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Better estimates of collision mortality to black-legged kittiwakes at offshore windfarms

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OWSMRF
Offshore Wind Strategic Monitoring and Research Forum

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Summary

This report presents a summary of existing evidence, and potential research opportunities, to inform assessment of cumulative collision with offshore windfarm of black-legged kittiwakes. This work has been undertaken on behalf of The Offshore Wind Strategic Monitoring Research Forum (OWSMRF) (https://jncc.gov.uk/our-work/owsmrf/). OWSMRF is an industry-led collaborative forum that aims to identify and develop research to fill critical knowledge gaps in our understanding of the impact of offshore wind development on the marine environment.

OWSMRF stakeholders identified cumulative impacts on kittiwakes as the priority need for improving understanding of offshore windfarm environmental impacts. Improving understanding of collision-induced mortality was identified as one of the key knowledge gaps in this area. JNCC has collaborated with experts in this field to provide a summary of potential research which might help to reduce uncertainty in estimates of collision-induced mortality. This report provides a summary of existing relevant research and evidence, and research opportunities that have been identified to help reduce the uncertainty.

The research opportunities (ROs) suggested as potentially very useful and presented in this report are:

RO1.1: strategic collision monitoring project; deploying turbine monitoring systems (likely to be primarily camera-based system such as DTBird, WTBird or similar) across a range of turbines and windfarms to collect empirical data on kittiwake collision rates. This would allow validation of CRM approach and empirical cumulative effects assessment. This project would need to be undertaken in stages:
RO1.1a updated review of technology to detect collisions with turbines (as in Dirksen *et al.* 2017). This may need to include a field test if promising technology has not yet been deployed in offshore situation.
RO1.1b power analysis and strategic framework for deployment of monitoring systems. RO1.1a and RO1.1b combined would maximise the value of such data collected across windfarms.
RO1.1c deployment of systems across a range of turbines and windfarms to collect empirical kittiwake collision data.

RO1.2: coordinated strategic GPS tracking programme across multiple colonies. This would include accelerometer deployment. Such a coordinated programme would improve understanding of spatial and temporal patterns in distributions and behaviour in and around windfarm, and how this evolves over the course of a consent: pre, during and post construction.

RO1.3: concurrent collection of flight height data using multiple sensors. This would improve understanding of accuracies, biases, and comparability of flight height information collected by a variety of different methods. This would inform accuracy of various available flight-height data to improve precision in resulting collision risk estimates.

Further research opportunities that could reduce uncertainty in estimates of kittiwake mortality at windfarms are described briefly:

- **RO1.4:** analysis of existing GPS tracking data to understand variation in risk across turbines.
- **RO1.5:** analysis of pre and post construction density data to inform macro-avoidance, and how windfarm design might influence this.
- **RO1.6:** analysis of pre and post construction GPS data to understand if/how kittiwakes alter behaviour in response to windfarms.

- **RO1.7:** assessing whether kittiwakes respond to changing wind conditions (turbine wake effect) within windfarms.
- **RO1.8:** tagging of juvenile birds to compare their collision risk to that of adults.
- **RO1.9:** GPS tracking to complement EOWDC bird avoidance study; providing bird movements over a broader spatial scale for comparison with EOWDC data collected within a functioning windfarm.
- **RO1.10:** strategic LiDAR survey to provide flight height information at a broad spatial scale, to inform kittiwake sensitivity mapping.
- **RO1.11:** simulation study to assess how accurately transect-based density estimates capture flux through a windfarm.
- **RO1.12:** strategic (non-GPS) tracking study, as described in Black and Ruffino (2019), using a combination of VHF radio tags, PIT tags and colour ringing, deployed as to maximise the ability to obtain survival rates of kittiwakes which interact with windfarms versus those not interacting with windfarms.

Each RO alone could lead to improvements in understanding of cumulative collision risk across windfarms, and the degree to which uncertainty is reduced is likely to increase as more ROs are undertaken. Undertaking a carefully selected, complementary selection of these ROs could significantly reduce uncertainty in assessments of cumulative mortality of kittiwake from offshore windfarm deployment.

Contents

1 Knowledge gap

Offshore wind farms (OWF) are seen as a key part of efforts to combat climate change (Cook *et al.* 2018a; Snyder & Kaiser 2009). However, there are a number of significant concerns about the potential of these wind farms to have a negative impact on wildlife and biodiversity, particularly in relation to birds (Drewitt & Langston 2006; Gibson *et al.* 2017). To inform the planning process of the potential impacts of the effects associated with wind farms, detailed Environmental Impact Assessments (EIAs) and Habitats Regulations Appraisal (HRA) are required. EIAs assess impacts to the wider environment, whilst HRAs assess whether a plan or project will have an adverse effect on a Natura 2000 site protected under either the European Commission's Habitats Directive (Directive 92/43/EEC) or Birds Directive (2009/147/EC))

As the number of wind energy developments increase globally both onshore and offshore, the potential associated environmental impacts are receiving considerable attention, particularly avian impacts. This is of particular concern at the cumulative scale, i.e. considering impacts of windfarms combined rather than of individual developments in isolation.

As the scale of offshore windfarm development expands, the risk of reaching unacceptable levels of cumulative impacts increases. In order to undertake meaningful cumulative impact assessments, there is a need for improved understanding of how birds respond to offshore windfarms and how to quantify the risk to populations of concern. Without such information, decision making is necessarily precautionary, and there is a risk that offshore windfarms may not be deployed at sufficient scale to contribute fully to emission reductions targets and ambitions.

The potential impacts of wind farms on bird populations can be grouped into three main types: i) collision mortality; ii) displacement and attraction effects and; iii) barrier effects (e.g. Cook *et al.* 2018a; Vanermen *et al.* 2015). As part of the impact assessment process, the likely effects (e.g. collision and/or displacement effects) of a proposed windfarm on birds are estimated. Once the magnitude of these effects have been estimated, it is necessary to understand which SPA colonies (if any) these affected birds originate from, in order to then be able to assess the impact of these effects on the SPA population (for HRA assessments) and/or which wider population these affected birds are part of (for EIA assessments). Finally, population modelling is frequently used to evaluate the likely population response to reductions in survival or productivity predicted to occur, once the scale of effect and population linkages have been established (Cook *et al.* 2018a)

1.1 OWSMRF background

The Offshore Wind Strategic Monitoring Research Forum (OWSMRF) (https://jncc.gov.uk/our-work/owsmrf/) is an industry-led collaborative forum that aims to identify and develop research to fill critical knowledge gaps in our understanding of the impact of offshore wind development on the marine environment. OWSMRF was initiated by JNCC and six offshore wind developers: EDF-Renewables, Equinor, Innogy, Ørsted, Scottish Power Renewables, and Vattenfall.

The OWSMRF Developer Group agreed to support an initial pilot year during which the focus was on ornithology issues. Key stakeholders were asked to identify which species and knowledge gaps they saw as currently posing the greatest uncertainty in impact assessments for offshore wind development, and most likely to lead to uncertainty in decision making around offshore windfarm consenting in the next few years.

1.2 The OWSMRF process

OWSMRF uses a collaborative process to identify knowledge gaps and research opportunities to fill those gaps. The process involves consulting OWSMRF key stakeholders (RSPB, Natural England (NE), Scottish Natural Heritage (SNH), Natural Resources Wales (NRW), Marine Scotland Science (MSS)) on what species and knowledge gaps currently pose greatest consenting risk to offshore wind development in the near future. Following a review of what is already known about the species and evidence base, academics and other experts are invited to suggest research that would address those knowledge gaps. Finally, the key stakeholders are invited to review the proposed research opportunities, providing feedback on which they see as most beneficial. Offshore wind developers who are funding OWSMRF observe the whole OWSMRF process. This feasibility review describes one of the knowledge gaps identified by OWSMRF stakeholders (reducing uncertainty around estimates of windfarm collision mortality) and relating to this knowledge gap it provides a review of the current evidence base and a list of research opportunities to fill the knowledge gap.

1.3 OWSMRF Pilot Year

At a meeting on 2 May 2019, OWSMRF key stakeholders agreed that uncertainty around in-combination and cumulative impacts of offshore wind development on black-legged kittiwake (*Rissa tridactyla*) populations currently posed the greatest uncertainty.

Three priority knowledge gaps (KG) to inform cumulative/in-combination assessments were identified:

- KG1: reducing uncertainty around estimates of windfarm collision mortality;
- KG2: improving understanding of connectivity between OWF and SPAs;
- KG3: development of a CEA (cumulative effects assessment) database to facilitate efficient, standardised and transparent cumulative effects assessments.

The CEA effects database was decided by OWSMRF to be better pursued via other avenues, and a new project under KG3 is being developed which will look at improving confidence in modelling population consequences of windfarm effects.

1.4 Estimating kittiwake mortality at offshore windfarms

The first knowledge gap (KG1) relates to improved understanding of the collision risk of kittiwakes interacting with offshore windfarms, both at an individual windfarm and cumulatively across windfarms. Kittiwakes are thought to be sensitive to collision with offshore turbines (Bradbury *et al.* 2014), and given the wide-ranging nature of this species, individuals may be interacting with, and at risk of collision with, several windfarms both during a season and across seasons/life-cycle. It is possible to collect empirical data on the number of collisions within and across species onshore (e.g. carcass collection, (Smallwood 2007)) but this is much more difficult offshore. Recent attempts to record collisions at a functioning offshore windfarm (e.g. Skov *et al.* 2018) have shown some success but at a limited scale (a few turbines) with costly and resource intensive methods required. In addition, given the complexity of collision risk and dependence on windfarm design factors such as turbine number, rotor size and height above sea-level, information on collision numbers at existing windfarms do not necessarily directly inform understanding of collision risk at planned windfarms. Therefore, collision risk modelling plays a crucial role within offshore windfarm impact assessments for kittiwakes (and other seabirds). Information on collision rates at existing (offshore) windfarms can however inform the interpretation of such modelled risks as well as improve parameter estimates for future impact assessments, thus reducing uncertainty.

This feasibility review aims to identify a set of potential research projects that could be undertaken in the near future to address uncertainty in kittiwake mortality estimates at windfarms. It follows on from previous work looking to identify research priorities for improved understanding of ornithological issues relating to the expansion of the UK offshore wind industry, such as the Strategic Ornithological Support Services group (SOSS, https://www.bto.org/our-science/wetland-and-marine/soss), Collaborative Offshore Wind Research into the Environment (COWRIE), and more recently, commissioned summaries of research needs e.g. (Furness 2016) and the Scottish Marine Energy Research (ScotMER) evidence maps (https://www2.gov.scot/Topics/marine/marineenergy/mre/research). This review is informed by discussions with ecological consultants, SNCBs and academic/kittiwake/seabird research experts.

Input was sought from a consortium of key scientific expertise to help define potential research opportunities. This included expertise from British Trust for Ornithology (Niall Burton, Chris Thaxter, Liz Humphreys), RSPB (Aly McCluskie and Saskia Wischnewski, Lucy Wright), and University of Highlands and Islands (Elizabeth Masden) in addition to this report’s authors. This consortium held a (remote) workshop in order to identify projects that could be carried out in order to address some of the uncertainties associated with estimating and predicting kittiwake collision risk, to reduce uncertainty in cumulative kittiwake mortality assessments.

2 Existing evidence and understanding

As stated above, given the strong dependence of collision risk on specific details of a windfarms design such as number and spacing of turbines and various turbine design parameters, it is not enough to simply understand a bird species behaviour and density in an area and use observed collisions from a different windfarm to estimate a predicted collision rate. Some kind of adjustment to allow for windfarm and turbine design would be required. Predictive collision risk models (CRMs) are used which explicitly allow for these variations and make predictions for the expected number of collisions based on the proposed turbine design and the physical and behavioural characteristics of the species of concern.

There are several models available for calculating collision risk (see Masden and Cook, 2016 for examples and review), such as (but not limited to) the Band (2012) model (developed as part of the SOSS programme and the most widely used CRM in the UK), Desholm (2006) which includes information on prevailing wind direction and variability in input parameters, and Tucker (1996) which has been used to demonstrate how turbine design can reduce the number of birds colliding (Tucker 1996b). There is also a recently published CRM (Kleyheeg-Hartman *et al.* 2018) which uses empirical collision probabilities, therefore reducing the reliance on some parameters which may be difficult to measure (such as within-windfarm avoidance rates) (however empirical collision probability is currently also difficult to measure at an offshore windfarm), and a recently developed stochastic tool for implementation of Band (2012) (Masden 2015; McGregor *et al.* 2018)

Avian collision risk models are generally based on three main elements:

- Some measure of exposure, or encounter rate, usually via a measure of flux rate of birds through a rotor-swept area. This is usually estimated based on the density of birds within an area as well as morphometrics of the bird (e.g. wing span, body length and flight speed).

- Calculation of the probability of a collision occurring (assuming no evasive action or behaviour). This is generally based on the probability of a turbine blade occupying the same space as the bird during the time that the bird takes to pass through the rotor, and relies upon information on both bird and wind turbine characteristics such as bird morphometrics and flight speed, turbine rotor speed and size, *etc*.
- An understanding of bird avoidance behaviour [1].

The remainder of this review considers collision risk as being estimated with the aid of Band (2012) collision risk model, as Band (2012) or it's stochastic equivalent (MacGregor *et al.* 2018) are the methods primarily used within the UK, and increasingly so across Europe. The key parameters within these are common across all quantitative collision risk models (Masden & Cook 2016) and evidence needs to reduce uncertainty in Band (2012) and MacGregor *et al.* (2018) mortality estimates are likely to apply across most collision risk methods, although the precise sensitivity of each model to each parameter may vary.

2.1 Collision Risk Model parameters

The Band model (2012) comes in two forms: Basic and Extended, with the Basic model using a uniform distribution of birds across the rotor swept area, to calculate the proportion of birds at collision height (PCH), while the Extended model uses a flight height distribution (such as provided in Johnston *et al.* 2014) and accounts for the fact that birds are usually concentrated towards the lower edge of the rotor swept area (where collision risk is lower than in the centre of the rotor swept area). There is inherent uncertainty introduced to the model, depending on what form of flight height data is used in the model (i.e. whether Basic or Extended is used). While the Extended model is considered a more realistic model, it is potentially more sensitive to uncertainty, particularly in relation to flight height estimates (Cook *et al.* 2014). The original Band model was a deterministic[2] model. The stochastic[3] version of the Band model was created in order to further develop the application of the Band model and uses a simulation approach to incorporate variability and uncertainty (Masden 2015, and updated version with online interface McGregor *et al.* 2018). While the new stochastic models allow us to characterise some of the variability and uncertainty around cumulative kittiwake collision estimates, it doesn't allow for all sources of uncertainty. For example, Avoidance Rates used in the model may be based on empirical data from only one site and/or inferred from similar species. Whilst it might be possible to estimate standard deviations of avoidance rates based on the data collected at a site, it is not possible to quantitatively characterise the uncertainty inherent within basing this on only one site (and season, which might be tied to site because a species might be present within a site primarily within one season only).

There are four options for the Band (2012) or McGregor *et al.* (2018) model, and the determining factor for which model is most appropriate is available flight height data. These options are:

Option 1: basic Band model using site specific data for proportion of birds at potential collision height.
Option 2: basic Band model using generic data for proportion of birds at potential collision height.
Option 3: extended Band model using generic data for flight height distributions.
Option 4: extended Band model using site specific data for flight height distributions.

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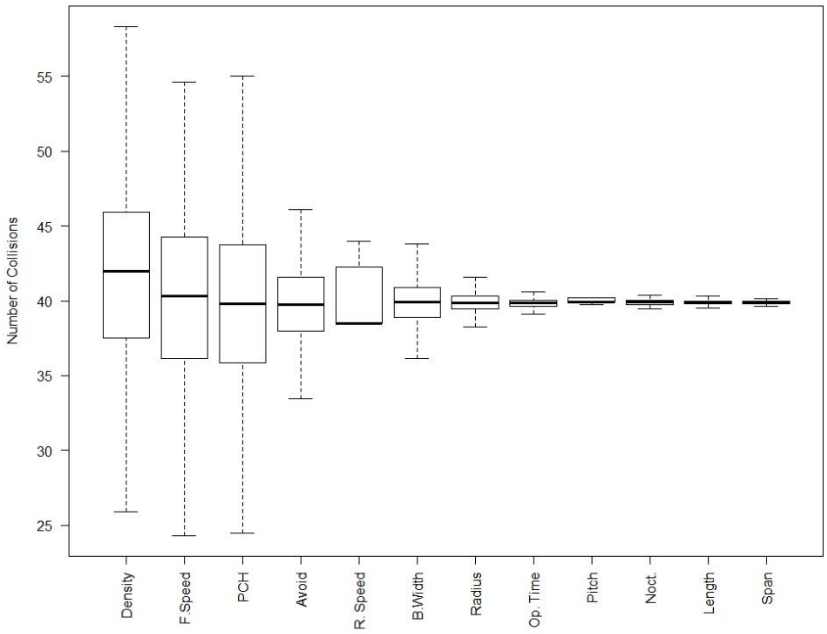
[1] However the model presented in Kleyheeg-Hartmen *et al.* 2018 combine the latter two of these elements.

[2] A deterministic model output is fully determined by the parameter values and the initial conditions.

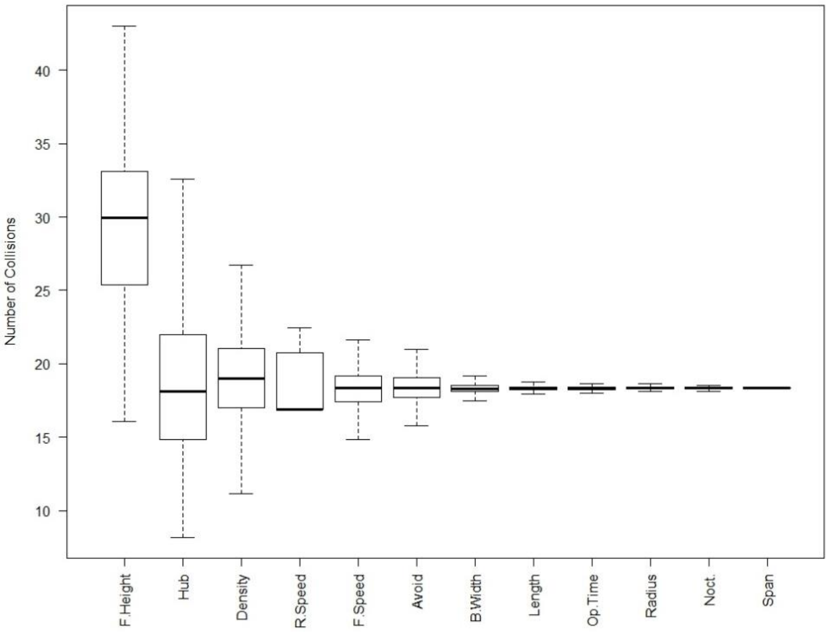
[3] Stochastic models possess some inherent randomness; the same set of parameter values and initial conditions will lead to an ensemble of different outputs.

Other than differences in the way flight heights are characterised, all four options are identical.

Masden (2015) highlights the importance of undertaking sensitivity analysis when assessing collision risk and provides a sensitivity analysis of a fictitious scenario, as an example (Figure 1). Although this is fictitious, it is a reasonable and realistic scenario and is based on kittiwake parameters that are used in impact assessments of real windfarm proposals. It therefore provides a useful indication of the strength of influence various parameters have on predicted kittiwake mortality. This suggested that density, flight speed, proportion at collision height (PCH) and non-avoidance rate (labelled as avoidance in Figures 1a and 1b but is actually non-avoidance, calculated as 1 – avoidance rate) all have similar scale on influence on predicted numbers of collisions for the Basic Band model. The input parameter that caused the greatest effect on the number of collisions for the extended model was flight height which had a considerably higher (median) influence than other parameters. Chamberlain *et al.* (2006) showed that if considering avoidance rate (rather than non-avoidance), then Band (2012) is far more sensitive to the avoidance rate than any other parameter.



a)



b)

Figure 1. Effects of variation in input parameters on predicted collision mortality of black-legged kittiwakes using the basic Band model (a) and the extended Band model (b). Density values are slightly skewed due to need for use of truncated normal distribution as negative density values are not possible. Plots taken from Masden (2015).

This sensitivity analysis was based on a ‘realistic parameter range’ estimated from available information.

Masden (2019) explored the importance of input parameters to a stochastic CRM (based on Band 2012, McGregor *et al.* 2018) (option 1) for lesser black-backed gull. Similar conclusions are reached as those from Masden (2015): Non-avoidance rate, bird density and proportion of birds at collision risk height all had equal effects on predicted collisions, with flight speed having a similarly large effect.

Although not a sensitivity analysis as such, work in Bowgen and Cook (2018) show the large impact using site-specific as opposed to generic flight height information has on estimated collisions for Kittiwake (Figure 2).

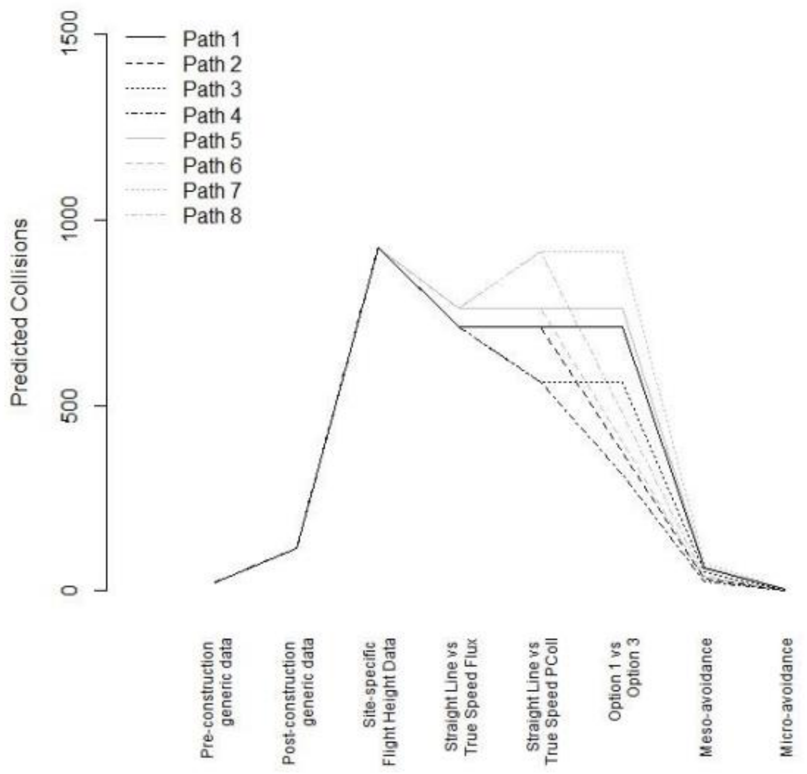


Figure 2. Change in predicted collision rate for kittiwake as model assumptions and parameters are refined. This is based on a gradual refinement of the Band (2012) predictions, based on moving from pre-construction densities and generic parameter information, assuming no avoidance, and in each step updating one aspect of the input parameters (e.g. moving from pre-construction to post-construction density information in the first step). Taken from Bowgen and Cook (2018).

2.1.1 Flight heights

Traditionally this has been estimated by boat-based observers or by digital aerial survey. Both have various sources of errors and inaccuracies. More recently, other methods of estimating flight height have been explored including GPS tags, optical laser rangefinders and LiDAR. Each method has pros/cons, limitations and biases and, so far, there has been very little work which has collected flight height data from multiple platforms concurrently to allow exploration of these biases and sources of error.

Generic flight height distributions and proportions of birds at potential collision height were estimated for Kittiwake and other species, using boat based data (Johnston *et al.* 2014) and digital aerial survey data (a combination of video and still methods) (Johnston & Cook 2016).

Each of the differing methods of flight height data collection provide data with apparently high accuracy, although the extent to which this has been tested and validated varies, and there has been little work comparing flight height distributions within site and across data collection methods, nor compiling flight heights across sites and data collection methods. A short summary of each method is provided here.

Optical laser rangefinders. These work by using a form of triangulation to estimate the distance to an object. The error associated with best available laser rangefinders has been estimated at approximately 2m (Borkenhagen *et al.* 2018). However, rangefinders can only be used during the day and rain or fog prevents successful measurements in poor weather conditions (Borkenhagen *et al.* 2018). Data were also found to be negatively biased against low and very high flight heights, with a bias against birds flying less than 10m above sea level (Borkenhagen *et al.* 2018). One recommended approach to reducing uncertainty is to collect visual observations of low-flying birds, but the risk of under-sampling of very high-flying birds remains.

Bowgen and Cook (2018) analysed flight heights collected as part of the Offshore Renewables Joint Industry Programme (ORJIP) Bird-Collision Avoidance project at an offshore windfarm in the southern north sea, and identified substantial differences between the flight height distribution estimated using laser range finders and the generic distributions presented in Johnston and Cook (2016) (for five species including kittiwake).They suggest that such differences should be treated with caution, as it is unclear the extent to which they reflect genuine differences between the two approaches versus bias in the data collection methodologies. However, they conclude that the results highlight the importance of using a robust and, ideally site-specific, flight height estimate in predicting collision risk, ideally estimated from multiple platforms concurrently.

LiDAR. LiDAR systems record the three-dimensional location of objects by emitting frequent, short-duration laser pulses. Each pulse is reflected off an object and the time it takes to return to the LiDAR sensor is recorded. The distance between the LiDAR and the object can then be calculated by multiplying the time it takes for the pulse to return to the sensor by the speed of light and dividing by two, in order to account for the return journey (Lefsky *et al.* 2002; Cook *et al.* 2018b).

Cook *et al.* (2018b) trialled the use of LiDAR for collecting data on flight heights of seabirds at sea. LiDAR and digital aerial photography were combined, with images being used to identify objects as birds and as far as possible to species, whilst LiDAR data was used to ascertain flight heights. LiDAR estimated flight heights were validated using drones flown at known heights (from GPS). This demonstrated that the height of birds in flight could be measured using LiDAR to an accuracy of within 1m. The flight height distributions derived in this study are biased against birds flying below 1-2m above sea level as a result of interreference close to the sea surface (i.e. it may overestimate the proportion of birds at greater altitudes for some species).

The study collected flight height information on 806 kittiwakes and used the data to derive continuous flight height distributions. Distributions obtained using LiDAR were very different from those obtained using digital aerial survey and boat-based survey data (Johnston *et al.* 2014; Johnston & Cook 2016). Without concurrent data collection, we do not know if such differences are due to differences in survey platforms and sources of error or bias, or due to spatial and/or temporal variation in flight heights. LiDAR offers greater precision in flight height estimates compared to boat or digital aerial methods but is relatively expensive to collect. The data presented in Cook *et al.* (2018b) come from a single location and are collected over a short time frame.

GPS loggers. Global Positioning System (GPS) loggers are small devices which can be attached to kittiwakes and other species to collect information on position in space at pre-defined intervals. They have been used to collect data on flight heights, and these height measurements were shown to have a similar pattern of flight height distribution to that of laser rangefinders (Borkenhagen *et al.* 2018). However, GPS loggers can only be placed on a limited number of breeding individuals, and so there is uncertainty around how representative these few individuals might be of the wider population. There is a need to match locations with digital elevation models in order to extract height above sea level.

For GPS loggers, error varies from approximately 3-14m depending on factors such as the sampling rate that is used (Borkenhagen *et al.* 2018; Thaxter *et al.* 2018) with a similar level of error for estimates derived from altimeters (Thaxter *et al.* 2016).

Barometric pressure loggers. As altitude increases, atmospheric pressure decreases. This relationship means that barometric pressure loggers can be used to estimate flight height, if attached to kittiwakes or other species. These have been used in conjunction with GPS loggers on breeding northern gannets (from Bass Rock) (Cleasby *et al.* 2015). Given the low weight of such loggers, it should be possible in theory to attach these to kittiwakes. Calibration is required, usually achieved by a tag left at the colony which records changes to pressure there for calibration purposes.

This sample produced a considerably greater proportion of birds flying at risk height than previously thought. Results of this study were compared to estimates based on LiDAR (Cook *et al.* 2018b) and showed clear differences. Although both methods are thought to be precise, differences could relate to sampling methodology with Cleasby *et al.* (2015) sampling only breeding individuals (and a small sample size of such) whilst the LiDAR data was collected in September when many birds are likely to have completed their breeding season, and will include non-breeding adults and immature birds, as well as potentially breeding birds from different colonies to that sampled in Cleasby *et al.* (2015).

2.1.2 Flight speeds

Kittiwake flight speeds for use within Band (2012) are usually based on the values in Alerstam *et al.* (2007) and Pennycuick (1997). ORJIP Bird-Collision Avoidance project (Skov *et al.* 2018) collected Laser-Range-Finder data which provided 3D locations of birds at known points in time, and from which flight speeds could be extracted. These were consistently lower than previously estimated generic flight speeds. This may be partly explained by foraging activity, often observed in videos recorded within the ORJIP project with 4.2% of daylight videos showing kittiwakes foraging inside the wind farm (Skov *et al.* 2018). The ORJIP data represents a single site with seabirds largely present outside of the breeding season, so there is a need to collect further flight speed data across locations and seasons in order to understand variability in speeds across space/seasons/behaviours, and if appropriate, provide updated generic flight speeds.

Work undertaken during 2019 by BTO on behalf of Marine Scotland Science has collated tracking data from several colonies for several species (including kittiwake) and is extracting flight speed information (amongst other information). This will provide a broader sample of sites but will cover breeding birds during breeding season only, and at fairly coarse resolution (ie if birds are not flying in a direct and straight line it may be difficult to accurately represent flight speeds). This work highlights the interaction between behaviour and flight speeds (e.g. slower flight speeds during foraging flights than commuting flights) as well as the interaction between wind speed and direction, and flight speed.

Masden (2019) shows the influence of wind direction on flight speed, with speeds in head winds much lower than those in tail winds, for lesser black-backed gulls. An ongoing, NERC-funded, BTO project has also shown the influence of wind speed and direction on lesser black-backed gull flight speeds (Cook 2019).

2.1.3 Avoidance behaviour

Studies of empirical mortality can usually provide information pertinent to assessment of avoidance behaviour and/or avoidance rates. Hence there is some repetition between this section and section 2.2 ‘empirical evidence of collision at offshore windfarms’.

It is worth noting here that there is a difference between empirical evidence of avoidance behaviour, and the ‘avoidance rate’ as used within Band (2012). The term ‘avoidance rate’ implies that this is a parameter which accounts for avoiding action taken by birds in order to avoid colliding with turbines (this can be either at a broader scale such as avoiding turbines completely, or as a 'last minute' adjustments to flight as approaching or crossing turbines). The avoidance rate as used within Band (2012) however, incorporates elements of error in relation to both the data used and the model itself, and does not only capture avoidance behaviour undertaken by birds. Therefore, although it is called an 'avoidance rate' in reality it will incorporate other sources of error and not only the error that would be introduced into collision estimates if we did not account for birds taking avoiding actions. Studies such as Skov *et al.* (2018) measure an avoidance rate based entirely on bird behaviour, and do not account for other sources of model error that might be incorporated within the avoidance rate as normally used within Band (2012). This means that the avoidance rates used within CRM are likely to be lower than those measured empirically, based only on bird behaviour, such as in Skov *et al.* (2018). The move towards quantification of variability around input parameters and production of a stochastic estimate of collision which considers this variability (such as in MacGregor *et al.* 2018) may account for some of the error in the data used, but this will not account for error in the model specification nor all error in the data.

A review of evidence for avoidance and analysis of avoidance rates, for a range species, provided a 'small gull' avoidance which kittiwake was considered a component (Cook *et al.* 2018a). There was limited data for kittiwakes included in the small gull avoidance assessment, including zero data for within-windfarm avoidance. Cook *et al.* (2018a) list some of the sources of uncertainty in relation to the avoidance rates produced:

- the avoidance rates only represent horizontal avoidance rates, and do not deal with uncertainty around vertical avoidance.
- a large component of the data comes from onshore wind farms, where flight heights and flight speeds are likely to differ from the marine environment.
- spatial differences in behaviour (i.e. whether the wind farm is being used for active foraging, or for commuting between foraging grounds and the breeding colony, e.g. see (Martin 2011).
- individual variation in avoidance behaviour, e.g. due to age and/or experience.

A collaboration of private and public sector bodies funded a Bird-Collision Avoidance project under the ORJIP programme. This collected empirical evidence of avoidance behaviour at an offshore windfarm in the southern North Sea (Skov *et al.* 2018). This used a radar/camera combination to assess tracks of birds within the windfarm and beyond windfarm perimeter (up to 3km), over several years. The project recorded collisions at observed turbines, as well as providing estimates of micro, meso and macro avoidance of key species (including black-legged kittiwake). This project provided the best available data on avoidance behaviour but limited to a single location where birds were largely thought to be transiting and with highest densities outside of the breeding season. Given the high levels of macro and meso avoidance (as expected, e.g. (May 2015), the sample size of birds interacting with the rotor-swept zone is low. The low sample size for micro-avoidance means that the resulting micro, and overall, avoidance rate, is very sensitive to even a single additional observed collision. Estimates of micro avoidance based on this data therefore have low confidence, as does the overall avoidance rate (because the overall avoidance rate is sensitive to changes in micro-avoidance rate).

Bowgen and Cook (2018) used the results from Skov *et al.* (2018) to assess the comparability and applicability of the 'empirical avoidance rates' derived from the ORJIP project in the more traditional (theorical) framework of the Band (2012) model, and presented overall avoidance rates for the key species, more suitable for use within Band (2012), based on comparison of predicted and observed collision rates.

The work undertaken by Skov *et al.* (2018) and Bowgen and Cook (2018) provided the first species specific kittiwake avoidance rates for use within each of the basic and extended Band model.

Work commissioned recently by Vattenfall will monitor flight patterns within and around the European Offshore Wind Deployment Centre (EOWDC) close to Aberdeen in the northern North Sea. This will use a high-performance radar/camera combination (similar to but more advanced than that used in the ORJIP study described in Skov *et al.* 2018) to collect 3-D tracks of bird behaviour in and around individual wind turbines and the wider windfarm, providing evidence of avoidance behaviour and collision rates during the breeding season for several species including kittiwake.

A similar study is currently ongoing at the Netherlands offshore windfarm Eneco Luchterduinen. This study uses radar/camera combinations both within and on the edge of the windfarm to investigate real-time collisions, flight patterns and avoidance in and around the windfarm.

Recent analysis of lesser black-backed gull GPS telemetry data (Thaxter *et al.* 2018) shows that, for two birds which used an offshore windfarm area, their 3-D overlap with the rotor swept volume was significantly lower than would be expected from a random distribution. Although this is one study of only two birds, it shows the potential for further analysis of avoidance using this kind of data.

2.1.4 Nocturnal Activity

Although Masden (2015) does not show particularly high sensitivity of predicted collisions to nocturnal activity scores, there are indications from ongoing work that breeding kittiwakes spend significantly less time in flight during darkness than would be indicated by the scores traditionally used in Band (2012) (loosely based on Garthe and Hüppop (2004) scores). The extent of this difference in activity levels is sufficient to have a considerable effect on predicted collisions. As suggested in Furness (2016), there are extensive existing GPS datasets which would allow quantification of levels of nocturnal activity relative to daytime, for twilight and darkness, and across latitudes and times of year. Work is currently ongoing by BTO on behalf of Marine Scotland Science, which has collated tracking data from several colonies for several species (including kittiwake) and is looking at bird behaviour and how this varies across weather conditions and time of day. Work currently being undertaking by McArthur Green and RSPB is also looking at nocturnal flight activity and implications for collision risk assessments.

2.1.5 Morphometrics

Although sensitivity analyses have suggested that Band (2012) is not hugely sensitive to wingspan or body length, extensive ringing data exists which may provide useful data on the extent of any spatial patterns in these (e.g. along a north-south gradient) or other patterns (e.g. differences between adults and juveniles) which might provide slight improvements to precision of collision rate predictions.

2.1.6 Density

In order to estimate collision risk, most models (including Band 2012) require an estimate of the rate of flux of birds through a turbine. The Band model currently calculates flux based on the density of birds within the windfarm footprint and the speed at which they travel through the windfarm. Density is usually derived from transect surveys such as digital aerial surveys which record stills or video information from planes which travel at a set speed and altitude along pre-determined survey transects. Images are then decoded and analysed to provide survey and species (to the extent to which individual species can be identified) specific density estimates. It is possible to estimate densities based on tracking data (e.g. as in (Cook 2019; Wakefield *et al.* 2017), but alternatively, it might be possible to estimate flux more directly using tracking data without the need to estimate densities.

2.2 Empirical evidence of collision at offshore windfarms

Across collision risk modelling methods, and especially in the marine environment, there is a lack of validation of predicted collision rates. There are several studies looking at how observed mortality compares with predictors of onshore collision risk, mostly using factors such as habitat suitability, passage rate and proportion flying at turbine height to indicate 'expected risk' rather than quantitative collision predictions (Ferrer *et al.* 2012; Heuck *et al.* 2019). Some weak relationships have been observed between some risk factors and recorded collisions, e.g. the numbers of some raptor species crossing the area (Ferrer *et al.* 2012). There is, as yet, very little empirical evidence of collision rates from offshore windfarms. Given the rarity of collision events that is expected on each individual turbine (Cook *et al.* 2018a), considerable effort will be required to collect useful quantities of data on collisions at offshore windfarms, across seasons and local environmental and weather conditions.

Empirical evidence can be used not only to give an indication of the actual scale of risk from offshore windfarms, and how this varies across space time and conditions, but also to improve our understanding of factors relating to turbine design and layout and bird ecology which influence collision risk. Such understanding will allow improved assessment of risk and reduced uncertainty during impact assessments, as well as facilitate meaningful mitigation to minimise risk.

2.2.1 ORJIP Bird-Collision Avoidance project (Skov *et al.* 2018)

This used a radar/camera combination to assess tracks of birds in three zones: rotor swept zone (+buffer), both within windfarm and beyond windfarm perimeter (up to 3km). Data was collected between July 2014 and June 2016, with equipment fitted to four turbines within Thannet Offshore Wind Farm. 12,131 separate videos showed seabirds in and around the windfarm, and six collisions were recorded. The project recorded collisions at observed turbines as part of micro-avoidance assessments. The number of observed collisions were very small, with only one recorded collision of a black-legged kittiwake, and two recorded collisions for unidentified gull, out of a total of six recorded collisions across the study. This low sample of collisions means that any single additional collision would have a substantial influence on the estimated 'collision rate' based on this data.

This project was located at a single windfarm in southern North Sea, which had seabirds present at high densities outside of the breeding season and which were thought to be transiting (but there is some evidence of foraging behaviour). The data quantity was very small for observed collisions and for micro avoidance, and resources did not allow a thorough processing and analysis of raw nocturnal data to assess comparability of collision rates/risk during low light or darkness conditions. As a result of these limitations and potential biases, the data may not be representative of typical collision rates for foraging, breeding adult kittiwakes.

2.2.2 EOWDC bird collision and avoidance study

Work recently commissioned by Vattenfall uses a high-performance radar/camera combination (similar to but more advanced than that used in the ORJIP study described in

Skov *et al.* 2018) to collect 3-D tracks of bird behaviour in and around individual wind turbines and the wider windfarm, providing evidence of collision during the breeding season for several species including kittiwake. This will provide data on bird behaviour leading up to a collision event, as well as data during the breeding season from an area known to be used by individuals from nearby colonies. This will be an important complement to the data collected in the ORJIP project (Skov *et al.* 2018) increasing the representativeness of collision data that is available.

A similar study is currently ongoing at the Netherlands offshore windfarm Eneco Luchterduinen. This study uses radar/camera combinations both within and on the edge of the windfarm to investigate real-time collisions.

2.2.3 Tracking data

There are various ongoing tracking studies which involve kittiwake (several are mentioned in this report in previous sections) and which might be able to provide some information on collisions. Given the low number of individuals that are usually tracked in such studies it is yet to be seen whether there is sufficient tracking effort to record collisions and provide useful empirical information on collision risk.

3 Gaps in understanding

There is a need for empirical evidence of collision rates for kittiwakes at different windfarms/in different contexts to provide a degree of validation to pre-construction modelled collision risk. This would provide both a means of assessing whether the current process for pre-construction assessments of collision risk (modelling collision risk based on windfarm design and kittiwake data/information) is appropriate, and of pinpointing in which situations predictions are most/least accurate (and therefore how predictions can be improved). There are studies occurring which can start to provide this information, but these are limited in scope and more studies which can provide this information are required.

Given that decisions on risk and on likely impacts of a proposal to kittiwakes where they are features of a protected area must be made before a windfarm is built, there will always be a need to be able to project (or predict) likely risk to as-yet unbuilt windfarms. Although more information on empirical collision rate can strengthen our confidence in such predictions and help us to understand what aspects of such predictions could be improved, there will still be a need to have accurate parameter estimates for use within predictive collision risk models.

Thus, we can design research projects which will provide data allowing us to improve precision of the most influential input parameters. If projects can be designed to provide information that will improve empirical estimates of collision and also provide data for key (most influential or most uncertain) input parameters, then they are likely to represent good value for money.

Uncertainty around input parameters can be due to either high levels of natural variation (stochastic uncertainty) or due to lack of information (systematic uncertainty). In both cases, additional information can either reduce uncertainty (systematic uncertainty) and/or improve understanding of causes of natural variation and provide data for further refinement of parameters (for example, if data shows that flight heights are consistently different depending on whether an area is primarily used for foraging, or for commuting, and sufficient data is available across both states, then behaviour-specific flight height parameters can be devised and applied as appropriate during CRM process).

Given that non-avoidance rate, bird density, proportion of birds at collision risk height and flight speed have a similarly large effects on predicted collision rates, and that available evidence suggests large uncertainties around these parameters and that (in particular for flight height and flight speed) some of this uncertainty may be down to differences in behaviour (e.g. commuting versus foraging) these are key areas where improved evidence can lead to reduced uncertainty in collision rate predictions.

4 Potential research opportunities to improve understanding

This section follows from collaboration with, and input from, a consortium of key scientific expertise. Discussions focussed primarily on methods that could improve estimates of mortality rates and factors that influence mortality rates, with the view that the data from such studies could also be used to improve parameter estimates for collision risk models. However, it was recognised that improved understanding of what makes particular turbines risky (e.g. turbine size and height or position relative to either bird flight paths or larger windfarm) and what birds do to minimise these risks, can lead to more precise estimates of collision across a windfarm, and therefore several of the projects described below would provide information relating to these factors. The first three ROs are those that the consortium of experts and SNCBs collectively thought would be worth describing in more detail than the remaining nine ROs, in order to provide information that is required to understand the relevance of the RO and what might need to be considered if taken forward. This does not mean that the nine ROs described in less detail are not important or cannot contribute to reducing uncertainty in kittiwake mortality estimates: rather this reflects that providing detail on all twelve ROs is outside of the scope of this review, but it was felt that these could be of relevance to the wider question and of interest to some stakeholders/developers, and so should be included in some form.

4.1 Priority research ideas/opportunities

This section provides information on research opportunities that the authors, consortium, and SNCBs thought were of the most direct benefit to reducing uncertainty in estimates of mortality to kittiwakes at offshore windfarms. These are therefore described in more detail. The remainder of the list is described in section 4.2.

4.1.1 RO 1.1 Strategic collision monitoring project across OWFs

Evidence need/rationale for doing this RO
There is a need for a better understanding of actual collision rates at offshore windfarms to both directly inform cumulative impact assessments and to validate collision risk modelling methods and approaches (and input parameters). Impact assessments use modelling to predict the likely rate of collision of kittiwakes with a proposed windfarm, but no empirical evidence is available for collision rates with offshore windfarms.

Collecting empirical evidence is inherently logistically difficult in the offshore environment because carcasses will not remain within the vicinity of a turbine to be observed/collected/counted. There are various technologies available which could, in theory, allow detection of collisions with offshore turbines, and therefore collection of empirical collision data within windfarms. These are costly, and have been only rarely deployed on offshore turbines, with very little evidence as yet available. The best evidence available so far comes from the ORJIP funded Bird Collision Avoidance project, Skov *et al.* (2018), but this constitutes a partial dataset from one windfarm with birds largely present outside of the breeding season and in relatively low densities.

Note that combined radar-camera systems as deployed in the ORJIP funded Bird Collision Avoidance project (Skov *et al.* 2018), can collect more extensive and detailed information on bird interactions with turbines than systems which do not include radar, but are more expensive. Large-scale deployment of the stand-alone camera systems (without the aid of radar, such as DTBird or WRBird) can provide information on empirical collision rates, micro-avoidance, and probability of collision (pCol) for those birds not undertaking avoidance behaviours at meso or macro scales. Due to lower cost per deployment, these can potentially be deployed at a larger scale covering more turbines and leading to larger sample size.

Work required
This has broken into three sub-ROs, which should be undertaken sequentially.

RO1.1a. Review of technologies
This is a desk-based review exercise, and it involves reviewing recent applications of systems listed in Dirksen (2017) and searching for more recently available systems which could be included in the review (including contacting technology providers, windfarm developers, statutory advisory bodies, consultancies and others to maximise the likelihood of capturing all relevant systems and experience). Information on each system that should be presented within the review would include:

- description of the technology/system
- deployment history (particularly offshore) and success at collecting quality data on bird collision rates, including smaller seabirds such as kittiwakes, and including the range of turbine and windfarm designs, sizes *etc*.
- availability
- deployment and maintenance requirements and logistics
- costs

It may need to involve a field-trial of potentially appropriate technology, if not sufficiently deployed within offshore environment to assess its viability.

RO1.1b. Power analysis and framework for deployment
There is a need to ensure that data collected to measure empirical collision rates covers the range of contexts for which there might be collision rates of concern; breeding, non-breeding and passage, foraging areas versus commuting areas, close to coast and further out to sea, *etc*. In addition, there will be limitations on which windfarms are able to host devices, where they can be positioned, as well as technical and logistical challenges with deployment and maintenance. Furthermore, their location within a wind farm is likely to influence the number of birds and range of behaviours they detect – e.g. a camera on the edge of a wind farm closest to the coast may detect more birds than one on the edge furthest from the coast. This sub RO will undertake a power analysis and develop a strategic framework in order to determine how systems can be deployed to ensure sufficient data over a range of behaviours are captured. This framework should consider how systems should be distributed between wind farms in order to capture a variety of different situations, and it would provide guidance for deployment of such systems within wind farms, accounting for factors such as the direction of flight, location of nearest colony, the size and layout of the wind farm and the limitations associated with deploying equipment on operational turbines, factors to consider when choosing equipment, sample size/effort considerations, processing and analysis requirements *etc*.

This is a desk-based exercise and will involve discussions with those involved in previous projects utilising similar technology, as well as a range of developers in order to fully assess the range of conditions and associated factors that would need to be considered.

RO1.1c. Strategic deployment to monitor collisions
Based on the outputs from ROs 1.1a and 1.1b, this would deploy technology to monitor collisions across a range of windfarms in order to collect a strategic dataset on empirical collision rates. Deployment would need to be for several years at each location to ensure sufficient coverage of between year variation in bird numbers and stochastic variability in resulting collisions. Data from existing or ongoing studies, such as the ORJIP Bird-Collision Avoidance project (Skov *et al.* 2018) and the ongoing EOWDC bird avoidance study, which although involve combined camera-radar systems aimed at collecting data on behaviours which influence estimated collision rates (in particular, avoidance behaviour), can also collect useful information on collisions and should be considered for inclusion in the strategic dataset and resulting analyses. As well as deployment, this sub RO will involve maintenance of equipment, processing of data and production of turbine-specific collision rates for collation into a strategic dataset. Ideally, it would also include further analysis of this data to assess how observed collision rates compare with expected.

Benefits/key outcomes
ROs 1.1a and 1.1b will ensure that resources are not focused in inadequate or inappropriate technologies and deployment locations, ensuring maximum gain for the resources required to undertake RO1.1c

If deployed, RO1.1c should provide several strands of information:

- empirical cumulative collision assessment
- validation of predicted collisions, and of overall collision-risk assessment methods and framework
- micro-avoidance observations
- probability of collision (pCol) for those birds not undertaking avoidance behaviours

This information can collectively be used to better understand the utility of using CRM within impact assessment, and combined with other studies (e.g. RO 1.2, and post-construction surveys) can inform flux rates and overall avoidance rates. It could also, potentially, be used to inform alternative CRM approaches which rely on collision estimates from existing windfarms in place of avoidance rates (Kleyheeg-Hartman *et al.* 2018).

Risks/inter-dependencies
There is a risk that technology develops within the timeframe of this RO and potentially suitable technology is not sufficiently assessed within RO1.1a for deployment within RO1.1c.

There is a risk that even with carefully planned deployment, available resources limit the sample size available, leading to uncertainty in resulting observed collision rates, and its utility for validation of CRM method and approach.

Predicted resources required to deliver this RO
RO1.1a. Review of technologies
As this is a desk-based study in the first instance, it is likely to be of restricted duration and cost. Familiarity with data of various types and format is required and experience of extracting, manipulating and combining data from disparate sources and in various formats is required.

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

If a field trial is required, costs will increase to MEDIUM or HIGH.

RO1.1b. Framework for deployment
As this is a desk-based study, it is likely to be of restricted duration and cost.

LOW (less than one year and £100,000)

RO1.1c. Strategic deployment to monitor collisions
Resources required will be better understood based on the outcomes of ROs 1.1a and 1.1b.

It is likely to be:
HIGH (several years and over £500,000), best achieved through collaborative approach.

4.1.2 RO1.2 Co-ordinated, strategic GPS tracking programme: multiple colonies

Evidence need/rationale for doing this RO
Collecting GPS tracking data from multiple colonies will give us a better understanding of spatial and temporal patterns in behaviour and how these may influence collision risk. Whilst such studies can be carried out by different research groups, it is important that such studies are co-ordinated to ensure consistency of approach and comparability of data for subsequent analyses. Such studies should use high frequency GPS tags equipped with accelerometers to ensure that fine-scale data are collected, and that behaviour can be inferred.

Work required
At present, there are planned, or proposed, Kittiwake tracking studies at several colonies within Special Protection Area (SPA)s over the next year. However, it is important to get a clearer indication of connectivity between kittiwake populations from SPAs and proposed, consented and operational wind farms and their behaviour within these areas. Additional tracking studies will be required in order to complement those already planned. These studies should use high frequency GPS tags equipped with accelerometers. At present, licensing restrictions mean that tags must be fitted using short-term attachment techniques (e.g. using glue to attach tags to birds' backs). Whilst they will typically remain attached to the birds for 2-3 weeks, this means that collecting data outside the breeding season is not possible. Consequently, as part of this study the use of harnesses to attach tags should be trialled, based on an approach used successfully with large gulls since 2010. If harness attachments prove successful this would enable longer deployment periods meaning it would be possible to collect data outside the breeding season and, potentially, from juvenile and immature birds. Collecting data from outside the breeding season and from juvenile or immature birds would enable us to understand how transferable existing data from breeding adults are to non-breeding kittiwakes. Furthermore, tagging studies must be supported over multiple breeding seasons in order to give a clearer understanding of how behaviour and distribution changes through time and in response to new wind farms becoming operational.

A strategic approach to colony selection is required in order to maximise the value of data collected across the individual studies (e.g. ensuring coverage across geographic range, colony size, proximity to windfarms). With tracking studies carried out at multiple sites, it is vital that the multiple research groups carrying out this work have the ability to co-ordinate the tagging work and collaborate on analyses. This will ensure that comparable data are collected at all sites and that they can be analysed using consistent methodologies. Such analyses will include assessments of bird flight heights and speeds and how these contribute to collision risk and, where data allow, assessments of birds fine-scale movements within operational wind farms. More broadly, analyses should also explore the distribution of birds from different colonies and how these overlap with wind farms, thus informing KG2 (improving understanding of connectivity between OWF and SPAs). They should also use approaches such as Hidden Markov Models[4] or accelerometery data to classify behaviour and explore spatial patterns in activities such as commuting and foraging. This would allow us to better understand how behaviour may influence exposure to collision risk. Analyses should be repeated over multiple years in order to demonstrate how behaviour changes in response to the construction of additional wind farms, and thus how cumulative risk increases with increasing deployment of OWF.

It is proposed that this is broken into three sub-ROs:

RO1.2a. This RO would involve a trial of harness attachment methods on kittiwakes to assess feasibility and suitability for kittiwakes.

RO1.2b. A review of existing tagging works and strategic plan for complementary studies. This would consider colony location, size, access and geography/location ‘type’ (e.g. direct access to open sea or enclosed, proximity to windfarms, *etc*). It would devise a set of requirements and guidelines for tagging studies to ensure comparability of resulting data and compatibility for a combined-analyses. It would set out a template for collaborative/combined analyses, both for data acquired from short-deployment, such as with tags glued to the backs of kittiwakes, and for data acquired from harness (i.e. longer) deployments.

RO1.2c. UK roll-out, over multiple colonies and years. Ideally this would include harness-mounted devices so that data can be collected over a longer period for each tagged individual. Ideally (and depending on outcomes of 1.2a) it would include deployment of harness attachments to acquire data for a longer period including outside of the breeding season.

Benefits/key outcomes

This RO will lead to an improved understanding of spatial and temporal patterns in kittiwake at-sea distributions and behaviour and how this may influence collision risk. Outputs from the analyses will provide valuable data with which to parameterise collision risk models, such as flight height distributions, flight speeds, behavioural changes within/outside windfarms, and potentially (but dependent on data resolution) avoidance rates. Fine-scale movement data will provide valuable insights into how kittiwakes interact with turbines, offering evidence-based assessments of avoidance behaviour. If harness trials are successful, this will enable us to collect data throughout the year and understand how key parameters for assessing collision risk, such as flight heights and speed, may vary across seasons. As a bonus, this RO would provide information which is relevant to KG2 by providing information on linkage between colonies and (some) potential windfarm footprints or zones.

Risks/dependencies

As a cliff-nesting species, there will be some health and safety considerations for personnel involved in capturing and tagging the birds. Thus, ensuring staff have appropriate training prior to undertaking this work (e.g. working at heights and rope-access) may be required. There is likely to be an inherent bias in the kittiwakes which can be sampled, due to variable access within a colony (e.g. central, or edge, portions may be more or less accessible, and this may influence the representativity of data collected due to variable condition and competitive advantage of kittiwakes in different locations within the colony). With any tagging project, there is a risk that birds may be negatively affected by the tag. Consequently, it is a key licensing requirement that there is a cohort of control birds against which impacts on

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[4] a statistical Markov model in which the system being modelled is assumed to be a Markov process with unobservable (i.e. hidden) states. They are known for their application in temporal pattern recognition including bioinformatics and behaviour recognition.

demographic parameters such as survival or productivity can be assessed. This will help determine whether data from tagged birds are likely to be representative of the wider population. However, it should be noted that GPS tags have previously been deployed successfully on this species.

Collecting data outside the breeding season will be dependent on the success of a harness trial.

Despite one of the aims of this project being to ensure data is collected strategically, there remains risks of lack of adequate coverage of important variables such as geographic range colony size and proximity to windfarms due to e.g. accessibility and logistics. Minimising this risk should be part of the planning stages and of RO1.2b.

Resources Required

RO1.2a. This is small-scale trial.

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

RO1.2b. This is a desk-based exercise.

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

RO1.2c. Some data are being collected and analysed as part of ongoing projects, reducing some of the resource requirements for this project. However, funding will be required in order to support studies that complement those already in place. Funding will also be required to support the strategic co-ordination of tracking projects and collaborative analyses of the resultant data. Ideally, any projects should be supported over multiple years in order to ensure a detailed picture of bird movements and behaviour through time could be developed.

MEDIUM (2 or more years and up to £500,000, potentially more depending on the number of colonies and individuals sampled).

4.1.3 RO1.3 Concurrent collection of flight height data using multiple sensors

Evidence need/rationale for doing this RO

Assessing the proportion of birds at collision risk height is a key part of determining collision risk. At present, estimates of species flight heights are available from a variety of different platforms including GPS tags, LiDAR and boat-based surveys. However, each of these approaches has its limitations and, with no concurrent flight height measurements from different sensors, there are debates over how representative, precise and accurate each of these are. As described in section 2.1.1, substantial differences have been found between the flight height distribution estimated using different sensors (e.g. flight height distributions estimated from laser range finders at a single windfarm site in Skov *et al.* (2018) differ from distributions presented in Johnston and Cook (2016) collected using digital aerial survey across several sites).

Work required

An initial review will be required in order to identify promising sources of flight height data. These are likely to include GPS tags, barometric pressure sensors, laser rangefinders, LiDAR and photogrammetry. It would be necessary to test these different sensors and, ideally, a range of models for each, in controlled conditions over water. This could potentially involve either drones or bird such as falcons which could be controlled by a handler. It would be necessary to identify a site that could be overflown safely by an aircraft and, with line of site for drone operators, falconers and people operating laser range-finders. It will be important to ensure devices are accurately calibrated on site, particularly in relation to time, in order to ensure data from across sensors can be accurately matched as part of the analysis.

Benefits/key outcomes
This project would offer, for the first time, the concurrent measurement of flight height data collected from a variety of different sensors. It would help us to understand the extent to which individual measurements, and resulting flight height distributions, may differ between different sensors and, consequently, the extent to which it may be possible to use data collected from one sensor alongside data collected from another when assessing collision risk. This would help reduce some of the uncertainty associated with the estimates of species flight heights, and therefore resulting collision risk estimates, used as part of the consenting process.

Risks/dependencies
As with any field-based project, there are likely to be health and safety implications associated with this work. In particular, flight safety is likely to be a key concern and limiting factor. This can be mitigated by carrying out the work during the summer when weather conditions are likely to be more conducive to carrying out this work and allowing a suitable time period for the work to allow for contingencies in the case of unexpected poor weather.

Resources Required
This would require careful logistical planning. A plane would need to be chartered with a suitable LiDAR and camera system and an area identified, ideally over water, where it could be flown. Multiple tags and laser rangefinders and multiple drone operators/falconers would be needed in order to obtain flight height estimates from moving objects equipped with tags.

LOW – MEDIUM resource requirements (could be done within 1 year and less than £500,000)

4.2 Additional research opportunities

This section provides information on further research opportunities that the authors, consortium, and SNCBs thought could contribute to reduced uncertainty in estimates of kittiwake mortality at windfarms. Although described in less detail than those above, it is still felt that these could contribute either to improved parameter estimates, or contextual information with which to interpret and understand quantitative impact assessments.

4.2.1 RO1.4 Analyse existing GPS tracking data: what makes particular turbines risky?

This project would make use of the wealth of kittiwake GPS tracking data that has been collected in recent years. GPS tags record bird positions in three dimensions, and some data can be at high resolution (frequent 3D location data points). The tracking data that have been collected to date cover a wide range of colonies, many of which are thought to have birds vulnerable to collision with offshore wind farms.

There are several elements that can be explored within this broad umbrella. Individually they provide data to improve parameter estimates, whilst collectively they can inform understanding of what makes particular turbines or windfarms riskier than others (e.g. turbine height and/or spacing, windfarm location and shape relative to colonies, predominant ecological function of area):

RO1.4a: Analyse existing GPS tracking data to better understand sources of variation in bird flight heights. Whilst there are concerns about the precision of flight height estimates from GPS, the error in these estimates can be overcome as part of the modelling process. By analysing these data, we could get a better understanding of sources of variation in kittiwake flight heights and, therefore, spatial and temporal patterns in the number of birds flying at collision risk height.

RO1.4b: Analyse existing GPS tracking data to better understand sources of variation in bird flight speeds. Whilst existing data is variable in terms of temporal frequency of location 'fixes', some datasets me be of sufficient resolution to explore flight speeds. Such analysis could improve understanding of sources of variation in kittiwake flight speeds and, therefore, spatial and temporal patterns in collision risk.

RO1.4c: Analyse existing tracking data in order to investigate spatial patterns in behaviour and assess how these may reflect collision risk. Collision risk is likely to vary between different behaviours. For example, it may be greater when bird's attention is focussed on searching for prey rather than travelling between colonies and key foraging areas. Consequently, there is a need to better understand spatial patterns in behaviour and how this influences collision risk. Analytical approaches such as Hidden Markov Models (HMMs) enable us to classify tracking data according to behaviour. This enables us to identify areas used for different behaviours such as commuting, foraging and resting. Analysis of existing tracking data would enable us to get a better understanding of spatial patterns in behaviour and where birds may be at greatest risk of collision.

It is likely to be most efficient to combine these elements into a single project which explores existing kittiwake GPS tracking data to increase understanding of spatial variation in behaviour and how this influences collision risk.

4.2.2 RO1.5 Analysis of pre-/post-construction density data: how does windfarm design affect macro avoidance?

To get a better understanding of avoidance behaviour at a macro (and meso) scale, we need to better understand how existing wind farms are affecting the distribution of birds. Some initial analyses carried out in relation to Egmond aan Zee and Princess Amalia Wind Park in the Netherlands suggested that windfarm factors such as windfarm shape and turbine spacing may influence birds' response to wind farms. Whilst there are challenges in comparing pre- and post-construction data, similar analyses would give us a better understanding of birds' avoidance behaviour and therefore expected collision risk.

This project would involve collating data on kittiwake distribution across existing offshore windfarms (both pre- and post- construction) and undertaking a coordinated analysis to identify the extent of macro avoidance behaviour of kittiwakes across existing windfarms and factors which influence macro avoidance rates (factors such as season, distance from coast, distance from colony, windfarm size, windfarm orientation, turbine spacing, primary kittiwake behaviour within/around footprint, *etc*).

4.2.3 RO1.6 Analysis of pre-/post-construction GPS data: do kittiwakes alter behaviour in response to windfarm?

Many of the RO's described above will provide information on how birds move within an operational wind farm, and how this affects their individual collision risk. For the purposes of assessing collision risk during impact assessment, collision risk needs to be estimated pre-construction. Therefore, it is important to understand how such behaviour changes from the pre-construction period. Consequently, as part of strategic tracking projects, it is important to identify sites where data can be collected during the pre- and post-construction periods and support long-term data collection at these sites. This RO would in the first instance collate existing tracking data that has been collected both before and after windfarm construction (within foraging range of the source colony) and analyse to look for ways in which behaviour changes post construction. If appropriate, it could then make recommendations for additional data that would need to be collected in order to test/validate initial conclusions.

4.2.4 RO1.7 Are kittiwakes responding to changing wind conditions within offshore windfarms?

The turbine wake effect changes airflow patterns within operational wind farms. It is likely that birds respond to airflow patterns in order to reduce the energetic costs of flight. Understanding how birds move within wind farms, e.g. do they avoid the more turbulent air behind turbines, would give us a better understanding of meso-avoidance. High resolution data from GPS tags gives us an opportunity to investigate this behaviour and relate flight patterns within operational wind farms to changing airflow patterns.

4.2.5 RO1.8 Tagging of juvenile birds: how does collision risk compare to that of adults?

At present, much of what we know about behaviour of kittiwakes from tagging studies is based on adult birds. Younger birds however, particularly when they first fledge, may have different patterns of behaviour (e.g. more erratic flight patterns). Tagging of juvenile birds with small GPS devices collecting data at sufficient resolution would enable us to assess whether behaviour is significantly different in young kittiwakes from that of adults, and how this might influence collision risk. It would improve understanding of what role learned behaviour may play in reducing collision risk when faced with novel objects such as wind turbines. This would allow a more refined assessment of overall collision risk of proposed offshore windfarms by allowing us to estimate age-class related collision risks.

4.2.6 RO1.9 High resolution tracking study to complement ongoing radar/camera data collection at Vattenfall’s European Offshore Wind Deployment Centre (EOWDC)

The EOWDC bird avoidance study offers the potential to collect data describing the fine-scale 3-D movements of high numbers of birds in the vicinity of offshore wind turbines. It is not possible to determine how representative these movements are of other birds in the area because these data are limited to the immediate vicinity around the turbines. A tracking study from nearby kittiwake colonies such as Collieston and/or Fowlsheugh would complement the data collected by the EOWDC bird avoidance study by describing bird movements over a broader spatial scale. This would allow an assessment of macro and vertical avoidance behaviours, as well as any changes in behaviour inside versus outside the windfarm; these might alter the collision risk from that which might be estimated based on pre-construction data only.

4.2.7 RO1.10 Strategic LiDAR survey: Flight heights, and sensitivity mapping

LiDAR is an effective tool for collecting flight height data at broad spatial scale and at population level. This kind of data is complementary to flight height data collected at high resolution for few individuals as is the case with GPS data. Collecting flight height data on a broad scale using LiDAR would allow:

a) increased understanding of variation in population-level flight heights across broad spatial and temporal scales, and how this compares with individual-level variation in flight height patterns across space and time. This would inform understanding of how to make the best

use of flight height information to produce precise collision risk estimates at the scale of individual windfarms.
b) in combination with broad scale density distributions across months (such as soon to be available from the Marine Ecosystems Research Programme, MERP https://www.marine-ecosystems.org.uk/Research_outcomes/Top_predators) development of kittiwake collision sensitivity maps showing where kittiwakes are present in high densities and flying at collision-risk height and therefore at most risk of collision. This would enable sites to be chosen which would minimise the overall collision risk to kittiwakes, in advance of detailed site-specific data collection.

4.2.8 RO1.11 Boat/digital aerial survey: better understanding precision in density and flux estimates

Flux rate is a crucial element of collision risk models, and at present is usually estimated based on density estimates from boat or digital aerial surveys. It is unclear however how accurately such estimates reflect bird density and distribution within a wind farm given individual bird movements and behaviour.

This RO would test the appropriateness of using density estimates from boat or digital aerial surveys using a simulation study. Survey vessels and aircraft follow pre-determined transect lines at pre-determined speeds, and thus can ‘survey’ from simulated kittiwake flight paths based on GPS tracking data. We could then investigate how frequently birds were detected on transects (e.g. never, once, more than once) and how this may affect density estimates.

This would improve our understanding of the power of transect surveys to accurately capture kittiwake flow through windfarms, and highlight in which circumstances density data may under, or over, estimate flux rates.

4.2.9 RO1.12 Strategic (non-GPS) tracking

RO2.3 within Black and Ruffino (2019) describes a feasibility study to explore using VHF radio tags, PIT devices, or colour ringing to provide detailed and accurate information on kittiwake movements across many individuals and across UK waters. The RO was described in 3 stages: desk-based feasibility review, trial deployment, and if appropriate, UK-wide deployment. The primary purpose is to provide information on connectivity between populations and windfarms. VHF and PIT devices rely on receivers placed at windfarms of interest to ‘re-sight’ tags. If multiple receivers were placed within a windfarm, these could be used to triangulate the location of birds and track their movements within and through the windfarm. If of sufficient resolution, such information could be used in much the same way as GPS tracking data to analyse kittiwake behaviour within windfarms. As pointed out in Black and Ruffino (2019), this RO, if deployed across UK, might also provide information on survival rates of kittiwakes which interact with windfarms versus those not interacting with windfarms which could be used to validate estimated collisions. Thus, if such survival information is sought to inform KG1, then RO2.3 should consider during parts a and b the extent to which this kind of data can be collected, and part c should consider in particular where to place receivers in order to maximise the value of survival data for this purpose.

4.3 Synergies/overarching notes

Section 4 has provided several research opportunities, which can each individually improve the precision of mortality estimates (empirically estimated and/or predicted). Given the difficulties in providing empirical estimates described in sections 2.2 and 3, research which provides information for validating, and improving, predicted collisions remains necessary. Predicted mortality is sensitive to several key input parameters and as such, individual ROs which address one or other of these parameters can improve precision in mortality estimates, whilst ROs which could lead to empirical estimates of mortality or validation of modelled collisions (e.g. ROs 1.1 and 1.2) can inform cumulative collision estimates across existing windfarms.

Appendix 1 provides a schematic which shows how different areas of research within the broad umbrella of kittiwake mortality at OWFs can complement each other (but without reference to specific ROs as described in the main report). For example it shows that camera/radar tracking at more sites (as in RO 1.1) could feed into a comparison of flight height data across multiple sensors (by providing 3D tracks of birds within a windfarm), as well as provide data which can be analysed alongside relevant GPS tracking data (RO1.2) (for example to assess how differences in behaviour pre-post construction, observed within the GPS data, translates to collision risk as assessed with the camera/radar tracking data).

5 Conclusions

This report has set out a series of twelve potential research opportunities (ROs) which were suggested and discussed amongst a consortium of experts in kittiwake mortality/collision estimates. Some of the projects described consist of more than one stand-alone piece of work, for example RO1.1 includes a review of available technologies and development of an overarching framework, as well as strategic roll-out and data collection at a large scale. Although these sub-ROs work together and inform each other, they could in theory be approached as separate pieces of work. By and large, however, each of the ROs presented in this report represent a single coherent piece of work of varying resource requirements. Many are entirely desk-based (e.g. analysis of existing of data), but there are several which involve further data collection (e.g. RO1.2 involves collection of GPS tracking data from several colonies, RO1.3 would involve several strands of data collection simultaneously). This represents an appropriate balance between making the most of any data that is collected or already available, and where required, collecting additional data to answer the questions that are unable to be fully addressed with existing data.

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

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8 Appendix 1

Flowchart produced by Saskia Wischnewski (RSPB).