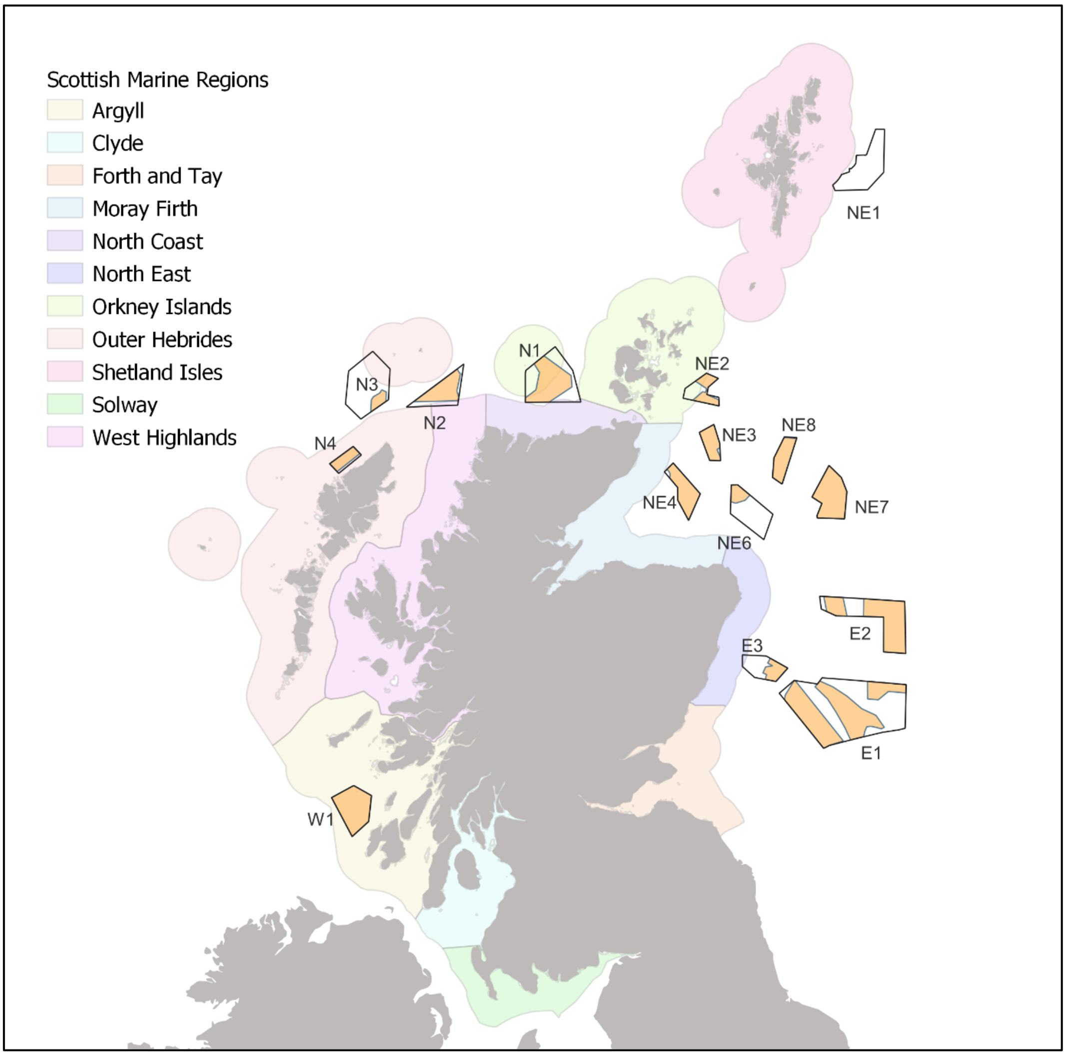

Figure 1. Scottish Marine Regions and Sectoral Marine Plan Options (black polygons). Orange areas within Plan Option polygons indicate sites awarded lease option agreements in the ScotWind leasing round. (Contains information from the Scottish Government (Marine Scotland) licensed under the Open Government Licence v3.0 and from Crown Estate Scotland under Crown Copyright.)

Here we present a review of the published literature to collate and synthesise the existing evidence base for the assessment of the impacts of offshore wind farms and associated activities on three focal species: Manx Shearwater *Puffinus puffinus,* European Storm-petrel *Hydrobates pelagicus* and Leach's Storm-petrel *Hydrobates leucorhous*. We have included less detailed accounts for two additional procellariiform species: Northern Fulmar *Fulmaris glacialis* and Sooty Shearwater *Ardenna grisea*. We identify critical gaps in existing knowledge, outline the challenges to filling data gaps, and make recommendations for possible approaches for improving the existing evidence base. Preliminary findings were shared with subject experts, and through two online workshop we clarified the state of existing knowledge and critical knowledge gaps, especially in relation to the attraction of focal species to artificial lighting of offshore renewable structures and support vessels. We include particular reference to Scotland's Sectoral Marine Plan Options, the specific risks posed to nocturnally active petrels and shearwaters by artificial lighting, and how light attraction may influence assessment of other risks (e.g. collision). We outline potential mitigation methods.

3 Methods

We conducted a systematic literature search to compile, for each focal species, a summary of the current knowledge of: (i) distribution; (ii) population status and abundance; (iii) demography; (iv) foraging ecology and (v) pressures on populations. Our review makes particular reference to attributes that are of critical importance in assessing the vulnerability of these species to potential impacts of offshore wind turbines and associated infrastructure and activities, including: (i) collision risk; (ii) displacement and barrier effects; and (iii) attraction to artificial light. Given the potential differences in the distributions and behaviours of a species during the breeding and non-breeding periods, at different stages of the breeding season and for different age classes, we considered attributes and risks separately for different groups and times of year. While we primarily focus on studies conducted within Scotland, relevant information collected elsewhere, and on closely related species, is also included. We used a set of search terms (listed in Appendix X) to search Google Scholar and Web of Science to identify relevant peer-reviewed and grey literature. We examined the first 100 publications produced by each search and also examined the reference list of publications identified by the literature search that were deemed relevant to the topic. We also made use of the extensive personal libraries and subject knowledge of the authors, noting any publications not identified by the systematic literature review.

We compiled a set of all input parameters required to populate the various methods, models and tools that are currently used for assessment of impacts of offshore wind farms on seabirds, specifically: (i) Collison Risk Models (Band et al., 2007, McGregor et al., 2018); (ii) the NatureScot Apportioning method (NatureScot, 2018); (iii) the Marine Scotland Apportioning Tool (Butler et al., 2020); (iv) the Fate of Displaced Birds Tool (SeaBORD; Searle et al., 2018); (v) displacement matrices (SNCBs, 2017) and (vi) the Natural England PVA Modelling Tool (Searle et al., 2019). We cross-referenced the publications identified by the literature search with the set of input parameters and catalogued the data sources accordingly, noting whether studies had been conducted in Scotland or elsewhere. Input parameters for which no information was identified by the literature review were considered to represent data gaps.

4 Species accounts

4.1 General ecology

The five seabird species that are the subject of this review all belong to the Order Procellariiformes, which includes the most pelagic of all seabirds. The three species which are the primary focus (Manx Shearwater, European Storm-petrel and Leach's Storm-petrel) are small-bodied and relative immobile on land, which renders them vulnerable to predation, so breeding colonies are restricted to islands that are often very remote, where the birds nest out of sight in burrows and cavities, and only attend the colony at night. The breeding season is divided into four distinct stages. During the pre-laying stage birds occupy and defend nest crevices, attract a mate and copulate. Females typically spend a protracted period (c. one week) at sea prior to laying (the so-called "pre-laying exodus") to acquire the nutrients needed to produce the single large egg. Once laid, the egg is incubated for around six weeks (the "incubation period"), until hatching. The newly hatched chick is incapable of full thermoregulation and parents take turns brooding the chick at the nest whilst the other feeds at sea ("brooding period"). Once chicks acquire the ability to thermoregulate independently, both adults spend the day feeding at sea, returning during darkness at intervals of 1 to 7 days to feed the chick (the "post-brooding" period). Although the storm-petrels are little bigger than a sparrow, and shearwaters the size of a pigeon, these species may cover thousands of kilometres at sea on a single foraging trip and the maximum range of a trip may lie hundreds of kilometres from the colony.

The eggs and chicks have very protracted development, requiring nearly four months from egg laying to fledging. For European Storm-petrels, within a particular colony the timing of breeding may be poorly synchronised among individuals, such that there will be birds engaged in breeding activities for more than six months of the year. The combination of large foraging ranges and very protracted breeding seasons means that birds will be exposed to risks from marine activities over a wider geographic area, and for a longer period of the year, than many other seabird species. All three focal species are trans-equatorial migrants, and immature birds do not return to the breeding colonies for several years, presumably remaining within, or close to, the wintering grounds in the South Atlantic. Storm-petrels and shearwaters do not reach breeding age for 3–6 years which, coupled with low fecundity, means that adults need to maintain a high annual survival rate for population stability, and any adverse impact on adult survival will have large, and long-term, consequences for population size.

While most of the above also applies to the two additional species included in this review, Northern Fulmars, and sometimes Sooty Shearwaters, will nest on mainland coasts as well as islands. Unlike the other species reviewed here, the Northern Fulmar is a surface nester, will attend its nest both during the day and at night, and is present in Scottish waters during both its breeding and non-breeding periods.

4.1.1 Note on spatial and temporal distribution

Information on the distribution of seabirds at sea is available from boat and aerial surveys, and more recently from tracking birds during the breeding season, and during their migration and non-breeding seasons. Both methods suffer from various drawbacks: aerial and vessel-based surveys tend to under-represent storm-petrel occurrence/density due to the birds' small size and dark colouration, and at-sea surveys are unable to determine the provenance, age or breeding stage of birds encountered at sea. The European Seabirds At Sea (ESAS) database used to produce maps of marine distribution of seabird (e.g. Stone et al., 1994, Waggitt et al., 2020) includes data collected over many decades and may not reliably reflect current marine distribution of seabirds, due to changing seabird population sizes, breeding colony distributions and prey distribution in recent decades. Tracking studies usually provide data on a relatively small number of birds from a given colony in a particular year and GPS tracking is almost exclusively restricted to the breeding season as birds must be recaptured to retrieve the tags and download the data. Therefore, tracking studies tend to provide a snapshot of the movements of a small number of birds within a restricted period. This snapshot may not always be representative of the foraging movements of the wider colony, particularly as the tagging itself may influence the behaviour of the birds (e.g.Gillies et al., 2020). Geolocators (GLS) can be used to track year-round movements but at a much lower resolution (two locations per day) and, again, the tags must be retrieved to download the data. The necessity of tag retrieval means that tracking studies for these species focus almost exclusively on breeding adults that return reliably to the colony, but tracking of juveniles and immature birds, which may not return to their natal colony for several years, presents methodological challenges.

4.1.2 Note on population status and abundance

The most complete population estimates available for seabirds breeding in Scotland are currently from Mitchell et al. (2004), which summarises the results of Seabird 2000, a census of Britain and Ireland's breeding seabirds, conducted between 1998 and 2002. The results of the latest census, Seabirds Count conducted between…, are due to be published in 2023 and will provide an important update on Scotland's seabird population status and trends.

4.2 Manx Shearwater

4.2.1 Spatial and temporal distribution in Scotland

4.2.1.1 Breeding distribution

The UK and Ireland's breeding colonies of Manx Shearwater are all located on islands, almost entirely on the western fringes, with additional colonies on the Irish Sea coasts (Figure 1). Very small numbers (< 10 pairs) formerly bred in Orkney (Cramp et al., 1974) and Shetland (Mitchell et al., 2004) but recent confirmation of breeding in these archipelagos is lacking. The species is present in Scottish waters between April and October, with nests occupied between April and August (Harris, 1966b, Guilford et al., 2009, Waggitt et al., 2020).

4.2.1.2 Marine distribution

4.2.1.2.1 Derived from at-sea surveys

Observations from offshore surveys in north-west European waters between 1979 and 1993 are collated in Stone et al. (1994) and show that, during the breeding season, the highest concentrations of birds are around the largest colonies of Rum (west Scotland), and Skomer and Skokholm (south-west Wales). During April, the highest densities were in the inshore waters of west Scotland. Feeding birds were observed in the offshore waters of west Scotland in May and June but occurred in inshore waters later in the season, during chick-rearing, when high densities of birds were present. This change in distribution is likely explained by the longer foraging trips during incubation when shifts average six days (Harris, 1966b), compared with chick-rearing, when each parent visits the nest at least every two days (Thompson, 1987). The species was observed around North Rona and Sula Sgeir between March and August and in low densities around Shetland, Orkney and the North Sea between May and August, remaining in the North Sea into September. Sightings in the North Sea were restricted to areas off the north-east coasts of Scotland and England, and especially the Moray Firth, Firth of Forth and Flamborough Head. The Manx Shearwater is a designated feature of the Outer Firth of Forth and St Andrews Bay Complex SPAfrom the ESAS database, that were collected between 1979 and 2006, showed distributions of Manx Shearwaters during the period May–October very similar to those described above, and during the period October–November low numbers were recorded, with small concentrations in the Celtic and Irish Seas and to the south-east of Orkney (Kober et al., 2009).

Waggitt et al. (2020) produced monthly distribution maps for seabirds in the north-east Atlantic based on distribution models using data collated from aerial and vessel surveys between 1980 and 2018. These maps show similar Manx Shearwater distributions in Scottish waters to Stone et al. (1994) and Kober et al (2009), with the highest densities to the west of Scotland, and densities increasing through the breeding season, peaking in August.

Projected distributions based on foraging range and colony sizes also indicate a Manx Shearwater hotspot to the west of Scotland (Critchley et al., 2018).

4.2.1.2.2 Derived from tracking data

Manx Shearwaters have been tracked using GPS tags from breeding colonies on Rum in Scotland, Copeland in Northern Ireland, High Island and Great Blasket in south-west Ireland, Lundy in the Bristol Channel, and Skomer and Skokholm in south-west Wales (Guilford et al., 2008, Dean et al., 2010, Freeman et al., 2012, Dean et al., 2013, Dean et al., 2015, Padget et al., 2019, Critchley et al., 2020, Kane et al., 2020). Prior to laying, females undertake a “pre-laying exodus”, during which they may travel a considerable distance to productive feeding grounds (e.g. at the edge of the continental shelf) which are not regularly visited when birds are attending eggs or chicks (Dean, 2012). During the breeding season birds from all colonies (except Lundy and Skokholm, where fewer birds have been tracked to date) visited Scottish waters. Birds tracked from Rum moved extensively through the North and West SMP regions (Dean et al., 2015, Padget et al., 2019), those from High Island and Great Blasket moved extensively through the West SMP region and into the North SMP region (Wischnewski et al., 2019, Kane et al., 2020), and birds from Copeland used the West SMP region extensively (Dean et al., 2015, Padget et al., 2019). The Solway and Clyde Scottish Marine Regions (SMRs) were used by birds from multiple colonies at all stages of the breeding season, although the extent of use varied between years (Dean et al., 2013, Dean et al., 2015).

In September, Manx Shearwaters depart in a south-westerly direction from the colonies to their wintering areas off South America, and arrive back from a westerly direction between March and May (Guilford et al., 2009). Fledglings depart on migration almost immediately after fledging and take a similar but more direct migration route than breeding adults (Wynn et al., 2021).

Few data exist on the distribution of immature Manx Shearwaters in Scottish waters. Immatures were tracked from Skomer in June–July 2013 and 2014 and, while adult movements extended into Scottish waters, immatures remained significantly further south, and there was little overlap between the core use areas of adults and immatures (Fayet et al., 2015).

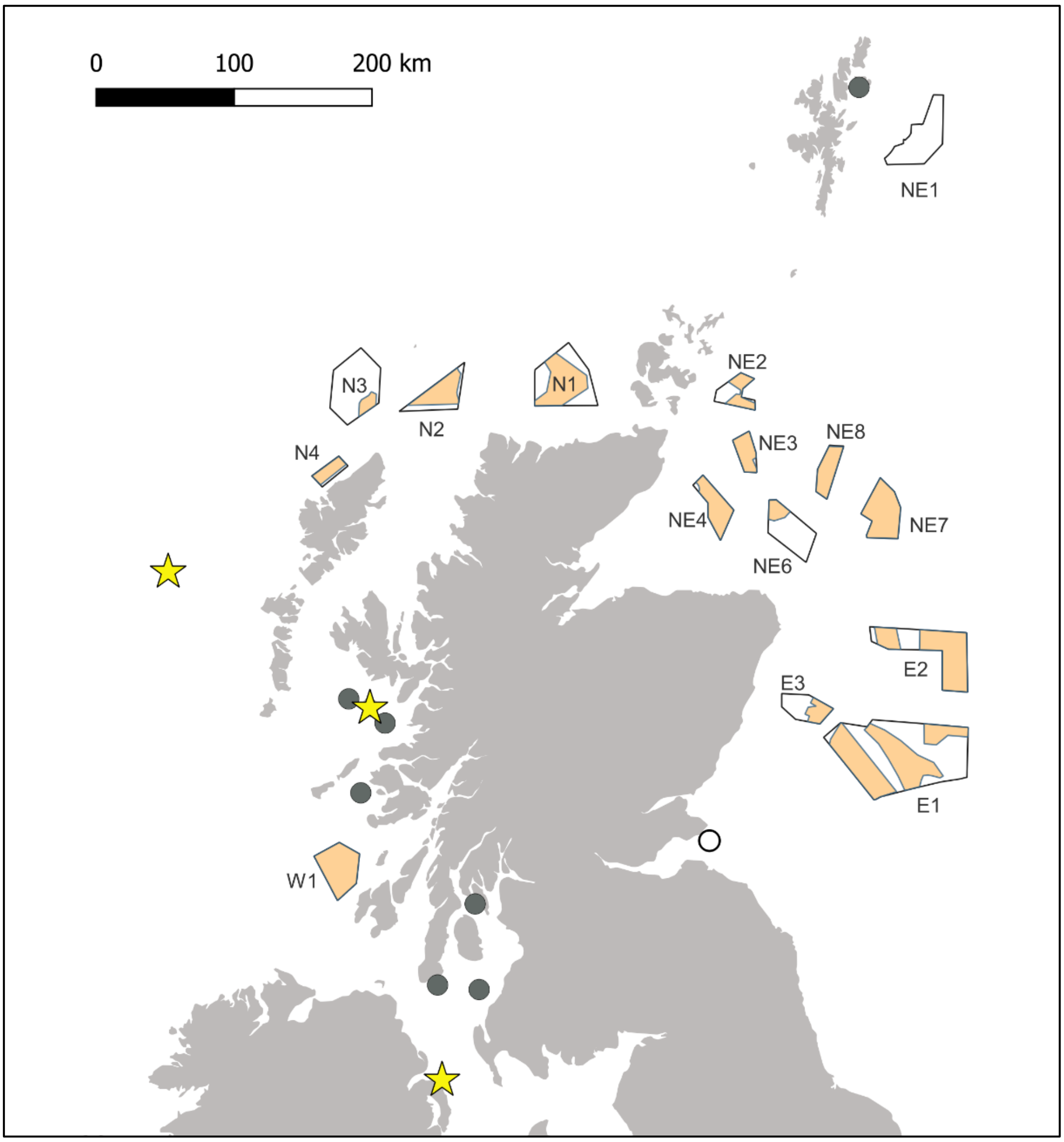

Figure 2. Manx Shearwater colonies (Mitchell et al., 2004) in relation to Plan Options. Yellow stars represent SPAs with Manx Shearwater as a designated feature. Grey circles are non-SPA colonies. White circles are colonies identified since Seabird 2000. Orange polygons within Plan Options indicate sites awarded lease option agreements in the ScotWind leasing round. Note that breeding colonies in Ireland and Wales (not shown) may also be at risk of impacts from developments in Scottish waters. (Contains information from the Scottish Government (Marine Scotland) licensed under the Open Government Licence v3.0 and from Crown Estate Scotland under Crown Copyright.)

4.2.2 Population status and abundance

4.2.2.1 Breeding

The most recent global population estimate for Manx Shearwaters is 338,000–411,000 pairs, with 305,000–374,000 of these breeding in Britain and Ireland. Scotland holds internationally important numbers of the species, with an estimated 126,545 (95% CLs 112,285–141,701) breeding pairs (Table 1), representing 38% of the population in Britain and Ireland (Mitchell et al., 2004). The breeding colony on Rum was estimated as 120,000 (107,000–134,000) breeding pairs in 2001 (Mitchell et al., 2004), making it the largest single-island colony in the world at the time. A more recent survey conducted in 2021, using slightly different survey methods, estimated the colony size as 288,894 (226,010 – 403,915) pairs (Inger et al., 2022). It is not clear to what extent the difference in survey estimate represents a genuine increase in population size since estimates of nesting density were similar in both surveys. The apparent increase in population size in 2021 resulted almost entirely from an increase in the size of the area considered to be suitable for nesting. The colonies at both Rum and St Kilda qualify as internationally important (Mitchell et al., 2004).

Table 1 Numbers of breeding Manx Shearwater Apparently Occupied Sites (AOS) in Scotland 1999–2002 (Mitchell et al., 2004). Only colonies designated as SPAs are listed individually

Administrative area	SPA colonies	AOS	95% LCL	95% UCL	Colonies counted	Colonies not counted
Shetland	*Non-SPA*	7	7	7	1	
Western Isles	St Kilda	4,803	3,593	5,909	1[1]	
Lochaber	Rum	120,000	107,000	134,000	1	
	Non-SPA	252	202	302	3	
Argyll & Bute	*Non-SPA*	1,483	1,483	1,483	2	1 possible
Cunninghame	*Non-SPA*	Present?			0	1
Kyle & Carrick	*Non-SPA*	Present?			0	1
Total		**126,545**	**112,285**	**141,701**	**8**	**3**

[1] Four islands of St Kilda treated as one colony.

4.2.2.2 Non-breeding

Skov et al. (1994) estimate that immatures could comprise around 25% of the entire population of Manx Shearwaters and Guilford et al. (2008) estimate that up to half the population could be non-breeders, in any given year (i.e. including birds of breeding age that were unpaired). An estimated 200,000 individuals are present in Scottish waters on passage (Furness and Wade, 2012).

4.2.3 Productivity and survival

4.2.3.1 Age at first breeding

Age at first breeding is not known for Manx Shearwaters breeding in Scotland but studies at the Pembrokeshire colonies suggest that some will breed from three years old, but that most do not breed before the age of five (Harris, 1966a).

4.2.3.2 Productivity

In Scotland, productivity data are collected on Rum, Canna and Sanda, and the average productivity between 1986 and 2018 was 0.62 chicks fledged per AOS (JNCC, 2021b), with no indication of a temporal trend over this period. Productivity as high as 0.97 has been recorded on Sanda (Mavor et al., 2006).

More experienced breeders may have higher productivity than first-time breeders. Hatching success on Skokholm between 1973–76 was lower in newly formed pairs (66.2%) than established pairs (79.2%; Brooke, 1978).

Manx Shearwater burrows can be susceptible to flooding and high rainfall during incubation has been shown to reduce hatching success on Rum and Canna (Thompson and Furness, 1991).

4.2.3.3 Survival

The average annual adult survival rate on Skokholm was estimated to be 0.902 between 1963 and 1968, ranging from 0.794 to 0.965 (Harris, 1966a, Perrins et al., 1973). Mean adult annual survival on Skomer was 0.87 between 1978 and 2018 (Zbijewska et al., 2020). Data from Rum (Hallival, Askival and Trollaval) from 1994–2014 and Sanda Island from 2000–2005 indicate a mean (± SD) annual adult survival rate of 0.93 ± 0.03 (Horswill et al., 2016).

Estimating survival for non-breeders is challenging due to the low re-encounter rates, but Harris (1966a) estimated that pre-breeders frequenting the Skokholm colony, from the age of four years old, have an annual survival rate of around 0.8. On Skokholm, average survival rates of young Manx Shearwater from fledging to returning to the colony as pre-breeders were estimated as 26.7% for 1964–69 (Perrins et al., 1973) and 21.8% for 1967–71 (Brooke, 1977), but these are likely to be underestimates as not all surviving birds will be recaptured, and Perrins (2014) suggests the actual survival rate is around 28–37%. The percentage of birds surviving to breed will be lower since pre-breeders spend more time on the surface at the colony and are at higher risk of predation than breeding birds (Perrins et al., 1973). There is some indication that chicks fledging later in the season have lower survival rates (Perrins, 1966).

4.2.4 Foraging ecology

The Manx Shearwater is a pursuit-plunger (Brown et al., 1978), and birds studied at Skomer had an average dive depth of 9.6 m, and a maximum depth of 55 m, with dives lasting 13.5 seconds on average and a maximum of 46 seconds, with no differences between the sexes (Shoji et al., 2016). For birds tracked from Skomer, diving occurred during the day and peaked in the evening (Shoji et al., 2016), but nocturnal foraging was observed from tracking of birds from High Island, Ireland (Kane et al., 2020). The species displays a dual foraging strategy during the breeding season, undertaking a combination of short trips for chick provisioning and long trips for self-provisioning (Shoji et al., 2015, Wischnewski et al., 2019). Since dual foraging can lead to bimodality in foraging ranges, it should be considered when using foraging range data to assess the risks posed by wind farm developments.

Currently, the standard foraging ranges for Manx Shearwater used in offshore wind casework come from Woodward et al. (2019), who collated the available data to give a maximum foraging range of 2890 km, a mean maximum of 1346.8 ± 1018.7 km, and a mean of 36.1 ± 88.7 km. Foraging trip durations and distances vary between years, colonies, breeding stage and the sexes (Thompson, 1987, Gray and Hamer, 2001, Guilford et al., 2008, Dean et al., 2010, Dean, 2012, Dean et al., 2013, Dean et al., 2015, Wischnewski et al., 2019). Published tracking data from Scotland is limited to 75 trips by 20 chick-rearing birds on Rum, which each lasted one day and had a median total trip distance of 184 km (interquartile range 128–274 km) and median maximum distance from the colony of 35 (29–73) km (Dean et al., 2015). The distances recorded by birds from Rum were shorter than those of chick-rearing birds from other colonies tracked simultaneously, the longest of which were undertaken by birds from Skomer, which covered a total of 297 (203–581) km during trips of one to two days, and reached a median maximum distance of 86 (61–134) km from the colony (Dean et al., 2015). Manx Shearwaters tend to travel further during incubation than chick-rearing, with incubating birds from Skomer undertaking trips of 8 (7–11) days duration, covering total distances of 1,517 (925–2,117) km and reaching a maximum distance from the colony of 254 (176–295) km (Dean et al., 2015). In some years, pre-laying females from Skomer have been found to make long trips to or beyond the continental slope, up to 727 km from the colony (Dean, 2012). Birds tracked from colonies in Ireland had foraging ranges of up to 1,109 km (Wischnewski et al., 2019).

Of the 528 trips from four colonies (Rum, Copeland, Skomer and Lundy) studied by Dean et al. (2015), almost all were largely restricted to the waters over the continental shelf, with only six trips extending beyond the shelf edge. Birds foraged in areas near their respective colonies, with little overlap between colonies, but individuals from all colonies also travelled to a more distant shared foraging area at the highly productive Irish Sea Front and nearby stratified waters of the Western Irish Sea (Dean et al., 2015). This productive area is approximately 375 km from Rum and was visited on 60% of the long-distance trips made from the colony (Dean et al., 2015). There is some evidence that the foraging areas of birds from the Pembrokeshire colonies may have shifted northwards since the 1950s (Guilford et al., 2008).

Manx Shearwaters gather in dense flocks on the sea in the vicinity of breeding colonies from late afternoon, before coming ashore after nightfall. This so-called “rafting” behaviour was studied using radio telemetry of chick-reading adults at Rum, Bardsey and Skomer to inform designation of colony extension marine protected areas (McSorley et al., 2008, Wilson et al., 2009). The maximum extent of rafts (95% kernel contours of raft locations) varied according to colony: 4, 6 and 9 km respectively for Skomer, Rum and Bardsey. Locations of radio-tagged individuals in rafts were estimated by triangulation from adjacent coasts, though some potential raft locations were unobservable due to the lack of direct line-of-sight from tracking locations. It would be instructive to analyse the large body of tracking data collected using GPS tags in recent years to improve our understanding of rafting behaviour. Dean et al. (2013) found that GPS tagged birds tended to roost on the sea within 20 km of the colony prior to landfall and that they resumed roosting on the sea adjacent to the colony after their visit.

4.2.4.1 Diet

Limited dietary analysis has been conducted for Manx Shearwaters. Thompson (1987) collected 104 samples on Rum in the 1980s and found that 65.8% contained fish (clupeids, sandeels and one sheppy Argentine), 47.4% squid (Ommastrephidae, Cranchiidae, Gonatidae, Onychoteuthidae and Mastigoteuthidae) and 7.9% crustaceans, although these were always associated with fish remains and were believed to be eaten by the fish rather than the shearwater directly. Most fish were likely around 5 cm or longer, and the largest intact fish was an 8 cm long sprat (Thompson, 1987). The data suggest that squid were more important before egg-laying and that the diet during chick-rearing was primarily fish, despite squid likely being over-represented due to their digestion-resistant beaks (Thompson, 1987). Ommastrephidae squid migrate to the surface at night and the other squid families identified, plus the sheppy Argentine, are all bioluminescent, suggesting that shearwaters were feeding at night prior to chick-rearing (Thompson, 1987). All diet samples observed by Brooke (1990) on Skomer contained fish, many of them clupeids around 15 cm long.

4.3 European Storm-petrel

4.3.1 Spatial and temporal distribution in Scotland

4.3.1.1 Breeding distribution

The UK and Ireland's breeding populations of European Storm-petrel are located on rat-free islands around the northern and western coasts (Figure 3; Mitchell et al., 2004, De León et al., 2006). The species is present in Scottish waters between May and October, with nests occupied between May and September, although small numbers may be present in nests in April and October (Davis, 1957a, Waggitt et al., 2020). Breeding was confirmed for the first time on the Isle of May (Firth of Forth) in 2021 (https://www.nature.scot/storm-petrels-breeding-isle-may).

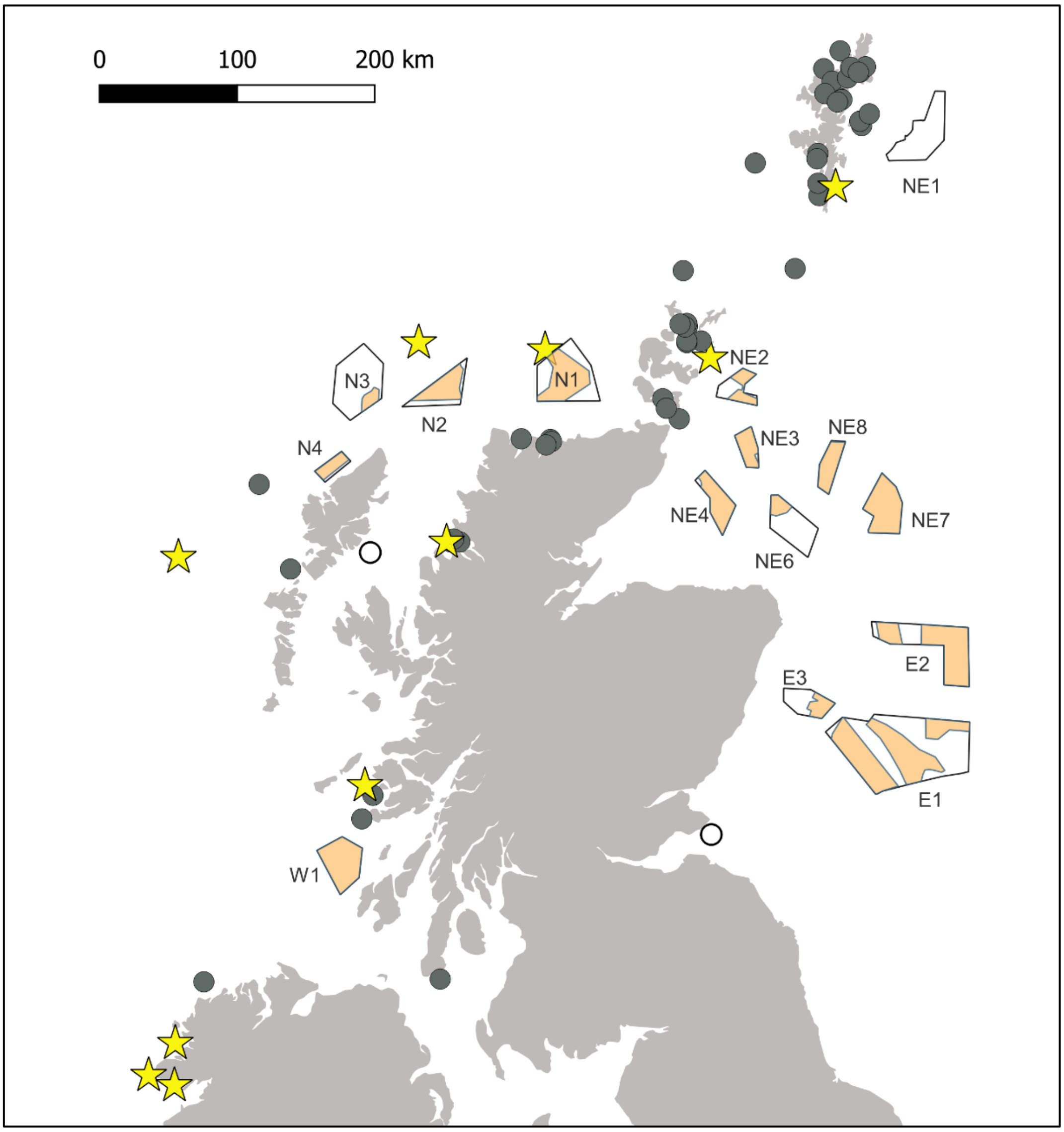

Figure 3. European Storm-petrel colonies in relation to Plan Option areas. Yellow stars represent SPAs with European Storm-petrel as a designated feature. Grey circles are non-SPA colonies surveyed in the Seabird 2000 census (Mitchell et al., 2004). White circles are colonies identified since Seabird 2000. Orange polygons within Plan Options indicate sites awarded lease option agreements in the ScotWind leasing round. Note that breeding colonies in Ireland and Wales (not shown) may also be at risk of impacts from developments in Scottish waters. (Contains information from the Scottish Government (Marine Scotland) licensed under the Open Government Licence v3.0 and from Crown Estate Scotland under Crown Copyright.)

4.3.1.2 Marine distribution

4.3.1.2.1 Derived from at-sea surveys

The ESAS data for 1979 to 1994 show that during May and June European Storm-petrels were mainly found over the outer shelf and shelf break to the north-west of Scotland, with low densities near Fair Isle, Shetland and the west coast of Scotland (Stone et al., 1995). In July and August the species was widespread to the north of Scotland and over the continental shelf to the west of Scotland, with densities highest at the shelf edge (Stone et al., 1995).

There were also low densities around Orkney, Shetland and the north-western North Sea (Stone et al., 1995). Between September and November densities were low, but birds were observed on the continental shelf west of Scotland, along the north-east Scotland coasts, and north-east of Orkney and Shetland (Stone et al., 1995). There were no sightings in Scottish waters between December and April (Stone et al., 1995).

Poisson kriging of ESAS data collected between 1979 and 2006 showed distributions of European Storm-petrels during the breading season (June–October) broadly similar to those described above, with high densities widely distributed over the outer shelf and a large area of high density situated around 100 km north of Lewis (Kober et al. 2009).

Monthly distribution maps based on data collated from aerial and vessel surveys between 1980 and 2018 suggest a similar distribution, with European Storm-petrels present in all SMP regions and peak densities along the continental shelf, from north-east of Shetland to south-west of Ireland (Waggitt et al., 2020). Peak densities are in August, and birds are still present in October (Waggitt et al., 2020).

4.3.1.2.2 Derived from tracking data

Few tracking data exist for European Storm-petrels in the Atlantic. Bolton (2021) tracked breeding adults from the largest UK colony on Mousa, Shetland, during incubation and chick-rearing between 2014 and 2017 using GPS tags. Rather than travelling to the shelf edge, all birds used an area to the south of Shetland, moving extensively over the north-east SMP region (Bolton, 2021). A further nine chick-rearing birds GPS-tracked from Mousa in 2018 travelled in a similar direction but remained closer to the colony than birds tracked in previous years (Z. Deakin, unpublished data). The broad area of use across all years is also identified in the distribution maps produced from at-sea survey data by Waggitt et al. (2020), and broadly indicated as an area of moderate usage in Kober et al. (2009). None of the birds tracked from Mousa travelled to the west or north of Shetland, suggesting that the high concentrations of birds at the continental shelf edge are from the large colonies in the Faroes, although may also include large numbers of non-breeding birds.

Contracted by Marine Scotland, the RSPB tracked 19 breeding European Storm-petrels from Lunga, Treshnish Isles, in 2021. All birds remained on the continental shelf, moving extensively through the West SMP region, with one bird travelling 198 km from the colony to the shelf edge (RSPB unpublished data).

To date there are no published tracking studies of the migration pathways and wintering areas of European Storm-petrels breeding at Scottish colonies, although eight individuals breeding in Shetland were successfully tracked using GLS tags for 9–10 months, from the chick-rearing period in 2016 to the onset of the following breeding season in 2017 (RSPB unpublished data). A further 20 GLS tags were deployed on European Storm-petrels breeding on Lunga, Treshnish Isles in 2021 for retrieval in 2022. Limited information from ringing recoveries of birds found dead indicates the wintering areas are located off southern Africa (Marchant et al., 2002).

4.3.2 Population status and abundance

4.3.2.1 Breeding

The global population of European Storm-petrels is thought to be in the region of 1.5 million individuals (Brooke, 2004), although estimates are far from accurate and the global population trend is unknown. Data from the Seabird 2000 census suggest that Scotland holds 83% of Britain's 25,710 (95% CLs 21,043-33,517) breeding pairs of European Storm-petrels (Table 2; Mitchell et al., 2004), including the largest colony on the island of Mousa, Shetland (Mitchell et al., 2004). There were more than 50 known colonies in Scotland during Seabird 2000, but only three (Mousa, Treshnish Isles and Priest Island) were estimated to hold more than 1,000 Apparently Occupied Sites (AOS), with both Mousa and Treshnish holding internationally important numbers (Mitchell et al., 2004). Resurvey of the Mousa colony in 2008 identified a 118% increase in the population since 1996 (Bolton et al., 2010), but this growth had slowed by the most recent survey in 2015 when the population was estimated at 10,778 (95% CLs 8,857-13,207) AOS (Bolton et al., 2017). A 2018 resurvey of the Treshnish Isles of Fladda, Lunga and Sgeir a' Chaisteil estimated the population to be 8,664 AOS, representing a 109% increase since the Seabird 2000 survey in 1996 (Ward, 2018). The population at Priest Island in the Summer Isles was estimated at 3,584 ± 437 individuals in 2012, having declined by 50% since the Seabird 2000 estimate in 1999 (Insley et al., 2014), but a 2019 survey estimated 4,640 AOS, a 5% increase since Seabird 2000 (JNCC, 2021a). Resurvey of North Rona, Western Isles, in 2009 resulted in an estimate of 371 AOS, suggesting the population had remained stable since the Seabird 2000 survey in 2001 (Murray et al., 2010).

Table 2 Numbers of breeding European Storm-petrel Apparently Occupied Sites (AOS) in Scotland 1999–2002 (Mitchell et al, 2004). Only colonies designated as SPAs are listed individually. LCL and UCL are lower confidence limit and upper confidence limit, respectively.

Administrative area	Colony	AOS	95% LCL	95% UCL	Colonies counted
Shetland Islands	Mousa	6,800	4,800	8,800	1
	Non-SPA	703	678	729	25
Orkney Islands	Auskerry	994	372	3,196	1
	Sule Skerry & Sule Stack	309	309	309	1
	Non-SPA	567	429	750	12
Sutherland	*Non-SPA*	449	339	594	4
Ross & Cromarty	Priest Island	4,400	3,300	6,100	1
	Non-SPA	66	50	88	3
Argyll & Bute	Treshnish Isles	5,040	5,040	5,040	1
	Non-SPA	208	208	208	3
Western Isles	St Kilda	1,121	825	2,242	1
	North Rona	368	335	413	1
	Sula Sgeir	9	9	9	1
	Non-SPA	335	303	377	4
Total		**21,370**	**16,997**	**28,855**	**59**

4.3.2.2 Non-breeding

An estimated 100,000 individuals are present in Scottish waters on passage (Furness and Wade, 2012).

4.3.3 Productivity and survival

4.3.3.1 Age at first breeding

Most immatures are thought to begin prospecting at colonies in their second year and begin breeding in their third year, with almost all birds recruited into the breeding population by year five (Okill and Bolton, 2005).

4.3.3.2 Productivity

On Mousa, Shetland, breeding success from laying to fledging was 0.76 in nest boxes and 0.50 in natural nest sites in 1993; a difference that was not statistically significant (Bolton, 1996). Productivity on Skokholm in the 1950s and 60s was estimated at 0.59 and 0.49 young fledged per breeding pair by Davis (1957b) and Scott (1970), respectively. This estimate from Scott (1970) does not include data from 1967, when breeding success was only 0.27, apparently due to loss of chicks by starvation during a period of poor food availability. Mean (± SE) productivity on Skokholm for 2014–20 was 0.58 ± 0.04 (range 0.45–0.74), and was 0.80 in 2021, although the number of monitored nests is small (Brown and Eagle, 2022). Breeding success on Enez Kreiz, Brittany in 1999 was 0.53 young fledged per egg laid (Cadiou, 2001), and 0.62 at Biarritz, south-west France in 1974-79 (Hémery, 1980).

Breeding success in a population of the Mediterranean subspecies, *Hydrobates pelagicus melitensis*, in 1993–2006 had a mean (± SE) of 0.53 ± 0.05 but was lower in birds less than four years old (0.22 ± 0.07) (Sanz-Aguilar et al., 2009). Higher infestations of the tick *Ornithodoros maritimus* have been found to reduce the body condition and survival of chicks in the Mediterranean Storm-petrel (Sanz-Aguilar et al., 2020).

4.3.3.3 Survival

Scott (1970) estimated that the annual survival rate of European Storm-petrels on Skokholm in the 1960s was 0.88-0.91. The mean survival estimate (± SD) for European Storm-petrels based on the BTO's Retrapping for Adult Survival (RAS) scheme is 0.79 ± 0.04, using data obtained without using tape-lures from Eilean Hoan, Sanda Island, Priest Island and Lunga between 1996 and 2015 (Horswill et al., 2016). A previous analysis using all BTO ring recoveries from 1967–97 estimated annual survival at 0.858 ± 0.016 (SE) (Dagys, 2001), and a similar analysis for 2001–12 suggests that survival across Britain and Ireland slowly increased during this period, staying above 0.90 from 2008–12 (Insley et al., 2014). On Priest Island, survival was 0.92 ± 0.08 (SE) in 2001–02 and 0.96 ± 0.08 in 2002–03, but was lower in 2003–12, with an overall annual survival of 0.80 during this period, and a low of 0.61 ± 0.10 in 2012 (Insley et al., 2014). Ringing data on Skomer for 2006-17 suggest an annual survival rate of 0.88 for breeding adults and 0.59 for transients (Zbijewska et al., 2020), although estimates for transient, pre-breeding birds that prospect multiple colonies before recruiting are likely to be underestimates. Survival estimates for European Storm-petrels at Aketx Islet in the Bay of Biscay for 1990–2006 ranged from 0.82–0.89, depending on the model used (Zabala et al., 2011).

Very small numbers of European Storm-petrels are ringed as chicks and immature survival rates are not currently available. Scott (1970) estimated that annual mortality between birds first returning to the colony and recruiting into the breeding population might be approximately 10-15%.

Sanz-Aguilar et al. (2008) found reduced survival in Mediterranean storm-petrels following their first breeding attempt or an unsuccessful breeding attempt.

4.3.4 Foraging ecology

European Storm-petrels are surface-feeders, although can make shallow dives up to 5 m (Flood et al., 2009, Albores-Barajas et al., 2011), and may target areas where prey is brought to the surface by upwellings and internal waves (Scott et al., 2013). Although, for the most part, European Storm-petrels are highly pelagic during the day (Bolton, 2021), they are known to forage inshore at night and occasionally during daylight (Stegeman, 1990, Koerts, 1992, D'Elbee and Hemery, 1997, Thomas et al., 2006, Poot, 2008, Flood et al., 2009, Albores-Barajas et al., 2011).

The continental shelf edge has been highlighted as having high concentrations of foraging European Storm-petrels (Stone et al., 1995, Waggitt et al., 2020), but breeding adults tracked from Mousa, Shetland Islands, all foraged in the shallow shelf waters to the south of the colony (Bolton, 2021). Birds from Mousa had foraging trips lasting one to three days during incubation, one day during brooding and one to two days during the post-brood stage (Bolton, 2021). Overall, the median total distance travelled was 391 km (maximum 958 km) and the median maximum range from the colony was 159 km (maximum 397 km), with no statistically significant difference between breeding stages (Bolton, 2021).

Nineteen European Storm-petrels tracked from Lunga, Treshnish Isles in 2021 (RSPB unpublished data) similarly foraged over shallow shelf waters. During the incubation stage, birds fed on average for 2–3 days at sea and ranged up to 142 km (max 198 km) from the colony, whereas when tending chicks, feeding trips tended to last for a single day and birds remained within 95 km (max 140 km) of the colony.

Six chick-rearing birds tracked from Illauntannig and High Island, Ireland, had a mean trip duration of 38 hours (maximum 67 hours), mean total distance travelled of 518 km (maximum 1,113 km) and mean range of 170 km (maximum 336) (Wilkinson, 2021). The maximum foraging range provided in the review by Woodward et al. (2019) is taken from these data alone, as presented by Critchley et al. (2018), so 336 km is the current standard foraging range used for offshore wind casework., although confidence in this value is poor. Most of the foraging locations for these birds were near or beyond the shelf edge at the Porcupine Bank and Porcupine Seabight and one bird apparently foraged close to the coast overnight (Wilkinson, 2021). There was also evidence of dual foraging, with some birds making shorter trips and remaining much closer to the colony (Wilkinson, 2021), and the possibility of birds using this strategy should be considered when using foraging range data to assess the risks posed by wind farm developments. All tracking to date in Britain and Ireland has been conducted between mid-July and mid-August, representing a fairly narrow time window relative the full extent of the breeding season (May to October).

The trips of European Storm-petrels tracked in the Atlantic are shorter than those of GPS-tracked Mediterranean storm-petrels, which lasted up to five days, covered total distances of up to 1,727 km, and ranged up to 469 km from the colony (De Pascalis et al., 2021, Rotger et al., 2021). Birds breeding at Benidorm Island in the Mediterranean had foraging areas that encompassed submarine canyons (Rotger et al., 2021). Birds breeding at Sardinia, Italy, foraged in shallow water with strong currents during their longer incubation trips but closer to the colony during chick-rearing, in shallow, productive waters (De Pascalis et al., 2021).

4.3.4.1 Diet

On Skokholm, Pembrokeshire, in the 1960s, regurgitates contained young herring *Clupea harengus* and sprat *Clupea sprattus* as well as amphipods and decapods (Scott, 1970). Two main prey groups were identified in birds breeding in the Bay of Biscay by D'Elbee and Hemery (1997). The first consisted of oceanic and neritic organisms such as ichthyoplankton (Gadidae, Ammodytidae, Myctophidae) and microzooplankton (Copepoda, Euphausiacea, Chaetognatha, Anthomedusae and meroplanktonic larvae), with an average body length of 4 cm (range 0.5–9 cm) and included bioluminescent species that migrate vertically in the water column at night. The second group consisted of littoral (Gobiidae) and suprabenthic intertidal organisms such as isopods (Cirolanidae), which were presumably collected during nocturnal inshore foraging (D'Elbee and Hemery, 1997). DNA analysis of faeces and regurgitates collected from European Storm-petrels breeding on Mousa, Shetland (Wood, 2017) identified fish in 97% of faecal samples and 92% of regurgitates, and invertebrates in 71% of faecal samples and 3% of regurgitates. No faecal samples contained squid DNA. The most common fish species were Norway pout *Trisopterus esmarkii* and Whiting *Merlangius merlangus*. European Storm-petrels will also scavenge on carcasses and waste from fishing boats and can be found foraging in high concentrations around fish farms (Hudson and Furness, 1989, Medeiros Mirra, 2010, Borg, 2012, Josa et al., 2021).

4.4 Leach's Storm-petrel

4.4.1 Spatial and temporal distribution in Scotland

4.4.1.1 Breeding distribution

Most Leach's Storm-petrels breeding in Britain and Ireland do so at colonies in Scotland's Western Isles, with smaller numbers on islands off the west coast of Ireland, and two small colonies (± 20 pairs) in Shetland (Figure 4; Mitchell et al., 2004). However, for two of the seven Scottish colonies for which breeding was confirmed in the Seabird 2000 census, there is no recent evidence of breeding (Foula, Shetland and Old Hill, Lewis). Breeding was confirmed at Gloup Holm, Shetland in 2020 (Miles et al., 2021). Birds are present at the breeding colonies between April and October.

4.4.1.2 Marine distribution

4.4.1.2.1 Derived from at-sea surveys

Based on data from at-sea surveys, during May to August Leach's Storm-petrels were highly concentrated over the shelf edge, Rosemary Bank seamount and the deeper waters to the north-west of Scotland (Skov et al., 1994, Stone et al., 1995, Kober et al., 2009). Numbers were highest in the waters around St Kilda, with occasional sightings in the northern North Sea (Hall et al., 1987, Stone et al., 1995). The species was more widely dispersed between September and November, with low numbers around the Outer Hebrides, Shetland, and the east of Scotland (Stone et al., 1995). There were no sightings of Leach's Storm-petrels in Scottish waters between December and April.

Poisson kriging of ESAS data collected between 1979 and 2006 showed distributions of Leach's Storm-petrels during the breeding season (June – October) similar to those described above, with the highest densities on the northern slope of the Rosemary Bank seamount (Kober et al. 2009).

4.4.1.2.2 Derived from tracking data

Tracking of breeding Leach's Storm-petrels from St Kilda in 2021 confirmed their use of deep waters (>1,000 m) around the Rosemary Bank seamount that were identified as hotspots by at-sea surveys (RSPB unpublished data). There is no information from either tracking or ringing regarding the marine distribution of Leach's Storm-petrels (of any age-class) from Scottish colonies outside the breeding season. Twenty Leach's Storm-petrels breeding on St Kilda were equipped with GLS tags in 2021, for retrieval in 2022 (RSPB unpublished data).

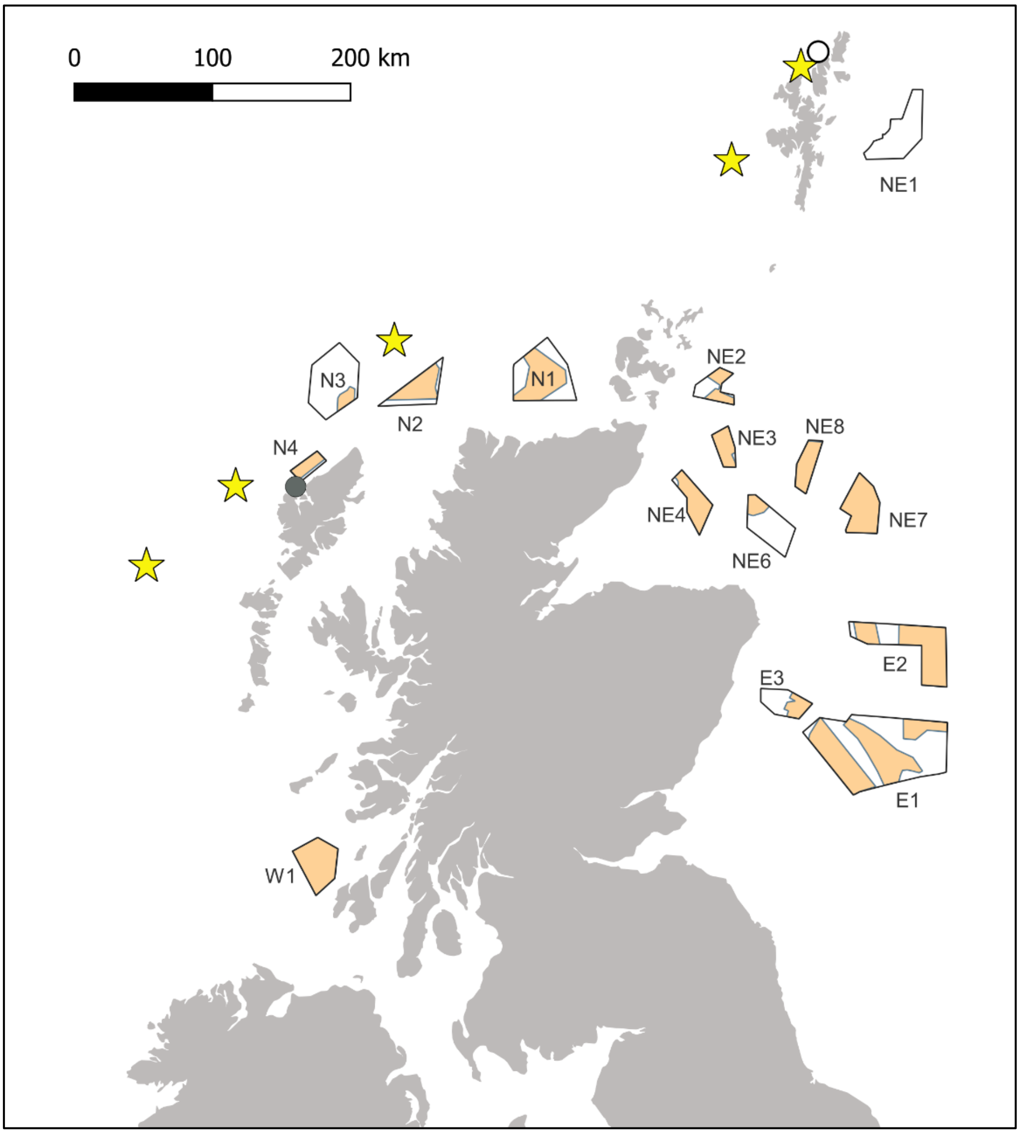

Figure 4. Leach's Storm-petrel colonies in relation to Plan Option areas. Yellow stars represent SPAs with Leach's Storm-petrel as a designated feature. Grey circles are non-SPA colonies surveyed in the Seabird 2000 census (Mitchell et al., 2004). White circles are colonies identified since Seabird 2000. Orange polygons within Plan Option areas indicate sites awarded lease option agreements in the ScotWind leasing round. Note that breeding colonies in Ireland (not shown) may also be at risk of impacts from developments in Scottish waters. (Contains information from the Scottish Government (Marine Scotland) licensed under the Open Government Licence v3.0 and from Crown Estate Scotland under Crown Copyright.)

4.4.2 Population status and abundance

4.4.2.1 Breeding

The global population of Leach's Storm-petrels is estimated at 6.7–8.3 million breeding pairs, with 40–48% of these in the Atlantic (>90% of which breed in the western Atlantic) and 52–60% in the Pacific (BirdLife International, 2022c). There is genetic evidence for long-distance dispersal between colonies in the Atlantic, suggesting that Leach's Storm-petrels in the North Atlantic should be considered as a metapopulation for conservation and management purposes (Bicknell et al., 2012). At the time of the Seabird 2000 census Scotland held more than 99% of Britain and Ireland's breeding Leach's Storm-petrels, with 94% of these on the St Kilda archipelago (Table 3; Mitchell et al., 2004). Additional surveys of Dùn, the island of the St Kilda archipelago with the largest Leach's Storm-petrel population, indicated a 54% decline between 1999 and 2006 (Newson et al., 2008). Data from a further survey of the four main St Kilda islands in 2019 suggest a 68% decline across the archipelago in the 20 years since Seabird 2000, with the population currently estimated at 8,869 (95% CLs 7,787–10,102) AOS (Deakin et al., 2021). This decline led to the species being up-listed from Amber to Red in the UK's Birds of Conservation Concern assessment (Stanbury et al., 2021). The population on North Rona was estimated at 713 AOS in 2009, a 34% decline since 2001, and a 2009 survey of Sula Sgeir found no Leach's Storm-petrels (Murray et al., 2010).

Table 3 Numbers of breeding Leach's Storm-petrel Apparently Occupied Sites (AOS) in Scotland 1999–2002 (Mitchell et al, 2004). All colonies except Loch Roag are SPAs with Leach's Storm-petrel as a designated feature.

Administrative area	Colony	AOS	95% lower confidence limit	95% upper confidence limit
Shetland Islands	Foula	15	3	30
	Gruney	20		
Orkney Islands	Sule Skerry	0		
Western Isles	St Kilda	45,433	34,310	61,398
	Flannan Isles	1,425	1,232	1,708
	Loch Roag	17	15	20
	North Rona	1,132	849	1,700
	Sula Sgeir	5	3	7
Total		**48,047**	**36,432**	**64,883**

4.4.2.2 Non-breeding

An estimated 100,000 individuals are present in Scottish waters on passage (Furness and Wade, 2012).

4.4.3 Productivity and survival

4.4.3.1 Age at first breeding

While the age of first breeding is not known for populations breeding in Scotland, in Canada Leach's Storm-petrels typically breed for the first time at 4–5 years of age (Huntington and Burtt, 1970).

4.4.3.2 Productivity

Breeding success was estimated at a minimum of 0.59 young per egg laid in burrows inspected with an endoscope on St Kilda in 2007 (Money et al., 2008) and 0.65 in 2008, with most failures occurring at the egg stage (Bicknell et al., 2009). The number of Leach's Storm-petrels breeding in nest boxes on St Kilda has increased from a single pair in 2006 to nine pairs in 2021 and breeding success has risen each year from 0.00 in 2006 to 0.89 in 2021, presumably due to increased breeding experience of nest box occupants (Nisbet, 2021). On Kent Island, New Brunswick, breeding success varied with breeding age, increasing by 0.39 ± 0.04 (SE) per year for the first two years, and declining by 0.20 ± 0.04 per year for the final two years of breeding (Mauck et al., 2012).

4.4.3.3 Survival

Our literature search found one estimate of adult survival rate (0.880) for Leach's Storm-petrel in Scotland (1984), cited in MacDonald et al. (2015, Table 1). This value was estimated in 1984 based on ringing conducted during the 1970s and early 1980s. Since that time the number of Great Skuas *Stercorarius skua* breeding on St Kilda has increased substantially, and they have been found to exert high levels of predation on Leach's Storm-petrels (Votier et al., 2006, Miles, 2010), with inevitable, but currently unquantified, impacts on adult survival rates. There is a need to assess current survival rates of Leach's Storm-petrels on St Kilda.

Mean annual survival was 0.78 ± 0.04 at Bon Portage Island, Nova Scotia in 2009–14 (Fife et al., 2015), and 0.79 for colonies at both Baccalieu Island and Gull Island, Newfoundland (Pollet et al., 2019), which is considered low for Procellariiformes and appears to be driving the decline of the species in the north-west Atlantic. Estimates on Kent Island, New Brunswick, Canada suggest that survival increased with age, with annual survival of 0.749 ± 0.046 from breeding year 1 to 2, 0.802 ± 0.040 from 2 to 3, and 0.870 ± 0.030 thereafter (Mauck et al., 2012). Estimates of adult survival for two breeding locations in the East Pacific (Rock Island and Cleland Island, British Columbia) were considerably higher at 0.975 ± 0.011 and 0.975 ± 0.001, respectively (Rennie et al., 2020).

4.4.4 Foraging ecology

Leach's Storm-petrels are highly pelagic, foraging over deep waters, although the species has been observed foraging on the shoreline in eastern Newfoundland, apparently as a result of extreme food stress caused by a marine heatwave (D'Entremont et al., 2021). Incubating adults tracked from Country Island and Bon Portage Island in Nova Scotia travelled to or beyond the continental shelf with foraging ranges of 1,015 ± 238 km and 612 ± 166 km, respectively (Pollet et al., 2014). Foraging range varied between years (Pollet et al., 2014). Tracking of incubating Leach's Storm-petrels at seven colonies in eastern Canada (including Country Island and Bon Portage) revealed little overlap between foraging areas among colonies, although there was no evidence that this was due to intra-specific competition rather than the availability of pelagic foraging habitat (Hedd et al., 2018). Foraging range was not affected by colony size but tended to be shorter for birds breeding at the southern end of the range (Hedd et al., 2018). Trips averaged 4.0 ± 1.4 days, with birds travelling to or beyond the continental slope to highly pelagic waters 400–830 km from the colonies, on average (Hedd et al., 2018). Birds from all but one colony showed a preference for deeper waters, with tracked birds from five of the seven colonies foraging over waters with median depths of more than 1,950 m and average chlorophyll *a* concentrations less than 0.6 mg/m^3 (Hedd et al., 2018). In contrast, birds from the most southerly colony, Kent Island, mainly foraged in shallower neritic waters with a median depth of 181 m (Hedd et al., 2018). Woodward et al. (2019), the current standard reference for foraging ranges for UK offshore wind casework, present a mean foraging range of 657 km, which is based on 11 individuals from Gull Island, Newfoundland, which were the only birds tracked by Hedd et al. (2018) using GPS devices, rather than geolocators, which are less precise. Further GPS tracking has been carried out at Gull Island and the maximum foraging range for 182 complete trips during 2016–2021 was 953 km (Collins et al., 2022).

Fourteen Leach's Storm-petrels tracked from St Kilda in 2021 (RSPB unpublished data) foraged over deep (>1000 m) oceanic water to the north and north-west of St Kilda. During the incubation stage, birds fed on average for 2–3 days at sea and ranged up to 301 km (max 412 km) from the colony, whereas when tending chicks, feeding trips tended to last for two days and birds ranged up to 260 km (max 294 km) from the colony.

In their wintering areas off southern Africa, Leach's Storm-petrel abundance peaked in waters more than 2,000 m deep, particularly in areas with large salinity and sea surface temperature gradients (Camphuysen, 2007).

4.4.4.1 Diet

As far as we are aware there have been no studies of the diet of Leach's Storm-petrels in the UK, but analysis of 18 regurgitate samples from the Faroes found them to be comprised of fish (primarily Gadiformes), crustaceans and other invertebrates (Hey, 2019). The fish species consumed included the demersal species Norway Pout *Trisopterus esmarkii* and Whiting *Merlangus* and, in contrast to studies in the western Atlantic (see below), Hey (2019) found no pelagic fish species, suggesting that foraging habits may differ for birds breeding in the Faroes.

In Newfoundland, fish and crustaceans appear to make up the bulk of the diet of chick-rearing birds, with fish increasing through the breeding season, and mature myctophids and sandeels being particularly abundant in regurgitate samples (Hedd and Montevecchi, 2006, Hedd et al., 2009). Prey items collected range in size from 0.3 to 18 cm (Hedd et al., 2009). While myctophids are deep-water species, migrating to the surface at night, the amphipod *Hyperia galba*, abundant in diet samples, is a parasite of jellyfish commonly found inshore, suggesting both offshore and nearshore foraging by Leach's Storm-petrels. Other prey items include euphausiids, decapods, copepods, isopods and cephalopods (Montevecchi et al., 1992, Hedd and Montevecchi, 2006, Hedd et al., 2009). A more recent study of the diet of Leach's Storm-petrels at colonies in Nova Scotia and New Brunswick found that fish occurrence was lower and cephalopod occurrence was higher than in the Newfoundland studies, although fish still comprised the bulk of the diet (Frith et al., 2020). Diet samples from Daikoku Island, Hokkaido, Japan, consisted of similar taxa to those collected in the north-west Atlantic, although the species differed and cephalopods were more prominent (Watanuki, 1985). Leach's Storm-petrels will also scavenge on fisheries discards (Frith et al., 2020).

Leach's Storm-petrels are surface-feeders and the prominence of diel vertically migrating prey such as myctophids in their diet suggests that they feed mainly at night (Hedd and Montevecchi, 2006). However, the species has been observed feeding during daylight on the midwater fish *Vinciguerria lucetia* in the tropical Pacific when large numbers of fish apparently came to the surface to feed on an abundance of copepods, concentrated by an oceanographic anomaly, so care should be taken when assuming foraging habits based on diet (Pitman and Ballance, 1990).

4.5 Northern Fulmar

4.5.1 Spatial and temporal distribution in Scotland

4.5.1.1 Breeding distribution

Before the mid eighteenth century, the only Northern Fulmar breeding sites within Britain and Ireland were at St Kilda but following a rapid population and range expansion between the late 19th and late 20th centuries the species now breeds all around the coasts of Britain and Ireland, both on mainland cliffs and offshore islands. The largest colonies and most breeding birds are in the north and west of Scotland (Mitchell et al., 2004).

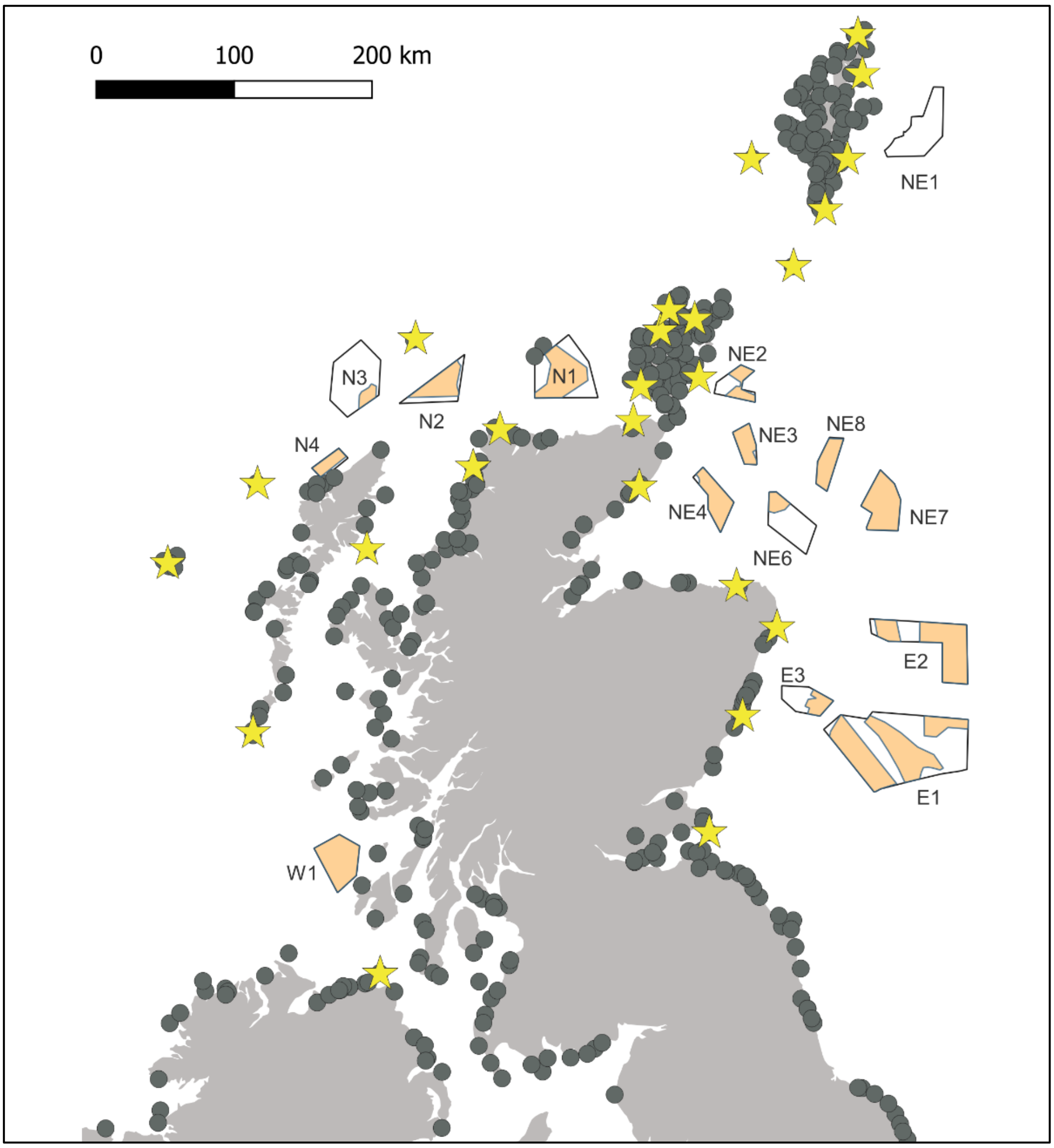

Figure 5. Northern Fulmar colonies in relation to Plan Option areas. Yellow stars represent SPAs with Northern Fulmar as a designated feature. Grey circles are non-SPA colonies surveyed in the Seabird 2000 census (Mitchell et al., 2004). Orange polygons within Plan Option areas indicate sites awarded lease option agreements in the ScotWind leasing round. Note that breeding colonies in Ireland, England and Wales (not shown) may also be at risk of impacts from developments in Scottish waters. (Contains information from the Scottish Government (Marine Scotland) licensed under the Open Government Licence v3.0 and from Crown Estate Scotland under Crown Copyright.)

4.5.1.2 Marine distribution

4.5.1.2.1 Derived from at-sea surveys

Fulmars breed in Scotland between April and mid-September but are present in Scottish waters throughout the year and may visit nest sites from November (Fisher, 1952). During March and April, the highest densities of Fulmars observed on at-sea surveys in Scotland were around the shelf edge to the north and west, including Shetland (Stone et al., 1995). During May to July the highest densities remained at these shelf edges, but the densities increased around colonies in Shetland, Orkney and the Hebrides. Fulmars leave the colonies during September, and from August to November high densities were found throughout the northern North Sea, as well as to the north and west of Scotland, and around Shetland and Orkney (Stone et al., 1995). The species remains in Scottish waters over winter. The results from Stone et al. (1995) are supported by those of (Kober et al., 2009) and Waggitt et al. (2020) who modelled at-sea survey data, and Darby et al. (2021), who modelled habitat preference based on tracking of 102 breeding adults from 11 colonies between 2009 and 2019.

4.5.1.2.2 Derived from tracking data

Tracking from Eynhallow revealed high variation in foraging trips during incubation, with Fulmars foraging in the North Sea, Norwegian Sea, Barents Sea and the central North Atlantic (Edwards et al., 2013, Edwards, 2015, Edwards et al., 2016), but trips during chick-rearing remained largely over the Scottish continental shelf and northern North Sea (Edwards, 2015). A male Fulmar tracked from Eynhallow to the Mid-Atlantic Ridge during incubation foraged over areas of persistent thermal fronts along the Charlie-Gibbs Fracture Zone (Edwards et al., 2013).

4.5.2 Population status and abundance

4.5.2.1 Breeding

The global population of Northern Fulmar is estimated at approximately 7 million pairs, or 20 million individuals (Carboneras et al., 2016), with 3.38–3.50 million pairs in Europe (BirdLife International, 2022b). At the time of the Seabird 2000 census, there were an estimated 537,991 AOS in Britain and Ireland, of which 90% (485,852 AOS) were in Scotland (Mitchell et al., 2004). The population growth in Britain appeared to have stopped between the 1980s and 2000, with overall numbers remaining stable but a mixture of increases and decreases at individual colonies (Mitchell et al., 2004). Scottish populations have been declining since the 1990s and in 2019 (the latest year for which data are available) were at their lowest since nationwide monitoring began in 1986 (JNCC, 2021b).

4.5.2.2 Non-breeding

An estimated 1 million Fulmar are present in Scotland outside of the breeding season (Furness and Wade, 2012).

4.5.3 Productivity and survival

4.5.3.1 Age at first breeding

The mean age at first breeding in the Northern Fulmar is 9 years (range 6–12 years; Dunnet and Ollason, 1978b), but this may be an overestimate (Dunnet et al., 1979). More recent estimates would be useful considering the change in the trajectory of Scotland’s Fulmar population since the 1970s.

4.5.3.2 Productivity

In Scotland, Fulmar productivity has been declining since the mid-1990s, and the number of young fledged per pair decreased from c. 0.55 to 0.39 between 1986 and 2019 (JNCC, 2021b). Productivity is monitored annually at the Isle of May (Newell et al., 2016), Fair Isle (Shaw et al., 2002), Canna (Swann, 2000) and Eynhallow, Orkney (Lewis et al., 2009). Mavor et al. (2008) present multi-year data for a large number of colonies in Scotland.

4.5.3.3 Survival

Annual adult survival has been estimated over several decades at Eynhallow by Grosbois and Thompson (2005). Survival estimates for the first time interval of the study (1962–1963) were 0.951 (95% confidence interval = 0.911–0.973) for females and 0.975 (0.9592–0.9888) for males, but declined over time and for the last time interval (1994–1995) were 0.898 (0.843–0.936) for females and 0.8674 (0.8105–0.9091) for males. Previous studies provide estimates of adult survival at Eynhallow going back to the 1950s (Dunnet et al., 1963, Dunnet and Ollason, 1978b, Dunnet and Ollason, 1978a).

Data on the survival of juvenile and immature Fulmars are lacking. Dunnet and Ollason (1978b) used indirect methods to estimate that mean annual survival of pre-breeders in the 1950s–1970s was between 0.88 and 0.93, but this may be an overestimate.

4.5.4 Foraging ecology

Fulmars are predominantly surface-seizers but will also make shallow dives (Garthe and Furness, 2001). The species is a common scavenger at fishing vessels (Garthe and Hüppop, 1994), where it can congregate in large numbers (Camphuysen et al., 1995), but the evidence for fisheries driving the at-sea distributions of Fulmars is mixed, with some studies suggesting the spatial distribution of fisheries and Fulmar are not correlated (Camphuysen and Garthe, 1997), while others suggest a strong correlation (Darby et al., 2021).

Woodward et al. (2019), the current standard reference for foraging ranges for UK offshore wind casework, present a mean foraging range of 134.6 ± 90.1 km, a maximum range of 2,736 km, and a mean maximum range of 542.3 ± 657.9 km.

At some colonies, including St Kilda, the timing of colony attendance and/or the prevalence of nocturnally vertically migrating species such as lantern fish in the diet suggest that Fulmars are largely foraging at night (Furness and Todd, 1984, Danielsen et al., 2010, Danielsen, 2011), while elsewhere there appears to be little or no nocturnal foraging (Furness and Todd, 1984, Ojowski et al., 2001). Tracking data also indicates nocturnal foraging around fishing vessels (Dupuis et al., 2021), and Fulmars have been observed to feed on discards at night (Garthe and Hüppop, 1993).

4.5.4.1 Diet

The diet of Northern Fulmars in Scotland has been relatively well studied during the breeding season, and far more information is available than for other Procellariiformes in the region. The studies published to date reveal that Fulmars have a very broad diet, which can vary substantially between colonies and years (Furness and Todd, 1984, Camphuysen and van Franeker, 1996, Phillips et al., 1999b), as well as between the sexes and breeding stages (Ojowski et al., 2001, Owen et al., 2013).

Diets of Fulmars at Scottish colonies include fish, crustaceans, jellyfish, squid, pelagic zooplankton and offal (Furness and Todd, 1984, Fowler and Dye, 1987, Camphuysen and van Franeker, 1996, Bourne, 1997, Hamer et al., 1997, Phillips et al., 1999b). Several studies have suggested that sandeels (Ammodytidae) are particularly important in the diets of Fulmars breeding in Shetland (Furness and Todd, 1984, Hamer et al., 1997, Phillips et al., 1999b), and Gray et al. (2003) found that chick survival was reduced in a year of low sandeel abundance. In contrast, Ojowski et al. (2001) found that sandeels comprised only 1% of diet on Foula and Unst, where Gadidae, and Norway pout in particular, were the most common prey.

4.6 Sooty Shearwater

4.6.1 Spatial and temporal distribution

4.6.1.1 Breeding distribution

Sooty Shearwaters mainly breed on offshore islands around New Zealand and Chile, with smaller colonies recorded in southern Australia and the Falkland Islands (Brooke, 2004, Reyes-Arriagada et al., 2007, Catry et al., 2019, Clark et al., 2019, BirdLife International, 2022a). They are present at the breeding colonies between late September/early October and April (Richdale, 1963, Warham et al., 1982, Brooke, 2004).

4.6.1.2 Marine distribution in Scotland

The species undertakes one of the longest known avian migrations and tracking of non-breeding Sooty Shearwaters has uncovered a clockwise circular route in the Atlantic (Hedd et al., 2012, Bonnet-Lebrun et al., 2021). Those found around Scotland are likely to be birds that migrate from colonies around Cape Horn and the Falkland Islands (Phillips, 1963, Hedd et al., 2012, Catry et al., 2019). The species has been observed in Scottish waters between May and December, but mostly at low densities (Phillips, 1963, Camphuysen, 1995, Stone et al., 1995). Long-term data from vessel-based surveys show relatively low densities during July and August, with the highest concentrations in the Minch, and moderate densities around the Rockall Bank (Stone et al., 1995). The species is widespread but at mostly low densities over the continental shelf to the north and west of Scotland, around Shetland, the Moray Firth and the North Sea. During September to November, the highest densities are around Orkney and Caithness, with widespread low or moderate densities elsewhere and more widespread, low densities off the north-east coast and in the Firth of Forth than earlier in the year (Stone et al., 1995).

4.6.2 Population status and abundance

4.6.2.1 Breeding

Sooty Shearwaters are one of the most abundant shearwaters in the southern hemisphere, but the global population is thought to be in moderately rapid decline due to the impact of fisheries bycatch, climate change and the harvesting of chicks by indigenous communities, and the species is listed as Near Threatened (Newman et al., 2008, Newman et al., 2009b, BirdLife International, 2022a). The global population is thought to number around 4.4 million breeding pairs, with 19–23.6 million individuals in total (Newman et al., 2009b, Waugh et al., 2013, BirdLife International, 2022a).

4.6.2.2 Non-breeding

An estimated 7,500 Sooty Shearwaters are present in Scottish waters outside of their austral breeding season (Furness and Wade, 2012). Declines have been observed in other wintering locations (Veit et al., 1997, Oedekoven et al., 2001), but data for Scotland are lacking.

4.6.3 Productivity and survival

4.6.3.1 Age at first breeding

The mean age at first breeding of Sooty Shearwaters is 4.8 years (range 2–10 years; Fletcher et al., 2013).

4.6.3.2 Productivity

All the productivity data found in our literature search are from New Zealand colonies, where productivity is highly variable and non-synchronous. Mean breeding success across studied colonies ranges from 3% to 76% (Jones et al., 2003, Newman et al., 2009a). Hamilton (1998) found that at colonies with high levels of predation, chick survival was 0–41%, but where there was lower natural predation or predator management had been implemented, 64–100% of chicks survived to fledging age.

4.6.3.3 Survival

Adult survival is between 86–98% (Clucas et al., 2008). Fletcher et al. (2013) estimate the survival rate of juveniles in their first two years as 41–54% per year.

4.6.4 Foraging ecology

Sooty Shearwaters forage by surface-seizing and pursuit diving (Weimerskirch and Sagar, 1996). They are capable of diving deeper than other petrels (Dunphy et al., 2015), using a zigzag pattern to reduce buoyancy (Oka, 1994). Weimerskirch and Sagar (1996) give an average dive depth of 38.7 ± 20.1 m (range 2–67 m), but Shaffer et al. (2009) found that 90% of birds dived no deeper than 30 m.

4.6.4.1 Diet

Diet data for Sooty Shearwaters in Scotland are lacking, but elsewhere they are known to feed on fish, squid and crustaceans, mostly euphausiid krill and hyperiid amphipods (Brown et al., 1981, Jackson, 1988, Shiomi and Ogi, 1992, Kitson et al., 2000, Cruz et al., 2001, Petry et al., 2008). They will also follow fishing boats to feed on discards (Wahl and Heinemann, 1979, Otley et al., 2007).

4.7 Existing documented pressures

Pressures arising from human activities in Scottish seas are comprehensively assessed in the Feature Activity Sensitivity Tool (FeAST; Rogerson et al., 2021). Here, we summarise the most important pressures for the species considered in this review.

4.7.1 Climate change

Although the effects of climate change on seabird food availability, productivity and population trends are well-documented from some seabird species and locations (Arnott and Ruxton, 2002, Frederiksen et al., 2004, Frederiksen et al., 2006, Daunt and Mitchell, 2013) there is little evidence of such direct effects on the focal species of this review. Their large potential foraging areas and generalist diets argue for resilience to climate change impacts for these species. However, Scotland's breeding populations of Leach's and European Storm-petrels are predicted to be considerably reduced or extinct by the end of the 21st century, as a result of climate change (Russell et al., 2015), likely as a result of bottom-up effects on their food resources (Daunt and Mitchell, 2013, Mitchell et al., 2020).

Climate change may result in an increase in the incidence of heavy rainfall during incubation, which is negatively correlated with Manx Shearwater hatching success on Rum and Canna as a result of burrows being flooded (Thompson and Furness, 1991). Cold temperatures early in the breeding season may also delay egg laying, which could further affect productivity (Thompson, 1987). Although Manx Shearwaters are generally believed to be robust to changes in food availability due to their ability to travel long distances and consume varied prey (Mitchell et al., 2004), milder winters have been associated with reduced prey quality, later breeding, reduced adult attendance and lower peak and fledging weights of chicks at the Pembrokeshire colonies (Riou et al., 2011). Climate change may also result in an increase in soil erosion and the consequent loss of nesting habitat, or an increase the prevalence of diseases (see below).

Milder winters may also increase the survival of invasive predators such as rats, resulting in increased predator populations and a higher rate of predation on seabirds (Swann, 2000).

Climate change may result in an increase in the incidence and severity of extreme weather events, such as storms that cause large-scale wrecks of Leach's Storm-petrels in the north-east Atlantic (Wynne-Edwards, 1953, Boyd, 1954, Teixeira, 1987).

Ocean acidification has implications for calcium-based marine organisms (Orr et al., 2005). Storm-petrels produce one of the largest eggs, in relation for female body size, of any bird (Davis, 1957a), which exerts high demands on internal calcium stores for eggshell formation. Ocean acidification could affect the ability of these species to produce well-calcified eggshells.

4.7.2 Bycatch

Bradbury et al. (2017) assessed the risk to seabirds of surface, pelagic and benthic fisheries bycatch in UK waters based on (i) species-specific sensitivity (related to conservation status, life history, behavioural traits, bycatch literature and expert opinion) and (ii) the overlap in species distribution ("vulnerability") and relevant fishery activity in summer and winter ("exposure"). They concluded that Fulmars had extremely high sensitivity to bycatch at the sea surface (ranked second of 61 species considered, with a score of 90), Manx Shearwater ranked 8th (score = 66), Sooty Shearwater ranked 16th (score = 53), Leach's Storm-petrel ranked 39th (score = 31) and European Storm-petrel ranked 46th (score = 26). All species scored highly for their response to fishing activity, indicating their tendency to follow vessels. The storm-petrels scored lower than the shearwaters and Fulmar for surface entrapment risk (2 versus 4 and 5 for storm-petrels, shearwaters and Fulmar respectively), although instances of entrapment of both European and Leach's Storm-petrels in fishing nets have been recorded (Bradbury et al., 2017, Costa et al., 2020). All five species were assessed as having lower, and similar, sensitivities to bycatch in pelagic fisheries, due to lower entrapment risk. To date there has been a limited programme of seabird bycatch monitoring in UK waters, although instances of Fulmar bycatch in longline fisheries in Scotland have been recorded, suggesting several thousand individuals may be bycaught each year (Northridge et al., 2020). Currently there are no systematic data on rates of bycatch for other focal species in Scotland, or elsewhere in UK. Manx and Sooty Shearwater are also at risk of bycatch in fisheries operating in the southern hemisphere during their non-breeding and breeding periods, respectively (Uhlmann, 2003, Bugoni et al., 2008), but the level of risk will vary depending on the areas used by the birds (Bonnet-Lebrun et al., 2020).

4.7.3 Pollution

Levels of oil contamination of seabirds have fallen in recent decades both in UK waters (Schmitt, 2019) and elsewhere in the North Sea (e.g. Stienen et al., 2017) and chronic oil pollution is generally considered not to be an important driver of seabird population declines in Scotland (NatureScot, 2021). Procellariiformes are particularly vulnerable to plastic ingestion (Moser and Lee, 1992, O'Hanlon et al., 2017) and a programme of monitoring plastic ingestion in Fulmars in the North Sea has operated since 2002 (Van Franeker et al., 2021). Whether plastic ingestion leads to mortality and exerts population level effects on the focal species in the UK is currently unknown. In Canada, Leach's Storm-petrels have been found to contain some of the highest known levels of mercury contamination of any seabirds, but no deleterious effects have been identified (Pollet et al., 2017).

4.7.4 Invasive Non-Native predators

Invasive Non-Native (INN) species such as Brown Rats *Rattus norvegicus*, Black Rats *Rattus rattus*, various species of mustelid and feral cats *Felis catus* have been implicated in population declines and extirpation of Manx Shearwaters, Leach's and European Storm-petrels in Scotland and elsewhere in the UK. The breeding population of Manx Shearwaters on Canna declined by 99% between 1995 and 2004, with predation by Brown Rats and cats implicated as the primary cause (Swann, 2000, Patterson, 2006). Productivity on Canna averaged 0.6 in the 1980s, declining to <0.2 in the mid-1990s due to predation by Brown Rats *Rattus norvegicus* (Luxmoore et al., 2019), but increased following rat eradication in 2006, averaging 0.74 fledglings/pair between 2009 and 2017 (Luxmoore et al., 2019) and 0.90 between 2015 and 2019 (JNCC, 2021b). While breeding productivity has greatly increased, the Manx Shearwater population has not recovered and remains very small (Luxmoore et al., 2019), in contrast to the recoveries of Manx Shearwater populations following rat eradication on Ramsey (Bell et al., 2019) and Lundy (Booker and Price, 2014). Brown Rats were implicated in the decline of a Manx Shearwater colony on Eigg, where predation by native Eurasian Otters *Lutra lutra* may have also been a factor (Evans and Flower, 1967). Brown Rats are also present on Rum and, although in the 1980s it appeared that the location of the Manx Shearwater colony on a mountain 'island' surrounded by unproductive moorland offered the species some protection from rat predation (Thompson, 1987), more recently there have been concerns that the rats may be causing a problem (Mitchell et al., 2004). There is mixed evidence regarding the effect of rats on the productivity of breeding Manx Shearwaters on Rum (Thompson, 1987, Mitchell et al., 2004, Ratcliffe et al., 2009, Lambert et al., 2015) and some evidence that negative effects of Wood Mice *Apodemus sylvaticus* can substitute those of rats when rat numbers are reduced (Lambert et al., 2021).

Invasive mammalian predators are a key threat to both Leach's and European Storm-petrel populations, with the species breeding almost exclusively on rat-free islands, and rarely coexisting with other introduced mammalian predators (De León et al., 2006). The colonies of both species on Foula, where cats are present, were formerly more numerous but by the time of the Seabird 2000 census had apparently been restricted to a small number of inaccessible ledges (Mitchell et al., 2004). Despite an abundance of suitable habitat, European Storm-petrels had not been recorded on the Shiant Isles prior to the eradication of Black Rats in 2016 (Main et al., 2019), but calling birds were heard in 2017 and successful breeding was detected in 2018 (First Storm-petrel chick for Shiant Isles (rspb.org.uk)).

During the Seabird 2000 census an American Mink *Neogale vison* was found on Old Hill, Loch Roag, which threatened the survival of the small colony of Leach's Storm-petrels that existed there at the time (Mitchell et al., 2004). Preventing the colonisation of Leach's Storm-petrel breeding islands by mammalian predators is essential for their survival. The majority of Leach's Storm-petrels in the UK breed at St Kilda, where there is a high risk of invasion by mammals as the main island of Hirta is regularly visited by supply vessels and leisure boats.

4.7.5 Native predators

Native avian predators such as gulls and skuas may become problematic if populations increase or if changes in other food sources result in increased predation of seabirds (Votier et al., 2004b, Bicknell et al., 2013, Church et al., 2019).

The large decline of Leach's Storm-petrels on St Kilda has been attributed primarily to increased predation by the Great Skua population (Votier et al., 2004a, Votier et al., 2006, Miles, 2010, Deakin et al., 2021), which increased from 10 to 271 pairs between 1971 and 1997 (Phillips et al., 1999a). Great Skuas were estimated to consume approximately 14,850 Leach's Storm-petrels at St Kilda in 1996 (Phillips et al., 1999c) and 21,000 a year in 2007–2009 (Miles, 2010).

Great Skuas on St Kilda were estimated to consume 455 Manx Shearwaters in 1996 (Phillips et al., 1999c), which is roughly equivalent to 30% of the total estimated adult mortality (Mitchell et al., 2004), and 7,450 European Storm-petrels, which was more than three times the archipelago's estimated number of breeding adults in 1999/2000 (Mitchell et al., 2004).

Leach's Storm-petrel populations on North Rona and the Flannan Isles likely also face high levels of predation by Great Skuas and Great Black-backed Gulls *Larus marinus* (Mitchell et al., 2004). However, populations in the western Atlantic that are not subject to intense predation have also declined (Wilhelm et al., 2020) and the species may face additional important pressures away from the breeding colonies.

Storm-petrels are vulnerable to predation by a variety of owl species, including Little Owl *Athene noctua* (Lockley, 1947), Short-eared Owl *Asio flammeus* and Long-eared Owl *Asio Otis*

(Bried, 2003). Predation by breeding owls may contribute to storm-petrel population decline or hinder attempts to establish new colonies following INN eradication, as on Ramsey, Pembrokeshire (M. Bolton pers. obs.). Whilst no owl species breed at any Scottish storm-petrel colonies, Short-eared Owls do occur as regular migrants at colonies such as St Kilda and Mousa, but are unlikely to cause population-level impacts.

Otters will predate seabirds and have been found to impact the breeding success of storm-petrels at some colonies outside of Scotland (e.g. Quinlan, 1983), but more often their impacts at the population level are not large (Bolton et al., 2017, D'Entremont et al., 2020).

The endemic subspecies of Field Mouse on St Kilda *Apodemus sylvaticus hirtensis* is present at some Leach's Storm-petrel sub-colonies and seabirds are known to make up part of its diet, but it is unclear whether this is through predation or scavenging (Bicknell et al., 2009, Bicknell et al., 2020).

4.7.6 Breeding habitat degradation and loss

Decline of the European Storm-petrel population on Auskerry, Orkney, has been attributed to an increase in the number of sheep on the island, which led to the trampling and destruction of 65% of the rabbit burrows (Mitchell et al., 2004) that were previously the main nesting habitat for storm-petrels (Wood, 1997). Similarly, trampling and manuring by ground-nesting seabirds at a European Storm-petrel colony in Brittany, France, resulted in changes to vegetation cover, increased erosion and eventually the collapse of the old rabbit burrows that the storm-petrels nested in, leading to a population decline (Cadiou et al., 2010).

Competition for habitat with other ground-nesters can also be a problem. An increase in the Atlantic Puffin *Fratercula arctica* population on Sule Skerry apparently reduced the available habitat for European Storm-petrels by displacing them from burrows (Mitchell et al., 2004). Similarly, Manx Shearwaters breeding on Mingulay, Outer Hebrides, were apparently extirpated when their burrows were taken over by an increasing Atlantic Puffin population (Elwes and Guards, 1869).

In the western Atlantic, habitat changes at Leach's Storm-petrel breeding colonies have been associated with population declines (D'Entremont et al., 2020) and the colony on North Rona appears to be confined to the walls of man-made structures due to extensive soil erosion limiting the habitat available for burrows (Mitchell et al., 2004). High densities of Soay sheep on Hirta, St Kilda render the sward over most of the island unsuitable for breeding Leach's Storm-petrels, and most birds nest in boulder crevices. In contrast, the absence of sheep on Dùn, St Kilda allows the development of a deep tussock sward and, despite its small area, Dùn supports the majority of the UK's breeding Leach's Storm-petrels.

4.7.7 Parasites, disease and natural toxins

An outbreak of H5N1 Avian Influenza in Great Skuas in 2021, affected colonies at which Manx Shearwaters, Leach's and European Storm-petrel breed (e.g. St Kilda; Banyard et al., 2022). It is not known if Procellariiformes were also infected as none have been found dead, but they may benefit from lowered predation pressure from Great Skuas in the short term. The cause of recent wrecks of seabirds (mainly auks) in the North Sea from September 2021 to January 2022 is currently unknown, though one possibility is that they may be related to toxins associated with algal blooms, which have been detected in the blood of asymptomatic shearwaters in the Mediterranean Sea (Soliño et al., 2019). It is currently unclear to what extent petrels and shearwaters may be exposed to harmful algal toxins in Scottish waters. However, if toxic algal blooms increase in range and frequency due to climate change (Gobler, 2020), they could exert complex effects on seabirds and their predator-prey dynamics.

The disease puffinosis kills approximately 4% of Manx Shearwater fledglings on Skomer and Skokholm each year but is not considered to have population-level impacts (Brooke, 1990). While puffinosis has been linked to a coronavirus (Nuttall and Harrap, 1982), the cause is still not fully understood. A fatal case of avian malaria was recently detected for the first time in a Manx Shearwater in its wintering grounds in Brazil (Vanstreels et al., 2020).

The prevalence of parasites and disease in storm-petrels has not been well-studied at Atlantic colonies, but research on the Mediterranean subspecies of the European Storm-petrel indicates slower mass gain and reduced body condition and survival in chicks with higher parasite loads (Merino et al., 1999, Sanz-Aguilar et al., 2020).

4.7.8 Disturbance from recreation

The localised impact of disturbance by human recreational activities can be significant, with European Storm-petrels breeding within 10 m of a tourist trail on Mousa having significantly lower breeding success than those nesting in less disturbed areas (Watson et al., 2014), but due to the geographic remoteness of most colonies, and inaccessibility of the nesting areas at those colonies, most Scottish breeding colonies are not exposed to recreational disturbance. The impacts of disturbance at sea have not been studied, but Manx Shearwaters may be particularly vulnerable to disturbance by leisure craft when rafting in dense groups prior to visiting colonies.

5 Risks from collision, displacement and lighting attraction

Assessment of the risk of bird collisions at wind farms principally focuses on risks associated with a bird being struck by a rotating blade when passing through the rotor-swept area. The probability of collision, for a bird on a collision course with a turbine, depends on (i) the flight height of the bird, (ii) the likelihood of the bird altering its flight path to avoid the rotor swept area (i.e. avoidance), and (iii) if the bird passes through the rotor-swept area, whether it is struck by a rotating blade. Before considering these components in turn it should be noted that other collision risks may be associated with wind farms and their operations, such as collision with masts and aerials on the support vessels, or with moorings associated with floating wind platforms.

Whilst some components of the overall assessment of the collision risk posed by wind farms, and their population-level consequences, can be computed with estimable precision and accuracy, other components, such as the avoidance rate, or in the case of nocturnal procellariform seabirds, the attraction rate, are subject to considerably greater uncertainty, which render estimates of collision rate and population consequences highly speculative.

In this section we review the available published information to parameterise the collision risk models, and information which may assist the estimation of avoidance rates. Critical to the latter is the extent to which nocturnally active seabirds such as shearwaters and storm-petrels may be attracted to the illuminations required for turbines, support vessels and the construction or expansion of ports. We firstly consider factors other than illumination which may contribute to attraction of nocturnal Procellariiformes for offshore windfarms. In the final section, we explicitly consider the evidence for light attraction.

Flight height estimates presented below are obtained from aerial and vessel-based surveys, necessarily conducted under adequate weather and lighting conditions and usually including ship-following birds. These values may change under different weather and lighting conditions. Many sources providing assessments of the time a species spends at collision risk height do not specify the assumed turbine dimensions, and since turbine technology is rapidly evolving, collision risk levels may also change. Data on flight speeds have been obtained from tracking studies and refer to ground speeds, taking no account of non-linear flight paths and measured at the interval of the tracking device. They will therefore underestimate instantaneous flight speed to an unknown degree. Further, most tracking studies have been conducted on breeding adult birds, and parameter values may differ for immatures or juveniles or for different times of year.

5.1 Attraction of shearwaters and storm-petrels to offshore structures

A number of studies in Canada have found clear evidence that shearwaters and storm-petrels may be attracted to offshore structures such as drilling platforms, likely due to local prey enhancement as the structure acts as an artificial reef (Baird, 1990, Montevecchi, 2006, Burke et al., 2012). The foundations associated with offshore turbines may similarly act as artificial reefs, and cause changes in patterns of sediment transport and accumulation that could provide spawning grounds for benthic species. Whilst there is limited evidence for attraction of shearwaters and storm-petrels to oil and gas platform in the UK (Bourne, 1979, Sage, 1979), likely due to low densities of these species in the northern North Sea where seabird interactions with oil platforms have been studied, other authors report attraction of a variety of diurnal seabird species to oil platforms, likely as a result of local prey enhancement (Tasker et al., 1986). If fishery activity is reduced within windfarms, then local increases in fish density may result in these areas attracting seabirds, such as Manx Shearwaters, storm-petrels, and their avian predators such as large gulls and skuas. Aguado-Giménez et al. (2016) found that European Storm-petrels were attracted to fish farm cages 5 km from the coast during daylight, likely due to local prey enhancement. Procellariiform species are highly pelagic and are extremely unlikely to be attracted to offshore structures for the purposes of roosting, as is seen in species such as cormorants and shags (Dierschke et al., 2016).

5.2 Collision risk

5.2.1 Manx Shearwater

5.2.1.1 Flight style

Manx Shearwaters are classed as glide-flappers (Spear and Ainley, 1997b), using both flapping and gliding flight and engaging in slope-soaring behaviour (Thompson, 1987, Spivey et al., 2014). Gliding and soaring flight may increase with increasing wind speed (Gibb et al., 2017). Flight speed (see below), wing shape, relatively high wing loading, and tail shape (rounded, not forked) suggest that Manx Shearwaters have only moderate flight manoeuvrability (Warham, 1977, Furness and Wade, 2012).

5.2.1.2 Flight height

The species is generally considered to have low collision risk as it apparently spends limited time flying at rotor blade height (i.e. usually flies less than 20 m above sea level; Garthe and Hüppop, 2004, King et al., 2009, Cook et al., 2012, Furness and Wade, 2012, Furness et al., 2013, Bradbury et al., 2014, Certain et al., 2015). However, current flight height data for this species is based on aerial or vessel-based at-sea surveys, which can only take place during daylight and in relatively calm weather and may not be representative of the behaviour of Manx Shearwaters under all conditions. The species rarely uses level, flapping flight, but usually engages in slope-soaring, which leads to constant variation in flight height, although generally birds will remain low to the sea surface where the shear is strongest (Spivey et al., 2014). Flight heights may increase in stronger winds (Spear and Ainley, 1997b, Ainley et al., 2015) and modelling by Johnston and Cook (2016) indicated an increase in mean flight height between April and September.

Of 6,957 Manx Shearwater recorded during vessel-based surveys at 10 offshore wind farm sites, 0.04% (95% confidence interval <0.01–10.1%) were flying at heights that would put them within the rotor-swept zone (assumed to be 20–150 m above sea level), and models suggested their flight height distribution was unlikely to vary with distance to the coast (Cook et al., 2012). Models by Johnston and Cook (2016) estimated the proportion of flight time within the rotor-swept zone was 0.0 (95% confidence interval 0.0–0.0), based on boat survey data, and 0.0 (95% credible interval 0.0–0.02) based on digital aerial survey data.

5.2.1.3 Flight speed

Breeding Manx Shearwater GPS-tracked from Skomer, Wales, by Guilford et al. (2008) had a mean ground speed of 11.13 ± 9.55 m/s during flight. Behavioural models of GPS data for birds breeding on Skomer and Lighthouse Island, Northern Ireland, indicate median ground speeds of 8.9 m/s during direct or transiting flight and 2.01 m/s during foraging, when flight is more tortuous (Dean et al., 2013). Breeding Manx Shearwaters tracked from Great Blasket and High Island, Ireland in 2014 and 2015 had a mean ground speed across whole trips of 1.58 m/s (SD = ± 0.79 m/s, range 0.36–5.88 m/s), although ground speeds within trips would have shown greater variation (Wischnewski et al., 2019). Tracking from Lundy Island indicated mean ground speeds of 10.89 ± 3.31 m/s during flight, with clusters around 11 and 15 m/s in low wind speeds and greater variation in higher wind speeds, when birds were more likely to engage in soaring flight (Gibb et al., 2017).

Mean ground speeds differed between adults and immatures GPS-tracked from Skomer, with mean (± SE) speeds of 7.0 m/s ± 0.32 m/s for adults and 4.97 ± 0.25 m/s for immatures on short trips and 5.83 ± 0.17 m/s for adults and 5.14 ± 0.22 m/s for immatures on long trips (Fayet et al., 2015).

5.2.1.4 Temporal activity patterns

For breeding Manx Shearwaters tracked from Skomer and Lighthouse Island (Copeland) in July and August of 2009–2011, the percentage of time spent in different behaviours varied between breeding stages and colonies, with birds spending an average of 10% of their time in direct flight (i.e. transiting/commuting) and 63% foraging during incubation, and 15% in direct flight and 57% foraging during chick-rearing (Dean et al., 2013). Direct flight and foraging increased in the hour before sunrise, peaked just after sunrise and were lowest around midday when birds spent more time resting on the water (Dean et al., 2013). There was then a second peak in flight before sunset and a rapid decline at the onset of darkness. Foraging occurred almost entirely within daylight and twilight and birds roosted on the water in the evening and at night. Other GPS tracking studies from Skomer show similar activity patterns during incubation and chick-rearing (Guilford et al., 2008, Fayet et al., 2015). However, dietary analysis of Manx Shearwaters on Rum indicates that birds may have been foraging at night during the pre-laying period (Thompson, 1987).

5.2.1.5 Avoidance behaviour

Limited data are available on wind turbine avoidance behaviour of Manx Shearwaters given that there is little overlap between the species' distribution and currently operational wind farms, but Dierschke et al. (2016) preliminarily classified the species as weakly avoiding wind farms. Surveys of the Robin Rigg offshore wind farm in the Solway Firth detected a decline in the number of Manx Shearwaters in the area during construction and operation, compared with pre-construction (Canning et al., 2013b, Canning et al., 2013a), suggesting some macro-avoidance, but birds were observed close to turbines (Dierschke et al., 2016). An obvious gap in Manx Shearwater distribution was observed at North Hoyle wind farm in Liverpool Bay (Dierschke et al., 2016).

Flight speed, wing and tail morphology suggest that Manx Shearwaters may have limited manoeuvrability for micro-avoidance of turbine blades and associated structures. Flight agility is likely to be influenced by wind speed. Warham (1977) noted that in low winds shearwaters often come in fast and crash land at the colony but on windy evenings can stall and land lightly. In the context of collisions with turbine, shearwaters are likely to have lowered manoeuvrability under conditions when blades are turning more slowly. Adults, sub-adults and fledgling shearwaters of various species are known to collide with human-made structures on land, and this can sometimes result in high numbers of fatalities (Podolsky et al., 1998, e.g. Albores-Barajas et al., 2016), further indicating low levels of micro-avoidance.

5.2.2 European Storm-petrel

5.2.2.1 Flight style

European Storm-petrels fly with a combination of flapping and short glides, often moving in zig-zags and sometimes shearing in strong winds (Flood and Thomas, 2007). When feeding they hover or patter on the surface of the water, dipping to seize food items (Flood and Thomas, 2007). Smaller-bodied Procellariiformes have greater manoeuvrability in flight due to lower wing loading (Warham, 1977) and storm-petrels are highly manoeuvrable in snatching prey for the sea surface.

5.2.2.2 Flight height

Vessel-based observations suggest European Storm-petrels generally fly within 2 m of the sea surface, but occasionally up to 5 m (Flood and Thomas, 2007). They may fly lower in strong winds to shelter in wave troughs, as observed in the oceanitid and *Oceanodroma* storm-petrels (Ainley et al., 2015). Largely as a result of its low flight height, the European Storm-petrel is generally considered to be at low risk of collision (King et al., 2009, Cook et al., 2012, Furness and Wade, 2012, Furness et al., 2013, Bradbury et al., 2014, Certain et al., 2015), but data on flight heights for this species are limited. Observations of 52 European Storm-petrels on surveys of two offshore wind farm sites included a mean of 2% (range 0–2.5%) flying at heights that would put them at risk of collision with wind turbine blades (Cook et al., 2012).

5.2.2.3 Flight speed

European Storm-petrels tracked from Ireland had a mean trip speed of 4.05 (range 2.62–4.93) m/s and the maximum ground speed of any bird between two consecutive GPS locations was 11.18 m/s (Wilkinson, 2021). Mediterranean Storm-petrels tracked from Sardinia during incubation in 2020 had a mean speed of 4.0 ± 0.9 (range 2.1–5.2) m/s and a maximum speed of 9.8 ± 2.0 (6.7–12.5) m/s, while those tracked during chick-rearing in 2019 had a mean speed of 2.63 ± 0.9 (1.1–4.1) m/s and maximum speed of 7.38 ± 1.7 (4.5–9.8) m/s (De Pascalis et al., 2021). For Mediterranean storm-petrels tracked from Benidorm Island, the mean (± SD) speed was 4.18 ± 0.68 m/s (range 3.46–4.82 m/s) and the maximum travel speed was 10.17 ± 3.33 m/s (range 6.41–22.46 m/s) (Rotger et al., 2021). The mean speed for birds engaging in area-restricted search behaviour (i.e. foraging) was 2.03 ± 0.86 m/s (range 0.63–3.95 m/s) (Rotger et al., 2021).

5.2.2.4 Temporal activity patterns

European Storm-petrels depart from and return to the colony at night and while on foraging trips will forage both diurnally and nocturnally (D'Elbee and Hemery, 1997, Bolton, 2021). A two-state hidden Markov model for European Storm-petrels tracked from west Ireland assigned 60.6% of locations from High Island birds as foraging behaviour and 39.4% as transiting, while for Illauntannig foraging and transiting were assigned to 59.2% and 40.8% of locations, respectively (Wilkinson, 2021). Note that resting behaviour was not considered by Wilkinson (2021), but Mediterranean storm-petrels tracked from Benidorm Island spent a mean (± SD) of 35.23% ± 9.77 (range 19.00–54.00%) of the time resting on the water (Rotger et al., 2021).

5.2.2.5 Avoidance behaviour

We found no information in the literature regarding the extent of macro-, meso- or micro-scale avoidance by European Storm-petrels.

5.2.3 Leach’s Storm-petrel

5.2.3.1 Flight style

Leach’s Storm-petrel is classed as a glide-flapper, using a combination of flapping and long, shearing glides and hovering or pattering on the surface of the water to seize food items (Spear and Ainley, 1997b, Flood and Thomas, 2007). It has a very low wing loading (Warham, 1977) and its flight path can be irregular and unpredictable, with rapid changes of speed and direction, and becoming highly erratic in strong winds (Spear and Ainley, 1997b, Flood and Thomas, 2007).

5.2.3.2 Flight height

Vessel-based observations suggest that Leach's Storm-petrels generally stay within 5 m of the sea surface (Flood and Thomas, 2007) and they may fly lower during strong winds to shelter in wave troughs (Ainley et al., 2015). The species is usually assumed to have a low risk of collision, but data are limited and information for the European Storm-petrel is often used as a proxy (King et al., 2009, Langston, 2010, Furness and Wade, 2012, Furness et al., 2013, Bradbury et al., 2014).

5.2.3.3 Flight speed

Our literature search did not identify any estimates of flight speed for Leach's Storm-petrel, but Pollet et al. (2019) suggest it is relatively slow, similar to the 4 m/s given by Withers (1979) for Wilson's Storm-petrel.

5.2.3.4 Temporal activity patterns

Leach's Storm-petrels depart from and return to the colony at night (Ainslie and Atkinson, 1937) and are believed to forage both diurnally and nocturnally (Pitman and Ballance, 1990, Hedd and Montevecchi, 2006). More detailed information on their at-sea activity is lacking.

5.2.3.5 Avoidance behaviour

We found no information in the literature regarding the extent of macro-, meso- or micro-scale avoidance by Leach's Storm-petrels

5.2.4 Northern Fulmar

5.2.4.1 Flight style

The Norther Fulmar is a flap-glider, uses gliding flight extensively during foraging (Pennycuick, 1987) and increases gliding behaviour with higher wind speeds (Ainley et al., 2015). It has intermediate flight manoeuvrability (Warham, 1977, Garthe and Hüppop, 2004).

5.2.4.2 Flight height

Fulmars are generally considered to be at low risk of collision as they apparently spend limited time at collision risk height (Garthe and Hüppop, 2004, Cook et al., 2012, Fijn et al., 2012, Krijgsveld, 2014, Leopold and al., 2014, Harwood et al., 2018). Modelling based on 29,168 vessel-based observations estimates that the proportion of Fulmars flying at collision risk height (where the lower limit of the rotor-swept area is 20 m above sea level) is 0.002 (95% CI 0.000–0.061; Johnston et al., 2014). However, the species may fly higher in stronger winds (Spear and Ainley, 1997b, Ainley et al., 2015) and this behaviour is unlikely to be captured in vessel-based surveys, which are conducted only in relatively calm conditions.

5.2.4.3 Flight speed

The mean air speed of Fulmars measured off Foula, Shetland, using an ornithodolite was 13.0 m/s (Pennycuick, 1987). A male Fulmar GPS-tracked from Eynhallow, Orkney, during incubation, had an overall ground speed of 7.9 m/s and a maximum hourly ground speed of 17.6 m/s during its outward journey to the Mid-Atlantic Ridge, and an overall ground speed of 7.7 m/s and maximum hourly ground speed of 13.5 m/s on its return journey, although the return leg was largely against a headwind (Edwards et al., 2013). Hourly transit ground speeds were faster during the day (median = 9.4, range = 0.9–17.6 m/s) than at night (median = 4.6, range = 0.2–9.5 m/s), but hourly ground speeds during area restricted search (median = 1.2, range = 0.1–6.9 m/s) did not differ between day and night (Edwards et al., 2013). However, ground speeds from tracking data tend to be underestimates, and Weimerskirch et al. (2001) suggest the species regularly attains ground speeds of 19.4 m/s, aided by wind. Elliott and Gaston (2005) found that ground speeds of Fulmars in Nunavut, Canada, were lower during incubation (9.2 m/s) than chick-rearing (10.8 m/s) and, in contrast to Edwards et al. (2013), found that ground speeds were significantly lower for outgoing birds (8.8 m/s) than incoming birds (10.2 m/s).

5.2.4.4 Temporal activity patterns

The diurnal pattern of colony attendance by breeding Fulmars is very variable, suggesting different levels of nocturnal foraging at different breeding sites (Dott, 1975, Furness and Todd, 1984, Ojowski et al., 2001, Danielsen, 2011). Analysis of tracking data also suggests a combination of diurnal and nocturnal foraging (Edwards et al., 2013). Observations at sea near Shetland in the breeding seasons of 1992-94 found that Fulmars spent 81% of time resting or swimming and only 19% of time flying (Ojowski et al., 2001), but tracking by Edwards et al. (2013) suggested that foraging bouts involve short searching flights and only brief periods on the water, when prey is captured and consumed. Given the wide range of prey and varied foraging ecology of the Fulmar, it is likely that the time it spends in different behaviours is also highly variable.

5.2.4.5 Avoidance behaviour

Dierschke et al. (2016) classified Fulmars as weakly avoiding offshore wind farms, based on post-construction studies at 20 sites, but the authors note that data for this species are limited and it may actually display strong avoidance behaviour. It is possible that the lack of fishing vessels within wind farm areas makes them unattractive to Fulmars (Neumann et al., 2013, Braasch et al., 2015), but there is conflicting evidence regarding the influence of fishing vessels on Fulmar distributions (see section 4.5.4).

5.2.5 Sooty Shearwater

5.2.5.1 Flight style

Like Manx Shearwaters, Sooty Shearwaters are glide-flappers (Spear and Ainley, 1997b) with intermediate flight manoeuvrability (Warham, 1977, Garthe and Hüppop, 2004).

5.2.5.2 Flight height

Sooty Shearwaters are considered to have low collision risk as they generally fly very close to the sea surface and therefore below blade height (usually assumed to be 20–150 m above sea level), but this is based on very small sample sizes (Paton et al., 2010, Cook et al., 2012) and an assumption that Sooty and Manx Shearwaters fly at similar heights (Furness and Wade, 2012). Like Manx Shearwaters, Sooty Shearwaters may fly higher in stronger winds (Spear and Ainley, 1997b, Ainley et al., 2015).

5.2.5.3 Flight speed

Our literature search did not identify any estimates of flight speed specifically for Sooty Shearwater, but Spear and Ainley (1997b) estimated average ground speeds for diving shearwaters, a group which includes Sooty Shearwater, as 10.7 ± 2.3 m/s with a headwind, 14.0 ± 3.5 m/s with a tailwind, and 13.2 ± 4.6 m/s with a crosswind. Flying with a cross wind is by far the most common method used by Procellariiformes, including Sooty Shearwater (Spear and Ainley, 1997a).

5.2.5.4 Temporal activity patterns

While in the northern hemisphere, Sooty Shearwaters spend a large proportion of their time on the water and just 23.9 ± 15.2% of their time in flight, although this increases to 67 ± 24.1% once they begin their return migration to their breeding ground (Hedd et al., 2012, Bonnet-Lebrun et al., 2021). When on the water, they are resting, feeding, digesting (Bonnet-Lebrun et al., 2021) or moulting (Keijl, 2011). In July 2007, Keijl (2011) photographed 76 individuals in a flock gathered off Rockall, to the west of the Scottish mainland, 46% of which were in active primary moult. On their wintering grounds Sooty Shearwaters are particularly stationary at night, when they are on the water for 89% of the time (Hedd et al., 2012), although they are more active on nights with increased moonlight (Bonnet-Lebrun et al., 2021).

5.2.5.5 Avoidance behaviour

We found no information in the literature regarding the extent of macro-, meso- or micro-scale avoidance by Sooty Shearwaters.

5.3 Displacement and barrier effects

There is a lack of empirical evidence relating to displacement, disturbance and barrier effects for these procellariiform seabirds, and therefore high levels of uncertainty regarding their vulnerability (Wade et al., 2016, Kelsey et al., 2018). These species are all generally considered to have a low vulnerability to displacement and disturbance from offshore wind farms and associated activities such as ship and helicopter traffic, and often rank lower than all other Scottish seabird species in terms of population impacts (Furness and Wade, 2012, Furness et al., 2013, Bradbury et al., 2014, MMO, 2018, Rogerson et al., 2021). They will associate with vessels at sea and display limited escape behaviour and short flight distances when approached by boats (Furness et al., 2013). However, there is some evidence of Manx Shearwaters and Fulmars avoiding offshore wind farm developments during the construction and operational phases (see sections 5.2.1.5 & 5.2.4.5; Dierschke et al., 2016), and the deficiency of data for the other species does not indicate a lack of impact. A higher level of disturbance may occur during the construction phase, when activity, noise and light levels may be greatest. The impacts of artificial light on nocturnally active species may also result in increased levels of displacement (see section 5.4).

Habitat specialisation is a key consideration when assessing vulnerability to displacement, with the negative impacts likely to be greater for specialists than generalists. Manx Shearwaters, European Storm-petrels and Leach’s Storm-petrels cover large distances when foraging during the breeding season and appear to forage on a broad range of taxa (see section 4), which could suggest a lack of specialisation. However, all three species apparently travel long distances to target specific oceanographic features (see section 4; Scott et al., 2013, Dean et al., 2015, Hedd et al., 2018, Wilkinson, 2021), and displacement from these important foraging areas would likely have negative consequences. Displacement of Manx Shearwaters from key rafting sites may also result in population-level impacts, if displacement requires them to spend energy on flight, and thereby consume resources that would otherwise have been devoted to their chick on arrival at the colony.

Older chicks can be left unattended and unfed for several days at a time due to their accumulation of large lipid reserves (Ricklefs and Schew, 1994, Bolton, 1995b, Hamer et al., 1998), which could help to buffer them against a reduction in provisioning frequency due to increases in parental foraging trip durations caused by barrier effects. However, during the first week after hatching, chicks are unable to thermoregulate adequately and need to be brooded by adults. In this period they are particularly vulnerable to starvation and inclement weather as adults must divide their time between nest attendance to brood the chick and foraging at sea. Most breeding failures occur at this stage, as the energetic demands on adults, in relation to time available for foraging, are greatest (Bolton, 1995a). Increased energy demands on adults, for example due to displacement from profitable feeding areas, or increased flight paths due to barrier effects, would likely lower chick survival rates.

Several studies have shown that the flight paths of petrels and shearwaters are orientated to maximise the energetic benefits of crosswinds (Spear and Ainley, 1997b), often resulting in circular (rather than direct “out and back”) patterns to foraging trips (Ventura et al., 2020). Displacement and barrier effects may prevent the optimisation of foraging tracks to maximise the energetic benefits of cross winds. During the pre-laying exodus, female Manx Shearwaters undertake long foraging trips to oceanic waters (Dean, 2012) to acquire the nutrients required for egg formation. The single large egg represents a considerable resource investment, and the inward flight to the colony for egg laying is likely to be energetically expensive, at a critical time in the breeding cycle. Increased flight costs imposed by barrier or displacement effects during this period may have particularly high costs on breeding success. The foraging behaviour of female storm-petrels during the pre-laying period is unknown, but since they lay one of the largest eggs in relation to body size of any bird (approximately 30% of female body weight; Davis, 1957a), increased foraging costs imposed by displacement or barrier effects are likely to be particularly severe.

5.4 Lighting attraction and disorientation

The nocturnal attraction of birds to light, often with fatal consequences, has been known for several centuries. Early settlers of the Azores archipelago lit bonfires on the cliffs at night to attract seabirds, which they beat from the air with sticks, to be used as feed for their pigs (Fructuoso, 1561). Studies in the USA estimated that in the mid-1960s more than one million nocturnal migrant birds died annually by collision with illuminated communications towers (Gauthreaux and Belser, 2006) and observers in both the UK and Canada have reported that hundreds, or even thousands, of seabirds, predominantly species of storm-petrel, are killed by attraction to the gas flares of hydrocarbon platforms (Sage, 1979, Wiese et al., 2001, Baillie et al., 2005, Montevecchi, 2006, Burke et al., 2012), although Bourne (1979) disputed the identification of birds killed at platforms in the North Sea. Tasker et al. (1986) did not report shearwaters and storm-petrels attracted to platforms in the central North Sea, but observations were from a region and season associated with low densities of these species (Waggitt et al., 2020). Attraction distances and the possible influence of light position relative to flight paths are considered further in following sections.

There have been several reviews of the attraction of seabirds to artificial light (Montevecchi, 2006, Laguna et al., 2014, Rodríguez et al., 2017) and we do not repeat that information here.

Rather, we review the literature in the specific context of the issues surrounding the assessment of the impacts on seabirds of wind farm development and operation. Wind farms are required to be illuminated in accordance with marine navigation regulations (DECC, 2011, IALA, 2013, MCA, 2021) and the Air Navigation Order (CAA, 2016). In addition, a large programme of port expansion is underway in Scotland to support the construction and maintenance of new offshore wind farms, and this will result in increased illumination in coastal areas. The central issue is the extent to which illumination of wind farm structures, associated infrastructure (such as wet storage), construction activities and the vessels and ports associated with wind farm operations will: (i) attract seabirds, and (ii) modify seabird behaviour in their proximity.

The literature on light attraction in birds does not always make a clear distinction between: (i) attraction *per se* (i.e. "phototaxis"), which could potentially operate over ranges of tens of km, and (ii) the alteration of flight paths of birds when in close proximity (i.e. within tens of metres) of illuminated structures (i.e. "disorientation"). Long-range light attraction may result in birds being displaced from foraging areas and activities. Light-induced disorientation may cause birds to circle light sources for many hours (Gauthreaux and Belser, 2006) with obvious implications for collision risk. Existing models of collision risk assessment (Band et al., 2007, Band, 2012, Masden, 2015, McGregor et al., 2018) do not explicitly model the scenario of birds circling a turbine, but rather consider a straight flight path only. In the context of the assessment of impacts of wind turbines on seabirds, it is helpful to make a clear distinction between these two effects (attraction and disorientation), and the spatial scales at which they operate. The first will affect the number of birds brought into the vicinity of wind turbines and associated structures, vessels and shore facilities ("macro" and "meso" scales sensu Cook et al., 2018), and the second will affect the length of time birds remain within the proximity of potential collision surfaces and the number of occasions an individual bird may pass through the rotor-swept area ("micro" scale sensu Cook et al., 2018). These two effects of artificial light may have different drivers, and impact juveniles and adults differently, as discussed below. We do not consider light attraction to be a separate impact pathway, but it may exacerbate one or more of the recognised impact pathways (e.g. collision, displacement).

5.4.1 Evidence for light-induced disorientation

There is abundant evidence of light-induced disorientation for a wide range of avian groups, including shearwaters and petrels. Such evidence includes: the grounding of fledgling Manx Shearwaters, Leach's and European Storm-petrels in lit areas of the village on Hirta, St Kilda (Miles et al., 2010); collision of Manx Shearwaters with lighthouses and other illuminated structures (Archer et al., 2015, Guilford et al., 2019); grounding of European Storm-petrels onto rocks lit by researchers' head torches (Albores-Barajas et al., 2011); grounding of European and Leach's Storm-petrels on hydrocarbon platforms (Sage, 1979, Wiese et al., 2001, Baillie et al., 2005, Montevecchi, 2006, Burke et al., 2012, Gjerdrum et al., 2021), and the grounding of Leach's Storm-petrels on vessels (Wynn, 2005, Wakefield, 2018, Wilhelm et al., 2021) and industrial developments (Wilhelm et al., 2021).

While the distance from which birds have been attracted to such light sources is usually unknown, observers report that, once attracted to the vicinity (i.e. within several tens of metres) of a powerful light source, birds seem unable to escape and become vulnerable to collision. Rodríguez et al. (2022) showed formally that flight tortuosity of fledgling Cory's Shearwaters *Calonectris borealis* heading from inland breeding sites to the sea increases with the level of light radiance over which they are flying. Tracks of tagged individuals reveal that they remain in flight within the lit areas for several hours before grounding.

Many studies describe procellariform seabirds being drawn downwards towards bright light shining from below (e.g. Rodríguez et al., 2015a, Rodríguez et al., 2017, Rodríguez et al., 2022). In such cases the birds' natural flight height is lowered by light attraction/disorientation. It is not clear to what extent light attraction/disorientation may result in birds that are flying close to the sea (below rotor swept height), being drawn upwards to heights within the rotor swept area, although this is likely to be the case for storm-petrels stranded on oil platforms. The impact of light attraction on flight height must be considered.

Seabird species that rear their young underground seem particularly, if not exclusively, sensitive to light-induced attraction/disorientation. In the case of fledglings this is perhaps because young fledge with somewhat under-developed visual acuity due to a lack of visual stimulation in the darkness of the nest chamber (Atchoi et al., 2020). It is notable that measurements from eyes of two Manx Shearwaters captured on the point of fledging indicated that their optical structure was slightly myopic (i.e. would not produce a focussed image on the retina; Martin and Brooke, 1991). Hence, the young of burrow-nesting shearwaters, storm-petrels, and puffins appear particularly vulnerable to grounding in well-lit areas on their fledging flights from the colony (Atchoi et al., 2020), whereas the young of closely related surface-nesting species, such as Fulmars, are not vulnerable to light-induced grounding. While numerous studies have shown that light-induced grounding is much more prevalent among recently-fledged juveniles, the timing of some grounding events of Leach's Storm-petrels on offshore oil platforms (in April–August before any young of the year have fledged; Gjerdrum et al., 2021), and the stranding of likely breeding Leach's Storm-petrels on a docked seismic vessel (Wilhelm et al., 2021), show that adults may be light-attracted on occasion too. Collins et al. (2022) found no impact of oil platforms on the behaviour of breeding Leach's Storm-petrels GPS-tracked in Newfoundland, but only 1.1% of trips involved exposure to oil platforms at night and around 30% of tracked birds were not recaptured, so their fate is unknown. While juveniles are clearly more susceptible than adults to light-induced grounding, it is not clear for how long post-fledging such susceptibility persists, and whether birds grounded weeks or months after fledging were forced to land by severe weather (e.g. Teixeira, 1987) rather than light attraction.

Petrels and shearwaters are more likely to be disorientated by artificial light under conditions of low ambient light (i.e. a new moon), and during conditions of fog, mist or light rain. Guilford et al. (2019) showed experimentally that, during foggy conditions but not clear nights, light emanating from windows resulted in disorientation of adult Manx Shearwaters, causing them to collide with the building. They suggested that when the birds were suddenly close to a relatively bright light, the light-scatter caused by fog compromised the birds' dark-adapted visual guidance. Alternatively, they suggested that Manx Shearwaters may use a light-dependent magneto-receptor, located in the eyes, for navigation (Hore and Mouritsen, 2016), which could become temporarily disrupted by saturation in the presence of bright light. However, several experimental studies have failed to find evidence for the existence of such a magnetic compass in either adult (Padget, 2017) or fledgling (Syposz, 2020) shearwaters, and the sensory basis of navigation in Procellariiformes remains unclear.

Experimental reduction in artificial lighting (outside lights turned off and the majority of windows shielded with blinds) in the village of Hirta, St Kilda resulted in fewer grounded fledgling Leach's Storm-petrels, but the number of grounded Manx Shearwaters remained high (Miles et al., 2010). The authors concluded that Manx Shearwaters may be more vulnerable than storm-petrels to disorientation, or that they also navigate towards low-frequency sounds, since many grounded individuals were located close to generators or extractor fans, one being found impaled in the outlet duct of an extractor. Potential attraction of shearwaters to low-frequency noise, and implications for attraction to wind turbines and associated structures and vessels, requires further consideration.

5.4.2 Evidence for light attraction

While there is clear evidence for the disorientation of burrow-nesting Procellariiformes by artificial light sources, the extent of long-range attraction is more difficult to quantify. There are reports of European Storm-petrels being attracted to garden fireworks and moth traps (Miles et al., 2010), which they are unlikely to have been overflying, and suggests they were attracted by the artificial illumination. The number of individuals recovered in campaigns to rescue grounded fledglings are typically very low in relation to the local population size (e.g. Miles et al., 2010, but see Le Corre et al., 2002, Rodríguez et al., 2015b, Rodríguez et al., 2022), suggesting that birds are not attracted over large distances, or if so, only a small proportion of individuals are affected, or recovered. For example, the number of fledgling Manx Shearwaters recovered in the town of Mallaig, Scotland (Syposz et al., 2018), broadly corresponds, given the size and distance of the colony that is the likely source of the majority of individuals (Rum, 27 km away), with the number predicted if birds disperse randomly in all directions and the small proportion that orientate towards Mallaig are then attracted from very short range.

Two cases where large numbers of fledglings, representing large proportions (up to 40%) of the local population, are encountered grounded in brightly illuminated urban areas are Barau's Petrels *Pterodroma baraui* on Reunion Island, Indian Ocean (Le Corre et al., 2002) and Cory's Shearwaters on Tenerife (Rodríguez et al., 2015b, Rodríguez et al., 2022). The grounding of large proportions of the cohort of fledglings may imply that birds are attracted from large distances. In both cases, nesting sites are mainly located in high altitude areas in the island interior, and fledglings fly over brightly lit coastal areas (some more than 10km distant from the nearest colonies) to reach the sea. When flying over these areas birds become vulnerable to disorientation from powerful light sources below them. The sensitivity of birds to disorientation when overflying powerful light sources projected upwards is evidenced from the disorientation of very large numbers of nocturnal migrants by ceilometers (bright lights shone vertically to measure the height of the cloud base; Rich and Longcore, 2006), and the effectiveness of spotlights directed upwards to ground and capture storm-petrels returning to the colony at night (Ishmar et al., 2015). Whilst the minimum distance between colony locations and some grounding sites is more than 10km in these studies, the distance from which birds are attracted by light may be considerably less. Since birds may overfly these coastal areas on route to the sea, the high disorientation sensitivity of procellariiform seabirds to light sources from below could potentially account for the high rate of grounding in the case of Reunion Island and Tenerife, without birds being attracted from large range.

Several recent, and highly innovative, studies have started to assess the behaviour of fledgling Procellariifomes in response to artificial light. The first (Troy et al., 2013) modelled the numbers of Newell's Shearwaters *Puffinus newelli* recovered in different sectors of Kauai Island, Hawaii, in relation to location and size of colonies, light radiance levels across the island, and models of fledgling movement. They concluded that the observed spatial pattern of groundings indicated that fledglings were attracted back to the island by coastal illumination after they had reached the sea, and from distances of up to 10 km from the coastline. These modelled estimates of attraction range receive empirical support from two studies (Rodríguez et al., 2015b, Rodríguez et al., 2022) that tracked fledgling Cory's Shearwaters as they overflew brightly lit coastal areas in Tenerife on their flights to the sea. Both studies were conducted over multiple years, and each found that c. 14% of fledglings were later recovered grounded. Although neither study attempted to estimate the distance from which fledglings may become attracted towards artificial light, inspection of the tracks suggests that abrupt course deviations towards lit areas could occur from a range of several kilometres. All birds recovered by Rodríguez et al. (2015b) were grounded within 16 km of their breeding colonies, and 50% were found within 3 km of their nest site. Once above brightly lit areas many birds showed highly tortuous flight paths, circling to remain within the lit areas, before descending to ground level, as illustrated here. On multiple occasions birds that had reached the sea, and were up to 2.5 km from land, returned to brightly lit areas on the coast.

On St Kilda, considerable numbers of Leach's and European Storm-petrels breed within 2 km and in direct line of sight of the village illuminations, but the number of grounded fledglings is very small in relation to the size of the breeding populations, representing <<1% of the number of young likely to fledge annually (Miles et al., 2010). If the number of fledglings encountered grounded is an accurate reflection of the numbers attracted and disorientated, these findings suggest that fledglings are not susceptible to attraction to these light sources from long range, although the level of illumination in the village was relatively low (32 outside lights and 11 buildings with indoor lighting; Miles et al., 2010). In contrast, the vast majority of Manx Shearwaters breeding on St Kilda do not fledge in sight of the village and would not pass within sight on a direct route to the sea, raising the likelihood that they are attracted to illumination after having reached the sea, and may be attracted from a considerable range (>2 km) to illuminated areas. Similar differences in the numbers of storm-petrels and shearwaters encountered grounded in Hawaii and the Canary Islands have led other authors to suggest that the larger species of Procellariiformes may be more vulnerable to light attraction (Telfer et al., 1987, Rodríguez and Rodríguez, 2009). Any such conclusions may be premature however, since the smaller size and largely dark plumage of storm-petrels may result in lower detection rates during searches for grounded birds and storm-petrels may be able to take flight after grounding in enclosed situations more readily than shearwaters, which require an open space in which to take a “run up” to become airborne. Due to their smaller size, storm-petrels are also more likely to be depredated (e.g. by cats and dogs) and removed (Wilhelm et al., 2021). The susceptibility of storm-petrels to light-attraction and disorientation may be higher than implied by the numbers of individuals encountered grounded.

5.4.3 Attraction to vessels

In addition to attraction to or disorientation by lights at ports and on turbines, the potential for interaction of Procellariiformes with wind farm service vessels should also be considered. There are many anecdotal accounts of nocturnal seabirds, especially storm-petrel species, alighting on ships at night. For example, Wakefield (2018) reports that on several occasions during a research cruise by RRS Discovery to the mid-Atlantic, Leach’s Storm-petrels were found on the ship’s decks at night and caught by hand. These groundings usually occurred in misty conditions and were likely caused by birds being attracted to or disorientated by the deck’s flood lights. Of 1,823 seabirds (all burrow-nesting Procellariiformes) recorded on board rock lobster fishing vessels around the Tristan da Cunha archipelago and Gough Island between 2013 and 2021, 4% died after being attracted to/disorientated by artificial lights (Ryan et al., 2021). As discussed above, it is not clear to what extent the grounding of storm-petrels on vessels results from macro- or meso-scale light attraction, or whether they are attracted to vessels by other cues (such as olfaction, low frequency sounds, or visual cues associated with a food source). Storm-petrels are known to follow a wide range of vessels, probably in search of food brought to the surface by the wake or vessel lighting or, in the case of fishing vessels, for offal. They can also be attracted to stationary vessels if any oily waste is released. In calm conditions European Storm-petrels may be attracted from distances of >1 km (M. Bolton pers. obs.) and may aggregate in large numbers. In the context of use of vessels for service operations for wind turbines, nocturnally active Procellariiformes (especially storm-petrels) are sensitive to attraction (by phototaxis, olfaction, or visual cues associated with food sources), and may subsequently become disorientated, either by lighting associated with the vessel, or navigation lights on nearby turbines.

5.4.4 Implications of the capabilities and sensitivities of the visual system of petrels and shearwaters for light disorientation/attraction

Petrels and shearwaters have been a particular focus for studies of avian vision for many decades (Lockie, 1952, Hayes and Brooke, 1990, Martin and Brooke, 1991) due to the species’ need for visual capabilities to fly and forage under a wide range of light intensities, and in air and water, where the refractive properties of light differ. As a result, a considerable amount of detailed information exists on the microscopic and optical structure, and the visual fields, of the eyes of Manx Shearwaters, Fulmars and storm-petrels (Mitkus et al., 2016), which can inform our understanding of their behaviour in the vicinity of lit structures at sea (Atchoi et al., 2020). In brief, the retinas of Manx Shearwater, Fulmar and Leach’s Storm-petrel all possess a central region (variously termed “*Area centralis*” (Lockie, 1952), “horizontal strip” (Hayes and Brooke, 1990), “visual streak” (Mitkus et al., 2016)), which receives light input from the horizon when the bird’s head is normally orientated. The central part of this region is equipped entirely with cones—photoreceptors that operate under high light intensities (i.e. daylight) that are capable of colour vision and are responsible for high spatial acuity. This horizontal central structure is found in a range of seabirds and other species inhabiting open landscapes and provides high acuity to detect objects at, or close to, the horizon in well-lit environments. The outer margin of the central horizontal strip is equipped with rods—photoreceptors that operate under low light conditions—which have low spatial acuity. The density of rods increases from the central strip to the periphery of the retina (Lockie, 1952). The density of rods in the peripheral retina (which receives light from above and below the horizon when the head is normally orientated) is two-fold greater in the Manx Shearwater than Fulmar, and four times greater than the House Sparrow *Passer domesticus*, which is not active at night.

Martin and Brooke (1991) measured the visual field of the eyes of the Manx Shearwater and found that the eyes are directed slightly forwards and downwards when the head is normally orientated, with a blind spot above and behind the crown. In normal flight the eyes will therefore receive greater light input from in front and below the bird than from above and behind. During daylight, when the pupil is contracted to restrict the amount of light entering the eye, light falls on the centre of the retina, and objects on or close to the horizon are rendered with high spatial acuity, while objects further from the horizon are rendered with lower acuity. In low light levels at night the pupil opens to allow more light to enter and this is detected by the high density of rods located towards the periphery of the retina. Thus, the optic system of shearwaters and petrels provides high acuity for objects close to the horizon during daylight, and high sensitivity (though low acuity) to low light levels at night. Disorientation of shearwater fledglings when overflying brightly lit areas may result from saturation of the visual pigments of the rods (Verheijen, 1985), which cannot be adequately rectified by contraction of the pupil to limit entry of light to the eye. Birds are in effect blinded and can no longer see visual details that they could detect when dark-adapted. Alternatively, bright light may cause contraction of the pupil, so little light falls on the peripheral rods, and the birds are unable to discern poorly lit objects beyond the brightly lit areas, and so circle to remain within the illuminated field.

5.4.5 Influence of light wavelength on visual perception of shearwaters and storm-petrels

Manx Shearwaters are known to forage at depths of up 55 m (Shoji et al., 2016). Since light of shorter wavelengths (blue) penetrates water to greater depths than that of longer wavelengths (red), to maximise acuity when foraging at depth it is likely that the cones of Manx Shearwaters have greater sensitivity to blue than red light. Since storm-petrels dive to a very limited degree (max 5 m; Albores-Barajas et al., 2011), they have less need for enhanced sensitivity to blue light.

Experiments to examine the response of adult Manx Shearwaters in flight over the colony to different intensities and wavelengths of light showed that birds were more responsive to (avoided) bright white than dim white light and showed greater avoidance of blue and green light than red light (Syposz et al., 2021a). There was no difference in the birds’ behaviour when exposed to red light compared to no light. These results indicate that Manx Shearwaters have greater sensitivity to light of shorter wavelengths (blue and green) than long (red).

These findings appear to contrast with a number of largely observational (not experimental) studies that have examined the effect of light wavelength and pattern of illumination (constant vs flashing) on the collision rate of nocturnal migrants (principally passerines) with communication masts and onshore wind turbines in North America. These studies have compared the flight paths and/or number of birds found dead under structures with different types of illumination and may suffer from uncontrolled bias. However, they broadly indicate that flashing red lights causes less attraction and collisions than steady constant red light (Gehring et al., 2009, Kerlinger et al., 2010), and whilst constant red light caused greater attraction than flashing white light (Gauthreaux and Belser, 2006), Gehring et al. (2009) found no difference in the number of collisions at masts with flashing red or flashing white light. It has been suggested that red light may interfere with magnetoreception in migrating passerine birds: three passerine species showed normal orientation under dim monochromatic light from the blue-green range of the spectrum, while they were disoriented under yellow and red light (Wiltschko and Wiltschko, 2002). Gauthreaux and Belser (2006) recommend the use of flashing white lights in place of steady red lights to reduce the risk of collision of nocturnal (mainly passerine) migrants with communication masts in USA.

Several studies have failed to find evidence of magneto-reception in shearwaters (Padget, 2017, Syposz et al., 2021b) and it is possible that differences in the sensory systems used for navigation in nocturnal Procellariiformes and passerines may result in important differences in their sensitivities to attraction/disorientation by light of particular wavelengths. Several hundred million migrant birds cross the North Sea annually, at risk of collision with wind turbines (Hüppop et al., 2006), and the benefits of a particular lighting regime to reduce collisions of nocturnal Procellariiformes, such as the use of red navigation lights, must be weighed against likely impacts on other species.

5.4.6 Non-collision consequences of light attraction of seabirds that may affect their survival and productivity

If light-induced disorientation leads to individual birds circling the navigation lights on the nacelle or tower of turbines for protracted periods (as has been reported for birds disorientated by lighthouses or gas flares) the probability of collision with turbine blades or other surfaces is vastly increased, and may approach unity. However, individuals that are attracted to and disorientated by light associated with wind farms may become vulnerable to other lethal and sub-lethal impacts. If wind farms provide roosting opportunities for large gulls, or other predatory species (skuas, falcons), storm-petrels and Manx Shearwaters are likely to be vulnerable to predation (Hey at al. 2020), particularly if wind farm illuminations provide sufficient ambient light for effective hunting by these predators (Watanuki, 1986). Sub-lethal affects that may influence survival in the longer term, or the ability to rear young, could accrue from the wasteful expenditure of energy in circling flight for protracted periods. This may lead to loss of body condition resulting in birds becoming more vulnerable to starvation or predation. Flight costs of European Storm-petrels have been estimated at 3.9 times basal metabolic rate (Bolton, 1995a), close to the maximum sustainable work rate (Drent and Daan, 1980). Prolonged periods of flight, without opportunity to feed or rest, may lead to dehydration or exhaustion of birds that escape collision. Conversely, many fisheries use artificial light to attract prey and there is a possibility that birds could benefit from increased foraging opportunities if artificial lighting around wind farm developments increases prey availability by attracting it close to the sea surface. The evidence base around

Procellariiformes exploiting prey resources concentrated near the surface by artificial light is limited, but European Storm-petrels have been observed foraging around illuminated fish farms at night in the Faroe Islands (B. Porter, pers. comm.).

5.5 Options for mitigation

The second of the two expert workshops held as part of this project focussed on mitigation options to reduce the impacts on Procellariiformes of offshore wind farm developments and associated activities and infrastructure. Table 4 summarises the mitigation options discussed at the workshop and in the published literature. Full reports of both workshops are provided in Appendix 1. NatureScot (2020) have suggested several potential mitigation options for reducing the impacts on birds of lights placed on wind farms for the purposes of aviation safety. These mitigation options do not relate specifically to offshore wind farms or Procellariiformes but we include them in Table 4.

Table 4. Suggested mitigation options for reducing the impacts on Procellariiformes of offshore wind farm developments and associated activities and infrastructure, collated from the published literature and discussions during the two expert workshops held as part of this project.

Option	**Evidence base**	**Comments**	**Technical/legislative feasibility**
Alter pattern of illumination (flashing rather than steady lights)	Good evidence from numerous studies in USA that flashing lights cause less attraction/collision of migrant nocturnal passerines.	Not systematically tested for Procellariiformes. Bardsey lighthouse changed to a red flashing light in 2014 and this resulted in a huge reduction in collisions of Manx Shearwaters.	Need consistency in lighting across wind farms to avoid confusion to mariners and to comply with international standards, which precludes modification. Even apparently simple changes in lighting require intervention at early stage of turbine design/construction
Alter wavelength of lights	Studies conducted primarily on passerines provide little empirical evidence that white light causes less attraction/collision than red light (white light contains red). Green may be much better than white.	Experiments conducted on Manx Shearwater showed greater **avoidance** of white, blue and green than of red light. Not clear what the attraction properties of red vs white light are for Procellariiformes. Most vertebrate rods are maximally sensitive to green wavelengths and whether particular species are attracted to or repelled by green light would require specific behavioural	Need consistency in lighting across wind farms to avoid confusion to mariners and to comply with international standards, which precludes modification. Even apparently simple changes in lighting require intervention at early stage of turbine design/construction Search and rescue (SAR) lights need to be red to avoid reducing the night vision of crew.

		studies. Green light should only be used if it is highly directed.	
Directional intensity / shielding of lights	Some suggestion in the literature that birds are most sensitive to attraction of light from below. Fitting of shields to prevent upwards light radiation at a coastal resort in Hawaii reduced the number of grounded Newell's shearwaters by 40% over 2 seasons (Reed et al., 1985)	Birds may also be attracted upwards towards light, as is likely the case for storm-petrels stranded on offshore oil and gas platforms, which tend to be several tens of metres above the sea surface.	Already set out in ICAO requirements and EASA CS-ADR-DSN Chapter Q. This focusses the 2000 cd lighting in the horizontal plane and reduces the intensity of the light from above and below. Both regulations stipulate minimum requirements as well as additional recommended vertical angles, which cannot be ignored without justification. Most lights will incorporate this as standard. Marine lighting is also focused on the horizontal plane but needs to remain visible to all sizes of vessels both close to turbines and at the extreme range of the light.
Reduce intensity of lights	The effectiveness for reducing bird collisions is unknown, but likely to reduce the range from which any "attraction" might occur.	Not enough evidence on the impact this would have on different seabird species. Intensity more important than colour in bird night vision. Impact of different intensities	Already set out in CAA guidance CAP 764. Lights can be dimmed to 200 cd in good visibility (greater than 5km). 200 cd lights can still be visible to the human eye > 20 km in good visibility conditions.

		depends on atmospheric conditions. Any conditions creating large, diffuse pools of light likely to be a problem.	
Reduce number of turbines illuminated	Dependent on the range at which any “attraction” of birds to light might occur, the reduction in the number of turbines illuminated is likely to reduce the number of individual birds brought into the proximity of turbines		If the number of turbines lit is reduced, the intensity of lighting may have to increase to compensate.
Reduce or cover lighting associated with maintenance vessels and associated activities and infrastructure (e.g. ports, wet storage)	Reduction of vessel lighting and the use of blinds has successfully reduced the number of collisions of burrow-nesting Procellariiformes with fishing boats (Ryan et al., 2021).		Blinds for vessels should be easy to implement, but changes to safety lighting are likely to be more difficult.
No lighting, or turning off lighting at key times (e.g. fledging period)	There is good evidence for light-induced disorientation (i.e. circling) of Procellariiformes (especially storm-petrels), so elimination of lighting is likely to reduce the number of occasions an individual passes through the rotor-swept area, on a flight past a turbine.	Lack of lighting may result in collisions by birds that cannot see the turbines on nights with particularly low ambient light.	Not possible for offshore wind farms due to safety concerns. Should not be considered as a mitigation option.

Radar-activated lighting		Reduction in collisions will depend on the proportion of time turbines are left unilluminated, during periods when light-induced collisions would otherwise occur.	CAA support this in principle and are considering the parameters in detail. In the meantime, CAA are happy to discuss the approach on a case-by-case basis. In use in other countries, to differing extents, but it is acknowledged that the costs are high. Detection systems are not currently possible for all marine vessels, especially ill-equipped recreational vessels, and lighting provision must cater for all users.
Additional lighting to guide birds away from wind farms	Currently unclear whether this would be effective. May result in further attraction / disorientation / displacement of target birds.	Would need to consider wider impacts on species other than Procellariiformes.	Additional lighting may be more feasible than reduced lighting.
Shut down turbines during meteorological conditions likely to result in high collision rate	Collision risk is reduced if turbines are not rotating.	Since conditions that generate high collision rate are usually associated with lower wind speed, little economic impact on electricity generation?	Unlikely to be acceptable given the importance of offshore wind for future UK energy production.
Increase minimum blade height	May help to reduce collisions at times/in conditions when birds are flying higher (e.g. Manx Shearwaters fly higher in stronger winds).	Has benefits outside of mitigation for birds.	Requires feasibility assessment on a case-by-case basis.

Increase detectability by marking blades / towers	Maximising visibility of blades is likely to reduce the number of collisions as birds would be better able to avoid them.		There needs to be consistency across wind farms to avoid confusion to mariners and to comply with international standards.
Deter birds (seabirds and / or avian predators) using sound	Currently unclear whether deterrence using sound would be effective.	If birds could be deterred by sounds outside of human hearing range this would avoid interference with regulation sounds used for maritime safety.	There needs to be consistency across wind farms in their use of fog horns.
Train crew in safe handling / release of stranded birds	Would not prevent collisions but may reduce mortality of grounded / stranded birds.	Posters at harbours in Pembrokeshire, Wales, provide guidance for mariners in case of Manx Shearwaters stranding on their vessels. Similar schemes have been implemented in other countries for other seabird species.	Has been done elsewhere and could be relatively cheap to implement. Could be built into relevant consenting conditions.

6 Remaining evidence needs to inform assessment

The information below was compiled based on the literature review and workshop discussions. While some data are available for many of the parameters relevant to assessing the impacts of offshore wind development, including from studies in Scotland (see 'Catalogue of data sources'), there are some key evidence gaps remaining. While data are incomplete for all three species considered here, information for Leach's Storm-petrel in Scotland is generally more limited than for Manx Shearwater and European Storm-petrel. The order of knowledge gaps presented here and in section 8 is based on Table 6, which follows the trajectory for assessments of offshore wind farm impacts. Note that the Offshore Wind Strategic Monitoring and Research Forum (OWSMRF) is currently conducting a detailed review of the knowledge gaps and research recommendations relating to parameters required for PVA for Manx Shearwater and European Storm-petrel.

6.1 Detectability and diel variation in marine distributions

The use of Digital Aerial Surveys (DAS) is currently the most commonly recommended method for providing the baseline characterisation for wind farm assessments. There are several advantages to DAS, such as providing an audit trail and potentially causing less behavioural change in seabirds than vessel-based surveys. However, there remain a number of potential biases and these could be exacerbated by the behaviour and morphology of some procellariform species. These issues arise from detectability and identification and have not formed part of the main body of the current review as there has been scant work published that examines them. The issues with detectability are twofold: whether the size and flight characteristics of the species make them harder to detect and whether the nocturnal and crepuscular nature of some of the at-sea behaviours means that they are not captured by the survey flights that are restricted to certain daylight hours. All the procellariiform species covered by this review can be active throughout the day and night and with different levels of activity at different times. For example, for Manx Shearwater tracked from Skomer, diving occurred during the day and peaked in the evening (Shoji et al., 2016), while nocturnal foraging was observed from tracking of birds from High Island, Ireland (Kane et al., 2020). These diel variations in activity may mean that key activity periods are not picked up by the constrained timings of DAS. Even where birds have been detected it remains unclear whether morphologically similar species such as European and Wilson's Storm-petrel can be successfully identified to species level. Full consideration should be given to both detectability and species identification in relevant impact assessments. These aspects of DAS for marine ornithology surveys are currently being considered as part of a review being carried out by NatureScot's Scientific Advisory Committee.

6.2 Basic morphometric data

The basic morphometric data used in collision risk modelling (i.e. body length, wingspan) may vary geographically and is lacking for birds of all three species in Scotland. However, while Scotland-specific data would be useful, differences from birds outside of Scotland are unlikely to be large.

6.3 Flight data

The flight speed data currently available come from relatively coarse-resolution tracking data and will tend to be underestimates of the true travel speeds of birds, and measured flight height data are limited or non-existent for these species. There is a need to understand the extent of flight activity and flight heights in different weather conditions, at different times of day and whether flight heights change in response to turbines. While there has been some work on diurnal activity patterns for Manx Shearwater and European Storm-petrel, information for Leach's Storm-petrel is lacking. Flight heights when arriving at or departing/fledging from high elevation nesting sites are also unknown. Fledglings may have particularly poor flight control in the first few days after fledging, making them more vulnerable, but our knowledge of fledgling behaviour is poor.

6.4 Avoidance/attraction behaviour

Since currently operational wind farms overlap very little with the distributions of Manx Shearwaters, European Storm-petrels or Leach's Storm-petrels, very little is known about their avoidance or attraction in relation to offshore turbines, support vessels and associated lighting, infrastructure and activities. This means that many assessments of the impacts of such developments are based largely on expert opinion rather than empirical data. The ability of these species to detect rotating turbine blades is unknown but could inform mitigation options. Whether or not sound influences avoidance or attraction behaviour is also unknown. There are some data available on the energetic requirements of adults of all species to inform assessment of impacts of displacement (resulting from avoidance), but the review found no data in the energy requirements of chicks of European Storm-petrels or Fulmars.

6.5 Light attraction/disorientation

Critical knowledge gaps relate to light attraction and disorientation. Specific aspects include: the range over which light attraction of nocturnal Procellariiformes may occur (and therefore the size of the light catch basin for wind farms and related activities or infrastructure); the extent to which light attraction is exacerbated by particular meteorological conditions (e.g. fog, rain); the influence of wavelength and pattern of illumination (flashing/steady); the extent to which light attraction differentially affects adults and juveniles, and for how long after fledging juveniles may remain particularly susceptible to light attraction.

6.6 Diet

The level of impact caused by displacement of seabirds from foraging areas is related to the degree of dietary specialisation and the distribution of food resources. Food availability within wind farm developments may also influence the degree to which birds are attracted to the area. There have been very few studies of the diet of these procellariiform species, especially within Scotland, which means that prey distributions, and how prey distributions may change around wind farm developments, are poorly understood. A small amount of metabarcoding of Manx Shearwater diet samples from colonies in Wales has been conducted by the University of Oxford (K. Davies, pers. comm.), and similar work has been carried out at Cardiff University for European Storm-petrels from Mousa (Z. Deakin, pers. comm.), but the results of these studies are not yet published.

6.7 Apportioning impacts to protected colonies

Understanding the connectivity between specific offshore developments and SPA colonies is essential for apportioning impacts to colonies. While long-term data on distributions has been collected by vessel-based surveys, these data do not provide information on the provenance or age of the birds observed, and therefore the connectivity between SPA populations and Plan Option Areas is generally not known. Manx Shearwaters have been tracked extensively from colonies in Wales and Northern Ireland, but limited tracking data are available for Scottish colonies of all three species, and the marine habitat associations of these species in Scotland are therefore poorly understood. It is important to note that birds from colonies outside of Scotland (i.e. in Wales and Ireland) also use Scottish waters and need to be considered in apportioning assessments.

6.8 Evaluation of remaining evidence needs

The evidence needs relating to the key factors involved in the trajectory of assessment of impacts of offshore windfarms on protected colonies of procellariform seabirds are summarised and evaluated in Table 6.

The assessment trajectory commences with quantifying the baseline marine densities of the species of interest and concludes with a Population Viability Assessment for protected colonies, considering both collision and displacement impact pathways. Firstly, the key factors for each stage of the assessment trajectory have been scored ("medium" or "high") in terms of their relative importance within their respective assessment process. In the absence of a formal sensitivity analysis of all factors, we have scored those that may be considered to have an approximately linear effect on the outcome of their respective assessment process as having "medium" importance (e.g. the effect of body length, wingspan or flight speed on collision risk), and those which act in a non-linear manner (i.e. through the existence of a threshold or power relationship, such as flight height) as "high" importance. No factors were considered to have "low" importance. For each species we scored the level of uncertainty surrounding the estimation of each factor as "low", "medium" or "high", based on the availability of evidence identified in the literature review. The "evidence need" for each factor was then scored on the basis of both the importance of the factor, and the level of current uncertainty as shown in Table 5 below.

Table 5. Ranking of evidence needs of key factors in assessment of offshore windfarms on seabirds on the basis of their respective importance and uncertainty.

Importance	Uncertainty	Evidence need
Low	Low	Low
Low	Medium	Low
Low	High	Medium
Medium	Low	Low
Medium	Medium	Medium
Medium	High	High
High	Low	Medium
High	Medium	High
High	High	High

Finally, the tractability of conducting new research to fill the current evidence gap was assessed using expert judgement as “low”, “medium” or “high”, taking into consideration factors such as: (i) whether methodologies currently exist; (ii) have been widely used on these (or similar) species elsewhere, or (iii) whether further technological development would be required. Note that costs were not considered in the tractability factor.

Table 6. Summary of evidence needs of key factors involved in assessment of impacts of offshore windfarms on petrels and shearwaters in Scotland.

Assessment Trajectory	Key factors for impact assessment	Importance	Manx Shearwater			European Storm-petrel			Leach's Storm-petrel		
			Uncertainty	Evidence need	Tractability	Uncertainty	Evidence need	Tractability	Uncertainty	Evidence need	Tractability
Baseline marine density	Diel activity	Medium	Medium	Medium	High	Medium	Medium	High	Medium	Medium	High
	Detectability	High	Low	Medium	Medium	High	High	Medium	High	High	Medium
Collision	Bird morphology	Medium	Low	Low	High	Low	Low	High	Low	Low	High
	Flight speed	Medium	Medium	Medium	High	High	High	High	High	High	High
	Flight height	High	High	High	High	High	High	Low	High	High	Medium
	Avoidance behaviour	Medium	High	High	High	High	High	High	High	High	High
	Nocturnal activity	Medium	Medium	Medium	High	Medium	Medium	High	Medium	Medium	High
	Light attraction	High	Medium	High	Medium	High	High	Medium	High	High	Medium
Displacement	Avoidance behaviour	Medium	High	High	High	High	High	High	High	High	High
	Light attraction	High	Medium	High	Medium	High	High	Medium	High	High	Medium
	Vessel response	Medium	Medium	Medium	High	Medium	Medium	High	Medium	Medium	High
	Energetics	Medium	Medium	Medium	High	Medium	Medium	High	Medium	Medium	High
Apportioning	Colony size	Medium	Low	Low	High	Low	Low	High	Medium	Medium	High
	Colony location	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
	Foraging ranges	High	Medium	High	High	High	High	High	High	High	High
	Connectivity	High	Medium	High	High	High	High	High	High	High	High
PVA*	Colony Size	Medium	Low	Low	High	Low	Low	High	Medium	Medium	High
	Demographic rates	Medium	Medium	Medium	High	Medium	Medium	High	High	High	High

*Note that OWSMRF is currently conducting a detailed review of the knowledge gaps relating to parameters required for PVA for Manx Shearwater and European Storm-petrel.

7 Examination of challenges and recommendations for filling data gaps to assess the impacts of offshore windfarms

The suggestions below are based on the literature review and workshop discussions with respect to evidence gaps and approaches to filling these for Manx Shearwater, European Storm-petrel and Leach's Storm-petrel. Note OWSMRF is currently conducting a detailed review of the knowledge gaps and research recommendations relating to parameters required for PVA for Manx Shearwater and European Storm-petrel.

7.1 Detectability and diel variation in marine distributions

There is an important need for experimental validation of potential biases in aerial survey methods, including detectability, identification and diel variation. Detectability could be tested by carrying out targeted digital aerial surveys (DAS) or vessel-based surveys with an experimental approach. For example, decoy models of birds could be used to assess detectability under different conditions, but only for birds drifting on the sea surface. Surveys could also be performed alongside large scale high-resolution tracking of birds, or decoys, but achieving large enough sample sizes of tagged birds is likely to be difficult. Radar or thermal imaging could be used to conduct nocturnal surveys of leased areas, but identification to species level may not be possible. Evidence needs with respect to detectability are greatest for the two storm-petrel species and for diel activity the highest priority is Leach's Storm-petrel (Table 5).

7.2 Basic morphometric data

Body length and wingspan measurements would be relatively easily collected by ringers or fieldworkers working with Procellariiformes in Scotland. However, while these data could readily be collected, the evidence need is low for all three species (Table 5).

7.3 Flight data

The evidence needs for flight speeds and heights are high for all three species, with the exception of medium scoring for Manx Shearwater flight height (Table 5). Estimates of flight parameters such as speed and height can be gained from tracking data, but acquiring accurate estimates is difficult, even with high resolution data. Where possible, "instantaneous" flight speeds from GPS tags, based on Doppler-shift information derived from the movement of the tag relative to the movement of the satellites (Safi et al., 2013), will be more accurate than that derived from distance covered between successive fixes. Tags providing high resolution tracking data are available for Manx Shearwaters but the accuracy of flight height data from high resolution GPS tracking of this species is still low. Small (< 1.5 g) barometric pressure loggers can be used to estimate flight heights when deployed alongside GPS devices , but because of the need to calibrate to local environmental pressure, accuracy may sometimes be low. Since tags deployed on storm-petrels must be much smaller than those used on Manx Shearwaters, the limitations on battery life and data storage capacity mean that GPS data collected for storm-petrel foraging trips tends to be of lower resolution. However, it would be possible to collect higher resolution data for short periods of storm-petrel foraging trips. Tracking of fledglings is challenging due to the difficulty of retrieving tags for data download.

Flight height can be measured with radar, although these measurements have biases. Distinguishing between similar species (e.g. Manx vs Balearic Shearwater) is difficult, but mobile radar units could be deployed in areas where only a single species is expected (e.g. Rum for Manx Shearwaters). It may be possible to estimate flight heights from vessel-, or turbine-mounted cameras or from aerial or thermal imagery, but again, accuracy is likely to be low. Flight height can also be accurately measured using laser rangefinders (Largey et al., 2021).

It is important to note that flight within wind farm developments may differ from that elsewhere so work within wind farms is important, but currently limited for these species by the lack of overlap between their marine distributions and operational wind farms.

7.4 Avoidance/attraction behaviour

Assessment of macro-avoidance of windfarm development is best achieved by comparing marine distributions of seabird pre- and -post construction. In light of the limited tracking of the three focal species to date in Scotland, we recommend further tracking studies from key colonies to better understand the pre-construction movements and distribution of these species. Such tracking studies should continue as construction occurs and after it is completed, to inform understanding of meso- and micro-avoidance behaviour.

Currently there is little known overlap between operational offshore wind farms and shearwater and storm-petrel marine distributions, so there is limited scope for collecting data on the species' micro, meso and macro avoidance behaviour within and around wind farms, although the evidence need is high (Table 5). There is some overlap between Manx Shearwater distributions and wind farms in the Irish Sea/Solway Firth, and this could be an area in which to focus initial studies, although the number of birds moving close to/within wind farms may be small.

If a suitable site was available, GPS tracking birds could reveal macro- and meso-scale avoidance of wind farms. VHF receivers could be placed on turbines or other infrastructure, as has been done on oil and gas structures elsewhere, but obtaining sufficient sample sizes of VHF-tracked birds would be challenging. Radar can be used to quantify flight lines without the need for tagging birds, and changes to flight lines would provide evidence of avoidance or attraction. Portable radar devices are available, with a detection distance of 72 nautical miles.

Tracking or visual observations could be used to assess avoidance or attraction behaviour in relation to sound. Experiments with sound could be conducted using similar methods to those suggested for light attraction experiments, below.

Whilst no studies have been conducted to date on the energy requirements of chicks of European Storm-petrels or Fulmars, from which to inform assessment of the consequences on productivity of displacement of breeding adults from feeding areas, well—established methods are available and such studies would be feasible.

7.5 Light attraction/disorientation

The evidence need around light attraction/disorientation is high for all three species but there are challenges to addressing the knowledge gaps (Table 5). To address the current knowledge gaps regarding the spatial scale, age classes affected, environmental drivers, and influence of light characteristics on light attraction of nocturnal Procellariiformes, we recommend a series of experiments are conducted, for both Manx Shearwaters and storm-petrels, to examine the behaviour of both adults and fledglings at varying ranges from experimentally manipulated light sources. Such experiments will be logistically challenging to perform, but given magnitude of the current knowledge void, and the impact of potential light attraction on the estimates of collision rate, these studies could be considered a high priority.

Possible approaches could include use of thermal video equipment to record flight paths of adults attending the colony, and fledglings leaving the colony, in response to lights of differing wavelength, intensity and distance from the colony, under differing levels of ambient light, and visibility (i.e. foggy/clear). See Gauthreaux and Belser (2006) for an example of tracking flight paths of nocturnal migrants in relation to illuminated communications towers in USA. Monitoring for flight paths could be supplemented by targeted tracking of adults using GPS tags, and fledglings using coded VHF (MOTUS) tags. Tracking fledglings as they leave the burrow is challenging (see papers by Rodriguez et al. (2015b, 2022) for an account of the difficulties), but use of VHF tags, and a suitable array of detection stations, would overcome the difficulties of tag life and detection frequency.

Such fieldwork would require the erection of lights in view of a breeding colony, but ideally as close to the sea as possible. Lunga, Treshnish Isles might offer a suitable location where several small, low-lying skerries are situated between 700 m and 1500 m from nesting areas of European Storm-petrels and Manx Shearwaters. Such skerries would provide a suitable platform for installing lights, which could be varied in an experimental manner to systematically assess the attraction of light of differing wavelength, intensity, splay, pulse frequency etc. St Kilda may provide a suitable location for these studies on Leach’s Storm-petrel and Manx Shearwater, locating test lights on the coast opposite the breeding colony on Dùn, which currently hosts about 6,000 pairs of Leach’s Storm-petrel. Mousa, Shetland would provide a logistically favourable site for studies on European Storm-petrel.

Since behaviour in relation to lights near the colony may be different from behaviour at sea, experiments using lights on vessels or marine structures would also be beneficial. On-board observers and thermal imaging could be used to record the behaviour and number of birds in the vicinity.

Similar experiments, both on land and at sea, have been carried out in New Zealand by the Northern New Zealand Seabird Trust, University of Auckland and Saint Martin’s University, and Lukles et al. (2021) provide useful recommendations for future work. Studies on light attraction of Leach’s Storm-petrels are also being performed by researchers at Memorial University Newfoundland, using a portable radar system deployed at colonies. Coordination and discussion between research groups working on light attraction of Procellariiformes would be extremely beneficial.

7.6 Diet

While diet data do not explicitly feed into assessment methods and are therefore not considered a priority, an understanding of diet and the distribution of food resources is useful for predicting the level of impact caused by displacement or the likelihood of attraction to wind farms. Diet samples can be relatively easily collected by ringers or fieldworkers. Storm-petrels often produce regurgitates upon capture in mist nets, and faecal samples can be collected from nest sites (especially nest boxes). Obtaining diet samples from tracked birds would be particularly useful. Regurgitate and faecal samples from tracked (and untracked) European Storm-petrels have been collected on Mousa (Cardiff University/RSPB) and Treshnish Isles (RSPB), and for Leach's Storm-petrels on St Kilda (RSPB), but most have not been analysed. Molecular diet work (i.e. metabarcoding) is likely to provide more detailed information than traditional visual analysis, but visual analysis is also valuable, and much cheaper than molecular methods.

7.7 Apportioning impacts to protected colonies

Evidence needs with respect to foraging ranges and connectivity to Plan Options are high for all three species and medium with respect to colony locations (Table 5). Current knowledge of foraging ranges, locations and sizes of SPA colonies suggests that the following features of Scottish SPAs may be impacted by developments within Plan Options:

1) Manx Shearwater at St Kilda, Rum and Copeland
2) European Storm-petrel at Mousa, Auskerry, Sule Skerry, North Rona, Priest Island, Treshnish and St Kilda
3) Leach's Storm-petrel at the Flannan Isles and North Rona

Tracking of European Storm-petrels has been carried out on Mousa, Shetland over five years (2014-2018) between mid-July and mid-August, and at Lunga, Treshnish (19 individuals) for a single year in late July and August. Leach's Storm-petrels (14 individuals) have been tracked from St Kilda in a single year in July. Manx Shearwaters have been tracked from Rum, with GPS data for 20 trips from nine chick-rearing birds in 2010 and 58 trips from 15 chick-rearing birds in 2011 included in Dean et al. (2015). To establish ecological connectivity between Plan Options and these protected features, it would be beneficial to carry out tracking at the remaining breeding sites and to increase the sample of birds tracked, and the seasonal coverage of tracking, at Rum, St Kilda, Lunga and Mousa. The logistics of tracking on the Flannan Isles or North Rona would be extremely expensive and challenging, and success could not be guaranteed. Tracking at the remaining sites would be somewhat more straightforward, though not easy.

Storm-petrels breeding in the Northern Isles may be vulnerable to impacts of wind farms in the east and north-east of Scotland when departing south on migration, if they migrate southwards through the North Sea. Migration routes are currently poorly known, particularly for juveniles, which may be at particular risk of light attraction in the days and weeks after fledging. Storm-petrels can be tracked using geolocator (GLS) tags to identify migration routes and nocturnal illumination events. GLS tags require recapture of the bird, which is difficult (though possible) for adults but considerably more challenging for juveniles, which do not return to UK waters for two years. Visual inspection of light curves from eight birds tracked by RSPB (unpublished data) indicates nocturnal “light spikes” in wintering feeding areas, possibly as birds approach fishing vessels. While VHF/MOTUS tags are too large to be deployed on leg rings (for long-term studies) on storm-petrels, they could be used to collect multi-annual data on the movements of juvenile or non-breeding Manx Shearwaters. A network of receivers would need to be established to use VHF/MOTUS tags, but it may be possible to place these on turbines or other offshore structures, if incorporated at the planning stage.

It is important to note that, given the long-distance movements of these Procellariiformes, there may also be connectivity between ScotWind Plan Options and colonies outside of Scotland, and as far away as Canada in the case of Leach’s Storm-petrel (Bicknell et al., 2012, Bicknell et al., 2014). Tracking of the species from colonies elsewhere would be required to determine the extent of overlap.

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9 Glossary of terms and acronyms

AOS	Apparently occupied site. Unit used for counts of seabird breeding pairs or nest sites.
ARS	Area restricted search. A movement pattern in which an animal travels more slowly and with greater tortuosity while foraging or searching for prey, thereby remaining for longer in areas with higher food availability.
brooding	Breeding stage during which a small chick cannot thermoregulate and must be attended by an adult at all times.
dual foraging	Foraging strategy in which chick-rearing seabirds undertake a combination of short foraging trips for chick-provisioning and long foraging trips for self-provisioning.
ESAS	European Seabirds at Sea. A partnership project, managed by JNCC, that uses a standardised vessel-based survey technique to gather data on seabird abundance and distribution.
GLS	Global location sensor or light-level geolocator. A lightweight, archival tracking device that records ambient light levels and time, which can be used to determine latitude and longitude. Often used to track bird migration. Provides two locations per 24-hour period and is only accurate to within tens of kilometres.
GPS	Global positioning system. Tracking devices that use satellite technology, giving highly precise locations which are accurate to within a few metres.
incubation	Breeding stage between the laying and hatching of an egg, when the egg is generally attended by an adult at all times to maintain its temperature.
littoral	Relating to nearshore or coastal environments.
magnetoreceptor	A device or organ that detects the earth's magnetic field. Some form of magnetic sense is found in a wide range of animals, but the nature of the magnetoreceptor organs is often poorly understood.
morphology	The structure and form of organisms, especially their external form.
neritic	Relating to the shallow part of the sea near a coast and overlying the continental shelf, approximately 200 m deep.
NMP	National Marine Plan. Legislation adopted by the Scottish government in 2015 which provides a framework for managing all developments, activities and interests in or affecting Scotland’s marine area (territorial

	and offshore waters), setting out high-level objectives, general policies and sectoral policies.
Oceanitid	Any member of the family Oceanitidae of Southern or Austral Storm-petrels.
OWSMRF	Offshore Wind Strategic Monitoring and Research Forum. An industry-led collaborative forum that aims to better understand the impact of large-scale offshore wind development on marine birds.
pelagic	Relating to the open ocean.
phototaxis	Directional movement in response to a light source.
post-brooding	Breeding stage following brooding, when a chick can thermoregulate independently and can be left unattended while adults are foraging.
Procellariiformes	An order of seabirds, commonly known as tubenoses after their specialised nostrils that allow them to excrete salt. The order contains four families: the albatrosses, petrels and shearwaters, and two storm-petrel families.
RAS	Retrapping Adults for Survival. A programme run as part of the British Trust for Ornithology’s Ringing Scheme, in which ringers aim to ring and then catch or re-sight adult birds of a single species in a well-defined study area, enabling estimates of adult survival.
SMP	Sectoral Marine Plan for Offshore Wind. The strategy through which the Scottish government aims to identify the most sustainable Plan Options for the future development of commercial-scale offshore wind energy.
SMR	Scottish Marine Regions. 11 regions identified by Scottish Ministers under the Marine (Scotland) Act 2010 based on physical characteristics.
suprabenthic	Organisms that live on the sea floor but migrate above it seasonally or daily.
surface seizing	A method of foraging in which a seabird on the sea surface grasps food items just below the surface with its bill.
thermoregulation	Regulation of body temperature, whether physiological or behavioural.

Annex 1: Workshop Report

Workshop 1: 1300 – 1600 UTC, 10th March 2022

Workshop 1 brought together ecological experts on the three key procellariiform species (Manx Shearwater, European Storm-petrel and Leach's Storm-petrel), as well as experts on seabird vision and the impacts of artificial light on seabirds. A draft version of the literature was circulated to attendees in advance of the workshop and a summary of the draft review was presented at the start of the workshop, along with the knowledge gaps it had identified, the priorities amongst those, and brief suggestions for filling them.

Participants

43 participants attended the workshop and engaged well with the information presented and questions posed. The following 27 organisations were represented:

- Acadia University, Canada
- Azores University
- Bangor University
- BirdLife Greece
- Birmingham University
- BTO
- Cardiff University
- CORY'S (Spanish environmental consultant)
- Environment and Climate Change Canada
- Faroese Environment Agency
- JNCC
- LBHI (Agricultural University of Iceland)
- MacArthur Green
- Marine Scotland Science
- Memorial University of Newfoundland
- NatureScot
- RSPB
- Scottish Association for Marine Science
- South Iceland Nature Research Centre
- UKCEH
- University of the Azores
- Universidad Autónoma de Madrid
- University College Cork
- University of Gdansk
- University of Oxford
- Vilnius University

Discussion summary

Each participant was randomly allocated to one of three breakout rooms. Each breakout room included two members of the project team, one acting as a facilitator and one as a scribe. A Jamboard (online whiteboard) was set up for each breakout room in advance and a link provided for participants so that they could add ideas or comments during the session or at any time during the week following the workshop. The scribes aimed to ensure all comments were captured on the Jamboard, adding any points not written by the participants themselves.

Participants in each of the three breakout rooms discussed five key questions, during two sessions.

Session 1:

1. Have we missed anything important from the review?
2. Have we identified the knowledge gaps correctly?
3. What are the priority knowledge gaps in terms of wind farm risk assessments?
4. What risks/potential mitigation should we focus on (in the next workshop)?

Session 2:

5. Recommendations/challenges (technological, logistical, temporal, ethical, financial) for addressing knowledge gaps

Following each session, all participants returned to the main room and each of the breakout room facilitators provided a summary of the key points discussed within their group. It was generally agreed that the literature review was largely complete and that the knowledge gaps were correctly identified, but some suggestions for minor edits or additions were made. Each of the three breakout rooms came to similar conclusions regarding the priority knowledge gaps and there were lots of suggestions for addressing knowledge gaps, although it was acknowledged that many would be challenging to fill. A summary of the points raised, and the actions RSPB have taken as result, follows.

1. Have we missed anything important from the review?

Comment	RSPB Response	Notes
Did the review cover demographic consequences of displacement/collision etc? Possibly through individual based models?	No change	The review covers demographic parameters but implementing models is beyond the scope of this work.
Importance of considering dual foraging (where breeding birds alternate between long and short foraging trips) in these species.	Implemented	The review already mentions evidence for dual foraging in the Manx Shearwater and European Storm-petrel 'Foraging ecology' sections but we have now highlighted that it should be considered when using foraging range data for risk assessments.
Think about specific questions around light attraction to target future work, e.g. distance of attraction to lights - how large is the light "catch basin"?	Implemented	The review already mentions the range over which light attraction occurs as a knowledge gap, but we have added explicit mention of the 'light catch basin'.
Light attraction is important but note that there are two distinct processes: disorientation of adult petrels in foggy conditions, and response of fledglings which are orientated to move towards light to reach the sea.	No change	Already included
Important to consider lights at ports, harbours and other infrastructure developments associated with ScotWind as well as the actual wind farms and associated vessels.	No change	Already included
There is evidence in Canada of attraction to oil and gas platforms.	No change	Already included
Construction phase may be more important than operational phase as more lights/disruption.	Implemented	Added a sentence to point this out in relation to displacement and barrier effects and added 'construction activities' as part of light attraction considerations.
Many more collisions with buildings when lit (see Guilford *et al.* Bird Study paper).	No change	Already included

We need more information on the impact pathways; is light attraction/disorientation a separate pathway or are they part of impacts such as displacement, e.g. attraction displaces birds from where they would be otherwise. How do we incorporate that into impact assessments?	Implemented	Noted in lighting attraction introduction that light attraction may lead to displacement and added: "We do not consider light attraction to be a separate impact pathway, but it may exacerbate one or more of the recognised impact pathways (e.g. collision, displacement)."
Fledgling behaviour likely most important but has been the focus of other studies.	No change	Already included
Fledgling flight heights.	Implemented	Added to knowledge gaps: "There is a need to consider flight heights when arriving at or departing/fledging from high elevation nesting sites, as well as when birds are away from the coast."
Understanding of the first few days after fledging, when birds don't have good control of flight and are vulnerable to weather etc. Need to differentiate from light attraction.	Implemented	Added to knowledge gaps: "Fledglings may have particularly poor flight control in the first few days after fledging, making them more vulnerable, but our knowledge of fledgling behaviour is poor."
The review is bird-focused, what about structural elements of windfarm infrastructure.	No change	Beyond the scope of the review, although some discussion around mitigation options.
Maps in review don't show the Irish colonies. There will be connectivity with Scottish colonies, and non-Scottish colony birds might be using Scottish waters (e.g. Faroes).	Refer to MS	No change to maps requested, but note added to figure legends to highlight the need to consider colonies from outside of Scotland.
For apportioning, is it only the closest SPAs that are important, or all within foraging range? Is there colony segregation of foraging areas? e.g. Manx Shearwaters have a mixture of these effects depending on behaviour; on longer trips they aren't segregated to colony but they are on shorter trips.	No change	Foraging area overlap is discussed in the review. The details of the apportioning method (e.g. which colonies are included) are not part of the review.

Habitat preferences of prey/prey distributions (maybe limited data). How might prey distributions change in wind farm footprint and influence attraction?	Implemented	Added to knowledge gap around diet. Is already mentioned as a possible cause of attraction.

2. Have we identified the knowledge gaps correctly?

Comment	RSPB Response	Notes
Basic morphometric data		
Physiological/morphological differences between Welsh and Scottish birds are unlikely.	Implemented	Added to knowledge gap that differences are not expected to be large.
Flight data		
Need to understand how birds gain altitude when getting to burrows high up in colonies, e.g. Manx Shearwaters on Rum	Implemented	Added to knowledge gaps: "There is a need to consider flight heights when arriving at or departing/fledging from high elevation nesting sites, as well as when birds are away from the coast."
Current flight height assessment is unreliable, probably underestimates altitude. It is difficult/computationally complex to interpret altitude from biologging data.	No change	Limitations of current data are already discussed.
Flight heights in different weather conditions and day/night. If we can rule out that they fly at collision height under any circumstances, collision rate will be virtually zero.	Implemented	Added to flight heights knowledge gap.
Flight height/behaviour with wind speed/weather.	Implemented	Added to flight heights knowledge gap.
At-sea distributions/overlap with leased areas		
Likely to be site specific causes in variation	No change	
Diet		
Link between prey and habitat	No change	Already included.
Molecular techniques are an important method to carry out diet analysis	No change	Included in suggestions for filling knowledge gaps.

Some molecular analysis of diet is being carried out for Welsh colonies.	Implemented	Have noted in evidence needs section.
Behaviour (avoidance/attraction)		
Attraction/disturbance by boats	Implemented	Added to avoidance/attraction knowledge gap.
Light attraction/disorientation		
Distance over which light attraction may occur.	No change	Already included
Conceptual understanding whether it is attraction or disorientation that makes birds appear round lights.	No change	Already included
Multiple lights on multiple wind farms could appear more like a starscape and cause more problems than a single light.	No change	
Other		
Diurnal activity patterns.	Implemented	Added to knowledge gaps (especially for Leach’s Storm-petrel)
Construction vs operational phase impacts.	No change	The same knowledge gaps apply to both phases. 'Associated activities' are included in current attraction/avoidance knowledge gap.
Break down broad light attraction category.	No change	This is already broken down in the knowledge gaps section.
Detection, particularly at the start of the assessment, plus biases in detection, both with DAS (not detecting ESP) and boat based (including potential attraction of birds to survey vessels).	No change	We have commented on the problems with aerial and vessel-based surveys.

3. What are the priority knowledge gaps in terms of wind farm risk assessment?

Comment	**RSPB Response**	**Notes**
Effects of light influencing collision, displacement and barrier effects.	No change	Already included
Need to understand whether flight height changes in response to turbines.	Implemented	Added to flight heights knowledge gap.
Potential attraction to vessel lighting.	No change	Light attraction already widely covered.
Is there more published on birds attracted to fishing vessels?	No change	Attraction to vessels (including fishing vessels) is already discussed, but a full review of attraction to fishing vessels is beyond the scope of this piece of work.
Fledgling risks on first migration (at night especially). How long are juveniles vulnerable to light pollution and is this linked to visual physiology?	No change	Already included
There may be other drivers of attraction to infrastructure, such as sound.	Implemented	Possibility of attraction to sound is mentioned in the review, but have added to knowledge gap around attraction/avoidance.
Indirect pathways associated with effects of light on prey.	No change	Possibility of lights increasing prey availability is mentioned. Knowledge gaps include changes in prey distributions around wind farms.
Any novel pathways?	No change	Everything additional identified during workshops has been added.
How do the limits of our knowledge affect our ability to carry out assessments?	No change	
Collision rate	No change	Lack of empirical data regarding impact assessments is already discussed.

The birds' ability to detect rotating blades. Could inform mitigation measures to increase detectability of the pylon and blades under different light levels and visibility.	Implemented	Added to avoidance/attraction knowledge gap.

4. What risks/potential mitigation should we focus on in the next workshop?

It was noted that any mitigation must apply to a broad suite of marine birds, and not just petrels and shearwaters.

Light attraction

- How restrictive are permissible lighting patterns/wavelengths?
- Experimental design to understand changing light features (with a dark control).
- Consider key periods of the year when lighting is an issue, e.g. fledging period.
- Absence of light is potentially worse if birds cannot see the turbines. We need to better understand birds' response to light at sea.
- There is some evidence of storm-petrels foraging at night at illuminated fish farms. It would be good to understand the mechanisms.
- Training of vessel crew in handling and releasing birds attracted and grounded on vessels, according to an established protocol (noting that there are existing examples for oil and gas platforms in Nova Scotia).

Other

- Changing the height of turbines.
- Methods to increase the detectability of pylons/blades under different visibility and light levels. Make them detectable at a sufficient distance for birds to change flight path and avoid them.
- Preventing predators from nesting/spending time around turbines.
- Is it possible that an underwater array might provide shelter for fish and so attract birds that way? Can this be mitigated for?
- A better understanding of attraction to noise, e.g. diesel generators on St Kilda.

5. Recommendations/challenges (technological, logistical, temporal, ethical, financial) for addressing knowledge gaps.

The importance of identifying the easiest gaps to fill was highlighted, as well as the need to consider which aspects should be addressed by academia and which by the offshore wind industry.

Basic morphometric data

Focus on easier work (e.g. morphometric data) first, then look at more complex studies.

Scottish morphometric data won't be much different from Wales and can be done in a couple of days, e.g. by an established ringer.

Flight data

Radar: Flight height can be measured with radar but has biases. Species ID (e.g. Manx vs Balearic Shearwater) is difficult with radar but perhaps mobile radar units could be deployed in places like Rum with only one species of shearwater. However, there is a trade-off between radar size and accuracy.. Could the equipment be placed on buoys to measure flight heights at sea?

Thermal imaging cameras could be used to detect storm-petrels at sea and record behaviour. Could flight heights be worked out from these images? It may not be possible to identify to species level (e.g. Manx vs. Balearic Shearwater), but that may not be important.

Hi-Def have been doing interesting work on flight heights from aerial images, but confidence intervals may be large. A report on this work is forthcoming: Humphries G, Fail T, Watson M, Bickley D, Peters-Grundy R, Scott M, Keogan K, and Webb A (in review). Aerial photogrammetry of seabirds from digital aerial video images using relative change in size to estimate flight height. *Marine Biology*.

Data from cameras attached to birds has been used to estimate the height of birds based on the tilt of the horizon, but this is challenging.

GPS and altimeters have been used to measure flight heights of Manx Shearwaters, but both have large errors.

Behaviour/flight height may be different to normal within a wind farm, as in gannets, so work within wind farms is important.

When does behaviour change from shearing to gaining altitude and vice versa?

Tracking:

Tags providing high resolution data are available for Manx Shearwaters.

Long term tag attachment is possible on storm-petrels with sutures, but that method would be challenging to license in the UK. Short-term tagging during the breeding season is adequate for adults/immatures prospecting but not for fledglings.

PathTrack tags record instantaneous speeds. These are not currently automatically available with data download but can be requested.

Accelerometers are now/soon to be available for storm-petrels, but still won't give flight heights.

Is there an alternative to altimeters? The accuracy of altitude data from high resolution GPS data has been tested but still had large errors. High resolution data for storm-petrels is not yet possible due to the small battery sizes needed to keep tags small enough.

MOTUS could have potential for measuring height as well as location, but it is difficult to establish an array of receivers offshore. Receivers have been installed on oil and gas platforms and supply vessels in Canada, and it may be possible to deploy them on buoys at development sites. Any such inclusion of receivers in infrastructure would need to be considered at the planning stage for offshore wind farms. . GPS might be better, but remote-download tags are not yet small enough for storm-petrels so they need to be recaptured.

At-sea distributions/overlap with leased areas

This information becomes more important to understand if it is used in deciding where wind farms go.

There are huge impacts of Leach's Storm-petrel predation by Great Skuas at St Kilda. There is some genetic evidence that some of the birds eaten may be from Canada. This is an example of the need to understand connectivity between Canada and Scotland, and not just focus on birds from Scottish colonies.

Safe access to many colonies is a logistical constraint for tracking and determining at-sea distributions.

Radar can be used to look at density at sea before/after construction, and in combination with other studies such as tracking could help us to understand juvenile/adult ratios.

MOTUS: Tags are currently too big for storm-petrels but could be used on Manx Shearwaters. Useful for non-breeders/fledglings as long-term deployment outside the breeding season is possible. Detection distance is limited to line of sight. There is currently no UK network, but there is one in Canada which would be useful to learn from. It is important to incorporate at the planning stage if putting receivers on offshore structures. Unclear whether MOTUS could provide data on flight height and avoidance as well as distributions.

Detection*:* Carry out targeted digital aerial surveys (DAS) with experimental approach to detectability, for example using decoy models of birds to assess detectability under different conditions.

Rescue programmes, such as that for grounded Manx Shearwaters in Mallaig, could be used in association with ringing to identify source colonies. Birds could be tracked from wind farm areas or if stranded on vessels or structures, but remote download of data would be required.

Dye marking of large numbers of birds at colonies could be used to look at whether adults or young birds interact with wind farms.

Birds could be caught at sea and stable isotope or genetic analysis used to identify their origin, although catching at sea is challenging and may not be possible.

Diet

Change in community of marine life in wind farms is likely. It is important to understand birds' diet to understand how these changes affect the birds.

University of Oxford is currently carrying out diet studies, including metabarcoding. Cardiff University has performed metabarcoding of diet samples for many species, including storm-petrels. There needs to be a larger study using DNA metabarcoding, but it would be easy to collect samples.

Visual diet analysis is valuable and much cheaper than molecular. Molecular diet work is likely to be better than traditional visual analysis as it is very hard to identify prey to species level when samples are tiny/degraded (especially faecal samples), and visual identification is biased towards less digestible items such as squid beaks. Any diet studies are much cheaper than tracking.

Could faecal/regurgitate samples be collected by ringers? Would need to consider the logistics of transporting samples to the lab, but this is not too challenging.

It would be useful to link diet data to tracking information from the same individuals.

Is diet or productivity/prey distribution more important? Some knowledge of diet is required before being able to infer predator distributions from productivity/prey distributions.

Behaviour (avoidance/attraction)

Fledglings could be tracked, but it would be necessary to recapture them if remote download is not possible. Track adults and juveniles from the same colony to see if interactions with wind farms are different for different age classes.

VHF: receivers have been placed on oil and gas structures, but it is difficult to get a good sample size.

Radar could be used to quantify flight lines. Changes in flight lines are evidence for attraction/avoidance. The detection distance of portable radar is 72 nautical miles. Memorial University (Newfoundland) has a mobile radar system that will deployed at Leach's Storm-petrel colonies to study their behaviour around artificial light.

Look at circumstances of behaviour in the vicinity of existing lights.

Combine multiple methods (tracking, radar, camera etc). how do we get control site/set of birds, does this need to be tracking?

Light attraction/disorientation

An experimental approach is important, despite the challenges. Look at light range, wavelength, pattern and adults vs immatures.

Behaviour at the colony might be different from at-sea behaviour. Could you conduct experiments at sea using vessels or structures? Experiments will need to use lights that are possible to use on turbines/vessels and these should be standardised across studies using different locations/species.

Is response to light related to colony proximity? This would need both at-sea and landfall groups.

Studies at SPAs would require Habitat Regulations Assessment. Experimental studies might injure the birds and would be harder to licence than studies that take advantage of existing/proposed differences between developments/locations. Perhaps some sort of cushioning could be used on boats/structures to protect birds from impact during experiments.

Focus research on current windfarms in the Irish Sea (e.g. Robin Rigg) as there are Manx Shearwaters in the area. Can lighting on existing turbines be changed to monitor changes in behaviour using GPS tracking?

Could expertise within the offshore wind farm sector be harnessed to construct bespoke experimental structures at appropriate locations?

Bardsey lighthouse changed to a red flashing light in 2014 and there have been virtually no collisions since. There were a lot of reviews in the 19th century of birds flying into lighthouses, this should be reviewed as a starting point.

A questionnaire could be sent to vessel operators about birds found on deck. Onboard fisheries observer programmes could be used to gather data but are limited in the UK and only take place during the day. There is currently a project in South Georgia and previously one in New Zealand using these methods. Cruises around the UK with naturalists onboard (e.g. National Geographic) could be used for better species ID. JNCC also runs seabirds at sea surveys. We might be able to ask wind farm maintenance vessels/crews to partake, or it could be made a requirement in certain areas/settings.

Look at existing studies for the proportion of adults killed when attracted. It would be difficult to monitor the number of collisions at offshore structures.

Bio-acoustic studies could be used to pick up calls around structures/vessels/colonies. Caution is needed in interpreting the data because of changes in vocalisations in response to stress.

Systematic, rather than opportunistic, surveys of oil and gas platforms would help to understand the drivers of light attraction and would allow a finer scale temporal analysis.

Radar/cameras (BACI studies) could answer some of these questions.

Understanding the impact of different weather conditions is very important.

Light attraction is the biggest unknown but may not be the biggest issue. We don't know enough about collision/displacement either.

Workshop 2: 1530 – 1700 UTC+1, 31st March 2022

Workshop 2 focused on mitigation, particularly in relation to the potential impacts on procellariiform seabirds of the artificial lighting associated with offshore wind developments. The workshop began with a presentation on the key impact pathways identified in the review and Workshop 1, and some suggestions of mitigation options. A second presentation from Anatec described the current lighting requirements of offshore wind farms and associated infrastructure and activities.

Participants

39 participants attended Workshop 2, from the following 26 organisations:

- Anatec
- APEM Ltd
- BirdLife Malta
- Cardiff University
- Civil Aviation Authority
- EDF Renewables
- Environment and Climate Change Canada
- HiDef Surveying
- Houston Audubon Society
- JNCC
- Marine Scotland Science
- Maritime and Coastguard Agency
- Natural England
- NatureScot
- Northern Lighthouse Board
- ORE Catapult
- ØRSTED
- RSPB
- Scottish Power
- South Iceland Nature Research Centre
- SSE
- UKCEH
- University of Birmingham
- University of Gdansk
- University of Oxford
- Vattenfall

Discussion summary

Discussion was structured around three broad topics: changing the nature of lighting, changing lighting infrastructure, and other mitigation options. It was generally agreed that changing the nature of lighting (e.g. reducing lighting or changing the wavelength, intensity or pattern of illumination) would not be possible as lighting of vessels and structures is highly standardised and aims to maximise safety of vessels and aircraft. Shutting down turbines at key times was also considered not to be feasible, but other options were discussed, as follows.

1. Changing the nature of lighting

No lighting (or turning off lighting at key times, e.g. fledging period)

Not an option from a safety perspective. Shouldn't be considered as mitigation because of serious concern about turbines not being lit for even a short period of time.

Aviation lights only come on at night.

Reduce intensity

There is provision within aviation lighting rules to reduce lights when visibility is above 5 km. Lights can be dimmed up to 90% during reasonable weather.

There is not enough evidence on the impact this would have on different seabird species.

Intensity is more important than colour in bird night vision. The impact of different intensities also depends on atmospheric conditions (fog, rain, etc.). Any conditions that create large diffuse pools of light is the problem.

Bird vision is usually fully functional after a few days. However, there are suggestions that for burrow-nesting seabirds this may not be the case.

Juvenile burrow-nesting seabirds develop their eyes fully after they fledge:

- Mitkus, M., Nevitt, G. A., & Kelber, A. (2018). Development of the visual system in a burrow-nesting seabird: Leach's storm petrel. *Brain, Behavior and Evolution*, 91(1), 4-16.
- Atchoi, E., Mitkus, M., & Rodríguez, A. (2020). Is seabird light-induced mortality explained by the visual system development*? Conservation Science and Practice*, 2(6), e195.

Reduce number of turbines illuminated

If the number of turbines lit is reduced, the intensity of lighting would have to increase to compensate so this isn't always viable.

Lighting of non-turbine infrastructure could also pull birds off course (especially fledglings). Reduce, turn off, or cover other lights associated with turbines (e.g. maintenance vessels). Decrease the activity of maintenance vessels, or other lighting that isn’t crucial, during high risk periods for birds (e.g. fledging).

Alter pattern of illumination

There needs to be consistency across wind farms to avoid confusion to mariners (especially recreational) and to comply with international standards. Marine navigation lights (UK) generally have a character of 1 flash every 5 seconds (Significant Peripheral Structures) or 2.5 seconds (Intermediate Peripheral Structures).

Alter colour of lights

Again, there needs to be consistency across wind farms and compliance with international standards so this is unlikely to be possible.

Search and rescue (SAR) lights are red to avoid affecting the night vision of crew. No other colour is possible. White lights are used in some circumstances for obstacle lighting for aviation but this has the potential to disrupt night vision of crews.

Is there a way of changing the wavelengths of the lights (e.g. reduce blue wavelengths) to alter the birds' perception of the lights without changing the colour as perceived by humans (so as still to comply with maritime standards)?

Additional lighting

Is more lighting possible, as less is not? Could additional high attraction lighting on buoys be used to navigate birds around high risk areas, perhaps temporarily during the fledging period?

2. Changing lighting infrastructure

Shielding/directionality of lights

The peak of an aviation light beam is between 3-4 degrees above the horizontal plane and less than 10% is 1-1.5 degrees below the horizontal plane, so only 10% is directed down.

Vertical divergence of marine lighting is only a couple of degrees off of the horizontal, but the light needs to remain visible to all sizes of vessels, either up close to the turbine, or at the extreme range of the light.

Could you light up the wind farm at night from a light placed on another structure, pointing at the turbine? To avoid attraction and collision with the light itself, place it below the sea surface. This is unlikely to be feasible as turbine lighting is standardised to maximise efficacy and safety.

Lighting on ships could be directed towards the deck to reduce scatter.

There is probably potential to have design discussions with turbine designers as to how access door lighting could be altered, as well as with vessel suppliers. As such, there might be some mitigation solutions which could be explored with relative ease, or are already being implemented as standard, to minimise attraction for Procellariiformes.

Radar-activated lighting

There are already systems in some parts of the world where lights only come on when an aircraft is detected, but this is not in UK EEZ regulations at the moment. There are different technologies that can enable this. Could this be possible for vessels on the sea too?

A detection system isn't possible for all marine vessels, especially ill-equipped recreational vessels. The ability to detect and track small yachts/vessels, particularly in poor weather is difficult and would not be reliable. As such, the provision of lighting must always be for the lowest level user.

It is crucial to keep the importance of lighting in perspective and cater for all situations and everything that might be flying, e.g. civil aviation and search and rescue could be present at any time.

Lighting is required to provide ships with sufficient warning to take avoiding action so needs to consider all types of vessels, including very slow turning vessels.

3. Other suggestions

Increase blade height

This has benefits outside of mitigation for birds. 22 m of clearance is the required minimum to reduce impact on marine vessels.

Increased hub height would require feasibility assessment on a case-by-case basis of manufacturing and installation of foundations tower sections.

The threshold for crossover from fixed bottom vs floating turbines is likely to increase over time (perhaps up to 100 m). There's a relationship between increasing turbine size and jack-up/crane lifting capabilities and the latter may be a limitation for increasing blade height

As turbines become larger, we will likely see a slight increase in the sea level to lower tip clearance. We will also see a larger rotor diameter but not necessarily a large increase in the overall rotor-swept area (i.e. typically fewer/larger WTGs meaning the overall swept area of the rotor in the 'danger zone' for birds could be proportionally reduced.

Shut down turbines at critical times

The UK will be reliant on offshore wind in the future so switching off turbines would be the worst-case scenario.

Increase detectability by marking blades

Review recently conducted for Natural England. It is likely that something can be done to make blades more visible to birds flying through, and therefore prevent collisions.

Collision with towers is also possible. Maximising contrast between towers and blades (e.g. black/white stripes on blades and towers) has been looked at. There is currently a project in Norway looking at this.

However, the need for consistency across wind farms must be considered, to avoid causing confusion.

Use of sound to deter seabirds or avian predators

Operational offshore wind turbines have relatively high noise emissions (~110+ decibels). This could be a consideration if these species actively avoid noise sources. There is some evidence that Manx Shearwaters are attracted to generators on St Kilda by sound.

There is an Irish project testing if sound could be used to deter birds. Sound signals (e.g. foghorns) on turbines at periphery of windfarms which sound during poor visibility (under 2 nautical miles). There are characteristics that must be met (1 long blast, 2 short blasts every 30 seconds).

It would be interesting to test whether birds respond to foghorns or if there are sounds beyond human hearing range that might be detected and deter birds during times when risk is high. Although obviously has implications for displacement.

Train vessel crew in safe handling/release of stranded birds

SOPs for stranded birds.

Posters have been created for vessels anchored in St Brides Bay, Pembrokeshire, explaining what to do if Manx Shearwaters land on boats at night. This method has been repurposed for different species and locations around the world.

Annex 2: Catalogue of data sources

Parameter/data group	**Manx Shearwater**			**European Storm-petrel**			**Leach’s Storm-petrel**			**Northern Fulmar**			**Sooty Shearwater**		
	Scot	**UK & I**	**World**[a]	**Scot**	**UK & I**	**World**[a]	**Scot**	**UK & I**	**World**[a]	**Scot**	**UK & I**	**World**[a]	**Scot**	**UK & I**	**World**[a]
Marine distribution[R]	1, 2, 3, 4, 5, 6, 7, 8			2, 3, 5, 6, 9			2, 5, 6, 9			2, 3, 6, 9, 10			2, 9, 11, 12		
Tracking[R]	7, 8, 13, 14[b], 15[b], 16[b], 17[b]	18, 19, 20, 21, 22, 23, 24, 25, 26		27	28	29‡, 30‡			31, 32, 33, 34, 35, 36	10, 37, 38, 39, 40, 41		42, 43, 44, 45			46, 47, 48, 49, 50, 51, 52, 53, 54
Colony size & location[R]	55, 56			55, 57, 58, 59, 60, 61, 62			55, 62, 63, 64, 65			55, 66					67, 68, 69, 70, 71
Foraging range[R]	13	15, 16, 20, 25, 72, 73		27	28	29‡, 30‡			31, 32, 36		73				47, 48, 54
Habitat associations[R]	2, 13	14		2	28, 74	29‡, 30‡	2		32, 75	2, 10, 39	76		2		48, 53, 54, 77, 78
Age at first breeding[N]		79, 80		81					82	83, 84					85
Productivity[R]	86, 87, 88, 89	90, 91		92	93, 94, 95	96, 97‡, 98,	101, 102, 103		104	86, 105, 106, 107,					111, 112, 113

						99‡, 100‡				108, 109, 110					
Survival^{R}	114	79, 80, 115, 116, 117, 118		60, 114	94, 117, 119	120, 121‡	122		104, 123, 124, 125	84, 126, 127, 128, 129					85, 130
Body length^{G}			131			131			131			131			131
Wingspan^{G}			131			131			131			131			131
Flight type^{G}	89	132, 133	134, 135		136†	135		136†	134, 135	137		135, 138‡			134, 135
Flight height^{G}	139	140, 141	134‡, 138‡, 142†		136†, 139	142†		136†	142†	139, 143	140, 141	134, 138‡, 144		139†	134‡, 138‡, 142†, 145
Flight speed^{G}		15, 16, 23, 25, 132	134‡		28	29‡, 30‡, 134‡			134‡, 146‡	37, 137		42, 45, 134‡, 147			47, 134‡
Nocturnal activity^{R}	89†	14, 16, 23, 25		27†		148†	149†		150†	41, 151†, 152†, 153					53, 154
Adult body mass^{N}	89, 155	156, 157, 158	131, 159	160, 161	94, 162	131, 159, 163, 164, 165, 166	161, 167		131, 159, 168			131, 159			131, 159, 169, 170

Chick mass/growth rate^{R}	89	80, 157, 171, 172, 173, 174, 175	176	177, 178, 179	94, 180		102		181, 182, 183, 184	185, 186, 187					
Length of breeding season^{R}	89	24, 80, 157	131		93, 94	96, 131	102		131, 188	189		131			131, 169, 170
Energy requirement – adult^{N}	190	191	176	92, 192, 193	191			191	194, 195, 196, 197, 198, 199, 200, 201, 202, 203, 204, 205	190, 206, 207, 208	191	195, 209, 210, 211		191	195, 205, 212
Energy requirement – chick^{N}			176						183, 205						
Maximum brood size^{G}			131			131			131			131			131
Dive depth^{R}		19			213†	214‡				215					77, 216

Avoidance^G	217	218										218, 219, 220			
Non-light attraction^G	221†, 222		223‡, 224‡, 225‡	221†		223‡, 224‡, 225‡, 226‡	221†		223‡, 224, 225	221†		223‡, 224‡, 225‡, 227	221†		223‡, 224‡, 225‡
Light attraction/ disorientation^G	222, 228	229, 230, 231, 232	233†, 234, 235	222, 236, 237,		233†, 235‡, 238†	222		233†, 234, 239, 240, 241, 242, 243, 244†, 245			234			233†, 234, 246†

Notes:
Parameter superscripts refer to whether a parameter is likely to vary at a regional (R) or national (N) scale or is expected to be similar globally (G).
Superscripts elsewhere identify data source limitations:
† Qualitative data or expert opinion
‡ Data for closely related taxa (including Mediterranean Storm-petrel)
[a] 'World' includes general references or when unclear where data from geographically.
[b] These references relate to birds tagged at colonies outside of Scotland, but that used Scottish waters.

Whether or not an item was freely publicly available at the time of the review is stated at the end of each reference in the bibliography below as (Yes) or (No).

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