Consideration of avoidance behaviour of northern gannet (*Morus bassanus*) in collision risk modelling for offshore wind farm impact assessments

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Foreword

Natural England commission a range of reports from external contractors to provide evidence and advice to assist us in delivering our duties. The views in this report are those of the authors and do not necessarily represent those of Natural England.

Executive summary

Northern gannet (*Morus bassanus*) (hereafter ‘gannet’) are susceptible to numerous anthropogenic pressures introduced by the construction of offshore wind farms (OWFs). Impacts include mortality from collision with turbine blades and habitat loss resulting from displacement from the OWFs’ footprint and out to some distance beyond it (the ‘buffer’). Both impacts have direct implications for mortality of individual birds and could have population level consequences. Stakeholders aim to predict these consequences by way of modelling exercises during Environmental Impact Assessment (EIA) and Habitats Regulations Assessment (HRA) processes. However, there is a need to fully understand the most appropriate ways of integrating gannet avoidance behaviour into the assessment process to support more robust assessment, decision making and management strategies.

In 2022, Natural England (NE) commissioned HiDef Aerial Surveying Ltd. (‘HiDef’) to explore specific issues of macro-avoidance and displacement associated with gannets and OWFs. On consultation with NE, the work was re-focused on macro-avoidance only. The aim was to deliver an evidence-based method to ensure macro-avoidance behaviour is appropriately accounted for in collision risk models of gannet at OWFs. This should provide more realistic predictions of the number of birds at risk of collision for EIA and HRA.

The literature review identified that the two types of macro-avoidance (barrier effects and displacement) could not be disentangled from existing studies. For the purposes of this report, macro-avoidance is defined as ‘*the fraction of birds in flight that are unlikely to enter the turbine array following construction, where there is a risk of collision with rotating blade*s’.

In the available literature for gannet, nine studies report macro-avoidance rates for at least ten OWFs that could be used in collision risk modelling. These values ranged from 0.617 to 1.000 and were determined using a mixture of survey methodologies (e.g., horizontal and/or vertical radar, GPS tagging studies, visual, boat-based, aerial surveys and before/after comparisons of densities), and for several very different wind farm sites. Calculating a robust, overall gannet macro-avoidance rate is therefore, challenging.

Using a quality scoring system for studies, an overall macro-avoidance rate for gannet was calculated using a weighted mean (0.8330 [95% CI 0.4410 – 0.9959]) and unweighted mean approach (0.8564 [95% CI 0.5349 – 0.9736]). In the weighted mean approach, quality scores and the reported macro-avoidance rates themselves were utilised as weights which incorporated study quality as well as some level of precaution. However, upon discussion with the project steering

group, consideration of available approaches, consultation of published literature and expert opinion, it was concluded that a macro-avoidance rate for gannet should be calculated based on a simple mean approach. Nevertheless, the role of individual-based models needs to be fully investigated as an alternative for deriving macro-avoidance rates.

To incorporate macro-avoidance into collision risk modelling, it was recommended that the input densities are corrected by the pre-determined or calculated macro-avoidance rates, and a ‘within wind farm’ avoidance rate is then applied in the collision risk model. This would involve very little effort in terms of the tools currently available (e.g., stochastic collision risk model). In this way, temporal effects (i.e., differences in macro-avoidance throughout a year) could be incorporated as well.

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1 Introduction

Evidence suggests that northern gannets (Morus bassanus) (hereafter ‘gannets’) are vulnerable to both collision and displacement/disturbance pressures associated with offshore wind farms (OWFs) (Furness et al., 2013; Cook et al., 2014; Dierschke et al., 2016). Whilst some evidence indicates that gannets avoid entering operational OWFs entirely (i.e., display macro-avoidance), a behaviour which reduces their vulnerability to collision (Krijgsveld et al., 2011; Dierschke et al., 2016), other studies show that the avoidance response varies between individuals and development sites (Peschko et al., 2021).

Wildlife macro-avoidance at OWFs is comprised of two effects. The first is displacement, where “a reduced number of birds is occurring within or immediately adjacent to offshore wind farms” (Furness et al., 2013). The second is barrier effects, where a movement corridor for birds has been effectively blocked by the installation of a wind farm. Both effects have biological implications on the overall mortality of birds but are challenging to differentiate in existing published literature. The other implication of these macro-scale effects is that both need to be accounted for when trying to make predictions on potential impacts of OWFs that have yet to be constructed. Currently, estimates of mortality due to operational OWFs are derived by summing the estimated numbers from independent assessments of displacement and Collision Risk Models (CRMs). In CRMs, estimates of collisions are currently adjusted by an avoidance rate (AR) (i.e., 1 minus the collision rate), which is meant to incorporate aspects of seabird biology to ensure reasonable assessments of possible impacts are presented. Avoidance rates may take account of micro- (evasive reactions of birds within the immediate vicinity of the turbine), meso- (avoidance behaviour within the OWF footprint), and macro-avoidance (avoidance outside the OWF).

This approach is likely to result in some double counting of predicted impacts, with some gannets being subject to both displacement and collision risk within impact assessments when, in theory, displaced gannets will not be at risk of collision. Other anomalies in approaches between assessment of collision and displacement impacts exist, such as that collision rates are based upon an estimate of flux through the turbines based on flying density and flight speed of each species (Band, 2012), whereas displacement is based on an assumption that the peak populations available for displacement are representative of the actual population that is eventually displaced. Assumptions are also made about temporal and spatial variability in flux rates for collision risk modelling which are not, so far, accounted for. This has potential implications for consenting risk and planning, due to the ramifications for both project specific, cumulative, and in-combination assessments that form part of Environmental Impact Assessments (EIA) and Habitats Regulations Assessments (HRA) respectively.

1.1 Aims and objectives

This work aimed to deliver an evidence-based method to ensure macro-avoidance behaviour is appropriately accounted for in CRMs of gannets at OWFs. This should provide more realistic predictions of the number of birds at risk of collision and outcomes of assessment at EIA and HRA. The objectives are to:

- Collate, and appraise, all available evidence on gannet macro-avoidance behaviour from OWF's, considering survey and analysis methods, site-specific factors (e.g., array size and turbine spacing) and compatibility of results;
- Present the findings of the review, and a suggested approach to deriving a macro-avoidance rate, to the project panel at a workshop for discussion and agreement;
- Compare and evaluate different approaches to incorporating this macro-avoidance rate, and any associated uncertainty, during estimation of collision impacts;
- Detail the relative advantages and disadvantages of proposed methods and suggest which would be most appropriate for use in OWF impact assessments; and
- Suggest an approach or method for applying corrections to existing impact estimates for projects considered in cumulative and in-combination assessments.

The relationship between the different elements of collision avoidance behaviour, macro-avoidance effects and impacts are complex. An explanation of the terminology used in this document is provided in Table 1.

To answer the aims of the study, a systematic review of the literature was conducted to collate and assess all available evidence on gannet macro-avoidance behaviour at OWFs. All studies relevant to the scope of the study were then assessed through a quality scoring system to evaluate their contribution to deriving a macro-avoidance rate for gannet. The final ranking allowed identification of the most appropriate studies, which were then used in further analysis to derive macro-avoidance rates using an unweighted and weighted mean approaches.

Table 1: Explanation of different terms used in this document and their measurement

Term	Explanation and definition	Measurement
Macro-avoidance	We define macro-avoidance behaviour as the fraction of birds in flight that are unlikely to enter the turbine array following construction, where there is a risk of collision with rotating blades. It comprises birds that would otherwise have undergone normal activities within the OWF footprint, such as feeding, searching for food, resting, maintenance behaviour etc. It also includes birds that would otherwise be flying through the OWF boundary to reach other areas of habitat.	The effect is measured by multiple methods: remote sensing of tagged birds, direct tracking, radar, visual observers, pre- and post-construction surveys comparing densities/abundance/distribution. These measures are generally focussed on flying birds only, but could, less precisely, include sitting birds as well.
Meso-avoidance	Meso-avoidance behaviour takes place within the OWF boundary. It consists of changes in spatial distribution to ensure that approach to individual turbines does not occur. Such distribution changes can occur in three dimensions.	Meso-avoidance is measured using the same methods as for macro-avoidance, although when using studies of post-consent monitoring of distribution, more precise spatial locations of individuals are required than for macro-avoidance measurement.
Micro-avoidance	Micro-avoidance behaviour takes place within the immediate vicinity of turbines and represents evasive behaviours that take place when a bird might be on a flight path that would result in it flying through a turbine and potentially colliding with the blades.	Measurement of micro-avoidance behaviour have been attempted using radar studies, direct observations, and remote sensing by a combination of optical and radar sensors.

Term	Explanation and definition	Measurement
Displacement effects and displacement rates	Displacement effects are a functional change in habitat use. Displacement occurs where birds cannot access areas previously exploited, leading to an effective loss of habitat. It is generally analogous to macro-avoidance behaviour in that it does not discriminate between loss of habitat and barrier effects. Displacement effects, unlike macro-avoidance, can occur outside the OWF boundary and can be applied to flying birds or more usually to all birds. Displacement effects are potentially used twice in EIA and HRA: displacement rates are a measurement that are a component part of macro-avoidance behaviour used in CRM and as a displacement impact in its own right. The way these two impacts are measured has a bearing on whether in-combination impacts are over- or under-estimated.	Measures of displacement (displacement rates) rarely discriminate between displacement and barrier effects. To all intents and purposes, displacement rates can be used as measures of macro-avoidance because both measure the difference in abundance of individuals to which meso- and micro-avoidance rates can be applied in CRM. However, for displacement effects to be usable as a measure of macro-avoidance in CRM, only the displacement effect that takes place outside the OWF boundary should be used (i.e., no buffer applied), ideally for flying birds only.
Barrier effects	Barrier effects are associated with anticipatory evasion, of an OWF, affecting the movement of migrating and commuting birds between breeding colonies and foraging areas.	Obtaining empirical evidence for barrier effects requires disentanglement of displacement effects. Such evidence will likely only be feasible from individual tracking studies using radar, GPS tagging or visual tracking.

Term	Explanation and definition	Measurement
Collision risk modelling (CRM)	CRM is an estimated prediction of the number of collisions that might take place at a planned OWF, usually as part of the EIA and HRA processes. The numbers of predicted mortalities might also be used in cumulative and in-combination assessments.	In the UK, the methods derive from Band (2012) which adapted onshore methods to account for difficulties in measuring flux rates at OWFs. The predictions use a snapshot of flying bird density obtained from field data, generic flight speeds and either empirical or generic flight heights for each species to estimate the flux rate through each wind turbine, then use a range of physical characteristics of the turbines, location, and species to predict the proportion of these flights that might be expected to result in a collision if no avoidance were to take place. These are finally corrected to produce more realistic estimates of collision rates by combining macro-, meso- and micro-avoidance rates. The Band (2012) method has been further developed to take account of the stochasticity in the component datasets in the model (McGregor et al., 2018) and more recently undergoing adaptation for migrating bird species and better align with the Band (2012) methods.
Displacement impacts	Displacement is also identified as an impact during EIA and is the predicted outcome of a displacement effect. In impact	Displacement impact modelling can take place using individual-based models such as SeabORD (Searle et

Term	Explanation and definition	Measurement
	assessment, displacement is treated separately from barrier impacts, even though in empirical data collection, it is difficult to disaggregate barrier and displacement effects.	al., 2018) which rely on predictions calculated from flying and foraging behaviour data from tracked individuals from a specific location and calculations of energetic requirements of the populations from that location. Inevitably, this approach requires data that might not be available for a specific seabird colony or species and more commonly, a prediction is based upon a matrix of mortality outcomes based upon expert opinion. This second approach predicts the mortality rate from the mean of seasonal peak of population estimates within the OWF footprint and a buffer around it and assumes that the peak represents the maximum potential number of individual that might be exposed to the habitat loss and visual disturbance pressures of the OWF.

2 Literature review

A literature review was undertaken to collate and assess all available evidence on gannet macro-avoidance behaviour at OWFs. Following Cook et al. (2012), who define macro-avoidance as when birds do not enter the area bounded by the outer turbines of the array, macro-avoidance in this report is defined as 'the fraction of birds in flight that are unlikely to enter the turbine array following construction, where there is a risk of collision with rotating blades' (Table 1).

2.1 Methodology

A systematic review of online bibliographic databases was performed to identify relevant published reports, peer-reviewed and 'grey' literature. Primarily, two databases were used: Google Scholar (2004-present) and Web of Science (1997-present), with searches limited to English language studies for all years up to February 2022.

Keywords related to the subject such as 'avoidance rate' and 'barrier effects' were combined with keywords based on location such as 'Europe' and 'North Sea' to create phrases such as "offshore wind farm 'gannet' 'macro-avoidance' offshore wind farm OR avoidance OR rates North Sea" which could be used in advanced search tool functions within the databases. A full listing of these is provided in Appendix A.

Personal communication with leading experts further identified several 'grey' literature sources from existing OWF sites which were found using the standard Google search function. Additionally, existing reviews on the topic including Dierschke et al. (2016) and Cook et al. (2018) were assessed to identify any other relevant sources of primary literature.

2.1.1 Inclusion criteria

The initial 'long list' of collated references was filtered by title, abstract or summary and disregarded if no information relevant to gannet and avoidance of OWFs was present. Full texts were then reviewed to determine whether the information presented was directly applicable to the project, at which point the text was marked to be brought forward for appraisal. Ultimately, 43 literature sources were deemed applicable to the current scope of work and details of these were extracted into a database, which can be added to as new information becomes available (supplied in HC0071-101-03_NE_LiteratureReview_20230202). From all sources, only one study outside of the North-East Atlantic (east coast USA; Goodale and Milman, 2020) was identified, limiting the scope of the current project to European gannet populations.

Each literature source was assessed through a three-step quality scoring system, outlined in Table 2, to evaluate their contribution to deriving a macro-avoidance rate for gannet. The first step consisted in an initial pass/fail gate (section A: Type of Study) to primarily determine if empirical data and estimates of gannet macro-avoidance were available. The sources (studies) that "passed" this first criteria then progressed to further scoring to assess spatio-temporal factors (section B) and data quality (section C). After scoring, those studies with the lowest score overall were deemed to be of better quality than those with higher scores.

In section B, a lower (null) quality score (QS) was given to studies that present species-specific temporal and site-specific spatial variations when assessing macro-avoidance, as this was thought to provide the most specific and quantitative information. In other words, studies that present spatial variation data specifically on gannets, over different seasons and/or different years in a same OWF site were preferred. Any study meeting only one of those criteria was given a score of 1.

In section C, multiple criteria were deemed essential to assure good quality data for the determination of macro-avoidance rates, which were then used to compare the various studies' quality. The criteria thought to be the most essential to draw qualitative conclusions on gannet's macro-avoidance were scored with the highest value if not met (Table 2, Section C). When a criterion was not applicable to a study, a score of 0 (n/a) was given as default (e.g., use of radar might not apply to all studies). If no information in a study enabled a specific criterion to be assessed, the high score was given, however, this situation was not encountered in this research. Sample sizes make a major contribution to the resultant uncertainty and accuracy of estimates of macro-avoidance, therefore, if a study reports a too small sample size (i.e., smaller than the median), it was given a score of 1. Moreover, as previously defined, macro-avoidance directly affects flying birds, consequently, if a study provides a macro-avoidance rate based on data collected from flying and sitting birds, it was given a score of 2. Similarly, and as mentioned by Skov et al. (2012), studies using radar equipment with less than 3km range were not thought to be able to present a full view of potential avoidance behaviour around an OWF and received a score of 1. Finally, it is estimated that a minimum of three years of post-construction monitoring is essential to determine any changes in gannet behaviour (Petersen et al., 2006; Leopold et al., 2011; Royal Haskoning, 2013), and any study presenting less than three years of data or presenting post-construction data only (i.e., did not compare to pre-construction data) were given a score of 2 and 3, respectively.

Each score value applied to the aforementioned criteria were arbitrarily decided based on the literature review and expert opinion.

Table 2: Quality scoring system for studies identified in the literature review.

Pass	A) Type of study
Yes	Empirical data collection on gannet macro-avoidance rates (displacement / barrier effects)
No	Empirical data collection on macro-avoidance rates (displacement / barrier effects) (not specific to gannet)
No	Review of existing evidence in peer reviewed documents on gannet macro-avoidance rates (displacement / barrier effects) but did not re-analyse the data
No	Review of existing evidence in grey literature on gannet macro-avoidance rates (displacement / barrier effects) but did not re-analyse the data
No	Expert opinion
Score	**B) Consideration of spatio/temporal factors**
0	Inclusion of species-specific temporal **AND** site-specific spatial variation data in displacement / avoidance assessment
1	Inclusion of either species-specific temporal data **OR** site-specific spatial variation data in displacement / avoidance assessment
1	Inclusion of either generic temporal data **OR** generic spatial variation data in displacement / avoidance assessment
1	Inclusion of generic temporal **AND** spatial variation data in displacement / avoidance assessment
1	No inclusion of temporal or spatial variation data in displacement / avoidance assessment
Score	**C) Quality of macro-avoidance / displacement outputs (score for each that applies, when a criteria was not applicable to a study, a score of 0 (n/a) was given as default)**
1	Sample size is smaller than the median for data type (in empirical study)
2	Macro-avoidance rate reported for all birds (not for flying birds only)
1	Detection range of less than 3km in radar study
2	Less than three years of post-construction monitoring data
3	Post-construction only data analysed in study based on bird density / distribution or gradient studies

2.1.2 Study methodologies

The literature review identified two types of macro-avoidance (barrier effects and displacement) which could not easily be disentangled from each other. Many papers/reports were reviews of existing empirical studies and did not present new analysis or data, while those presenting empirical data were often superseded by later iterations for the same monitoring project; in these cases, the study containing the most up to date and comprehensive data (i.e., spanning the largest timeframe) was preferentially used. Variation in the scales of avoidance rates was observed and noted, with some studies presenting a single measure of avoidance or separating macro- from meso- or micro-avoidance rates. For the purpose of this review, all papers identified were assessed, however, only empirical measures of macro-avoidance rate for OWFs for which data were available were used for further analyses (see Section 3), and neither combined measures of avoidance (including micro- or meso- avoidance), nor separated rates for micro- or meso-avoidance were used.

Ideally, displacement or macro-avoidance and barrier effects would be considered separately within this review. Cook et al. (2018) described that many assessments of seabird macro-avoidance do not distinguish between displaced birds and those exhibiting barrier effects, since both are identified by decreased birds within OWF arrays. However, discrimination of these effects does not alter their overall contribution to collision avoidance, and we have, nevertheless, appraised literature sources describing the effects of macro-avoidance, without distinction between barrier and displacement effects. Similarly, sources simply describing 'avoidance' were also considered.

Due to the difficulty of directly quantifying avoidance rates of seabirds at OWFs, methodologies based on bird behaviour are typically used to derive these values (Cook et al., 2014). The survey methodologies implemented to measure avoidance rates varied, with differences between survey occurrence, survey period and platform, ultimately leading to differences in data analyses and presentation. All these methods may be subject to biases and thus their overall value as a measure of displacement or macro-avoidance rates. We describe these here and explain why some studies might have higher QS applied to them and thus, potentially, lower weighting values.

2.2 Results

2.2.1 Assessment of survey methodologies

Summaries of the range of methods used to study macro-avoidance behaviour of gannets are given in Table 3. Below, we discuss some of the limitations of each of the approaches and the implications for resulting estimates of macro-avoidance.

Some studies did not separate macro-avoidance rates for flying birds from the ‘all birds’ (sitting and flying) measurements provided. While using avoidance rates for all birds is not necessarily different from those for flying birds only, it would be most relevant for a rate that will ultimately be used for calculating collision impacts for flying birds if the displacement rate were calculated only using flying birds. Consequently, regardless of the methodology used in the studies, macro-avoidance rates calculated on all birds were given a higher QS than any based on flying birds only.

Radar tracking studies

Much of the earlier literature on avoidance behaviour of migratory birds and seabirds reports research using horizontal radar and often vertical radar to track the flight paths of birds flying close to the OWF in question. These studies usually used observers positioned nearby to identify individual or flocks of birds by sight and sound to be matched to the radar tracks (e.g., Christensen et al., 2004; Krijgsveld et al., 2008, 2011; Skov et al., 2012). Skov et al. (2018) used a combination of radar and cameras to track objects detected by the radar and visual tracking of birds by observers. The deployment of visual observers with laser rangefinders to record distance, altitude, and flight paths of birds in combination with other described methods is relatively common to give three-dimensional data of individual birds. Visual observers can also be deployed to do panorama scans (e.g., Christensen et al., 2004; Krijgsveld et al., 2008, 2011), to support and calibrate radar counts and supply species composition, density and flight altitude and direction data.

Issues with data collection in adverse weather can introduce bias towards good weather data. High sensitivity of radar devices can produce ‘clutter’ during high winds, biasing data collection towards calm conditions (Krijgsveld et al., 2008, 2011; Skov et al., 2012). Measuring macro-avoidance via radar may also present limitations associated with the range of equipment, which typically extends up to 3km, despite macro-avoidance behaviour being exhibited by gannets up to 5km away from OWFs (Fox et al., 2006; Vanermen et al., 2016). Efficacy of laser rangefinders can also be compromised, as the high volume of metal within OWFs affects compasses and associated geo-positioning data (Skov et al., 2018). It is assumed that flying birds have not already responded to the presence of the OWF (i.e., that all of the birds being tracked do not begin avoidance before detection). While this assumption might not be met, it is assumed that this will not be common for gannets and thus no reason to score studies with small radar range higher than those with wider radar range. However, Skov et al. (2012) noted that a minimum range for horizontal radar should be set at 3km from all parts of the OWF, because this is the range in which macro-avoidance might be expected to occur.

GPS or satellite tagging studies

GPS or satellite tagging has been used to track flights of gannets from their breeding sites (e.g., Garthe et al., 2017; Warwick-Evans et al., 2018; Goodale and Milman, 2020; Lane et al., 2020; Peschko et al., 2021). Of these, only Garthe et al. (2017) and Peschko et al. (2021) had empirical data for flight tracks around OWFs, with the latter having been performed on many more individuals than the former at the same site.

The use of telemetry data is beneficial as they provide continuous data recorded in all weather conditions, with equal probability of detection in all conditions. Given sufficient sample sizes, this method may also be used to discriminate between individuals impacted by habitat loss and barrier effects. Unfortunately, sample sizes are often small, and may not be representative of other breeding adults at their colonies. Typically, there are not enough data to distinguish avoidance behaviour and calculate empirical values for macro-avoidance and avoidance at smaller scales.

Density studies

Aerial and boat-based surveys can be conducted to quantitatively assess variation in abundance and density pre- and post-construction (e.g., Petersen et al., 2006, 2014; Leopold et al., 2011, 2013; Mendel et al., 2014). Ideally, data collection spans multiple years to capture spatial and temporal variation (Petersen et al., 2006), with monitoring in some cases occurring for many years post-construction (Leopold et al., 2011; Royal Haskoning, 2013). This is beneficial as gannet abundance can be highly variable in some areas (Petersen et al., 2006, 2014). Some surveys such as these are referred to as using a Before-After Control Impact (BACI) approach, which aims to capture between-year variation in abundance and distribution compared to a control site (Vanermen et al., 2013), although this may be influenced by external factors other than the presence of the OWF (Leopold et al., 2011). Other studies use a modelling approach, where changes along a gradient in bird density relative to the location of the OWF are compared between pre- and post-construction (e.g., Webb et al., 2016; Welcker and Nehls, 2016; Rehfisch et al., 2014). Gradient-based studies compare distribution patterns between the pre- and post-construction periods for the OWF in question, such as Webb et al. (2016), and are known as Before – After Gradient (BAG) studies.

Data collection spanning multiple seasons is often prioritised to determine changes in bird behaviour associated with the presence of OWFs throughout breeding and non-breeding seasons. Concentrating data collection within seasons may also be beneficial to assess impacts during key periods for the species, as shown by Rehfisch et al. (2014), who collected data during the gannet autumn passage period in the southern North Sea. However, due to large variation in abundance between seasons, applying calculated within-season avoidance rates to other periods might not be appropriate for the rest of the year. Within the literature for gannet, a tendency towards data within the breeding season (March – September; Furness, 2015) has been observed, with generally more surveys conducted in these months rather than during the winter period (e.g., Mendel et al., 2014; Nelson et al., 2015; Peschko et al., 2021).

Diurnal fluctuations in abundance are likely to occur in and around OWFs, with some sites experiencing higher flight activity during the night or around dawn and dusk, especially during migratory periods (Krijgsveld et al., 2008, 2011). Most data collected by visual observers from boats and/or digitally from aircraft are not collected around dawn and dusk and none take place at night, possibly resulting in biased data. Compromised visibility due to adverse weather contributes further bias towards good weather data from visual observers (Leopold et al., 2011).

2.2.2 Displacement and barrier effects

Displacement and barrier effects have the potential to lower the carrying capacity of bird populations on local scales, with stronger avoidance of OWFs increasing the likelihood for barrier and displacement effects to occur (Krijgsveld, 2014). Barrier effects can be calculated by tracking birds using GPS loggers (Garthe et al., 2017; Warwick-Evans et al., 2018; Peshko et al., 2021). However, macro-avoidance rates used in CRMs do not need to discriminate between these two effects as they both need to be accounted for when estimating collision impacts.

Increased energy expenditure associated with longer trip times between breeding sites and foraging areas can negatively affect local bird populations. This has the potential to cause population-level effects on many species, however, the typical long flight duration and gliding flight technique often exhibited by gannets means extra costs associated with additional flight distance are likely to have relatively small overall impacts (Masden et al., 2010).

Calculated macro-avoidance and displacement rates

Nine literature sources provided ten empirical measures of gannet macro-avoidance rates (Table 3; Table 4).

Gannet were highlighted as a key species exhibiting a macro-avoidance response but avoidance rates varied between sites. The most conservative estimate (0.617; Webb et al., 2016), suggests a low proportion of gannets actively avoided the Lincs OWF, although variation in abundance between years was observed. The highest avoidance rates were found at Alpha Ventus and Robin Rigg OWFs (Mendel et al., 2014; Nelson et al., 2015) where no gannets were recorded in the OWF boundary, although they were present outwith OWF boundaries. Seasonal flux intensity is likely to impact macro-avoidance rates. Estimated macro-avoidance rates at the Greater Gabbard OWF were some of the highest rates for any species (0.9502) when calculated for the autumn passage period (Rehfisch et al., 2014). Changes in abundance at the site are likely to influence true macro-avoidance rates seasonally, making it difficult to directly compare rates from the autumn passage period to other seasons. Despite several studies indicating a seasonal effect, little empirical data is currently available, and since seasonality is not split per species in many studies, it is difficult to directly apply any evidence to gannets specifically (Krijgsveld et al., 2011).

The range of estimated macro-avoidance rates for gannet suggests macro-avoidance is site-specific and influenced by a variety of external factors. This highlights the need for increased monitoring at OWF sites and a standardised method of calculating macro-avoidance (Cook et al., 2014). The calculation of empirical avoidance rates such as by Skov et al. (2018) is beneficial as they are generated from site-specific offshore data.

Table 3: Summary information for studies including empirical data on gannet macro-avoidance of offshore wind farms (OWFs). This table includes all studies that have passed the Section A of the quality scoring assessment (see Section 2.1.1).

Authors	Year	Survey method	Survey effort	Seasonal coverage	Spatial extent	Analysis method	Data type
Krijgsveld et al.	2011	Radar, visual	• February 2007 - December 2009 • **Visual**: 53 days, 6 nights (405 panorama scans) • **Radar**: April 2007 to May 2010 continuously	All	OWF site (up to 5.6km radar range)	Flux of birds into OWF area + behaviour - difference in number of birds inside and outside of OWF area	Flying birds
Mendel et al.	2014	Boat-based, visual aerial	• **Pre-construction**: March - September 2000 - 2008; data from relevant EIAs • **Post-construction:** March - September 2010 - 2012; 8 boat-based surveys, 21 visual aerial surveys	Breeding season	OWF site + control area to the east	Modelled difference between pre- and post-construction (GLMs)	All birds
Nelson et al.	2015	Boat-based	• **EIA baseline:** twice monthly May 2001 - April 2002 (exceptionally only 1 survey in May and October 2001) • **Pre-construction:** monthly April - May 2003 and January - September 2004 (two additional survey in July 2007) • **Construction**: twice monthly January 2008 - February 2010 (exception no survey completed in November 2009) • **Post-construction**: monthly March 2010 - February 2015	All	OWF + buffer (unspecified area but covered 10 parallel transects of 18km in length and separated by 2km)	Modelled difference between pre- and post-construction (zero-inflated Poisson GAMMs with bird abundant per segment as	Flying birds

Authors	Year	Survey method	Survey effort	Seasonal coverage	Spatial extent	Analysis method	Data type
						response variable)	
Peschko et al.	2021	GPS tags	• 28 tagged incubating or chick-rearing gannets (over 2 years (2015-2016) during the breeding season - no months specified) • Gannets were from the island of Helgoland • GPS tags provided positions every 2-5min and up to 15-30min when low in battery	Breeding	n/a	Modelled time spent outside OWF area compared to within (GAMM-PPM)	Flying birds
Rehfisch et al.	2014	Digital aerial	• Four surveys (October 2014 - November 2014)	Non-breeding	OWF + buffer (unspecified area but each transect covered the OWF + 10km before and after the OWF)	Modelled gannet density with distance to OWF (density gradient)	Flying birds
Skov et al.	2012	Radar, visual	• September 2010 - May 2012 (pre-construction surveys 2008)	All	OWF site (up to 6km radar range used)	Modelled gannet density with distance to OWF (density gradient; GAMM) Before-After-Control-Impact statistical analysis (BACI)	Flying birds

Authors	**Year**	**Survey method**	**Survey effort**	**Seasonal coverage**	**Spatial extent**	**Analysis method**	**Data type**
Skov et al.	2018	Radar, visual	- **Visual**: July 2014 - June 2016 - **Radar**: August 2014 - June 2016	All	OWF site (up to 3km radar range)	Modelled density of tracks within and outside OWF area	Flying birds
Vanermen et al.	2016	Boat-based	- 2005 to 2016 (no months specified)	All	OWF site + 3km buffer + control areas to the southwest	Before-After-Control-Impact statistical analysis (BACI)	All birds
Webb et al.	2016	Visual aerial, digital aerial	- **Pre-construction:** November 2003 - October 2006 - **Construction**: October 2006 - March 2013 - **Post-construction**: April 2013 - March 2016 (monthly basis April - August 2015/ twice a month April 2013 - March 2015 and September 2015 - March 2016)	All	OWF site + 5km buffer	Before-after-gradient (BAG)	All birds

Table 4: Estimated gannet macro-avoidance rates and quality scores (QS) from studies collecting empirical macro-avoidance data for gannet, i.e., studies that have passed the Section A of the quality scoring assessment (see Section 2.1.1).

Authors	Year	Offshore Wind Farm	Country	Avoidance rate	Uncertainty	Total QS
Krijgsveld et al.	2011	Egmond aan Zee	Netherlands	0.64	n/a	6
Mendel et al.	2014	Alpha Ventus	Germany	1.000	n/a	6
Nelson et al.	2015	Robin Rigg	UK	1.000	n/a	1
Peschko et al.	2021	Multiple	Germany	0.890	n/a	7
Rehfisch et al.	2014	Greater Gabbard	England	0.9502	n/a	6
Skov et al.	2012	Horns Rev 2	Denmark	0.86	n/a	5
Skov et al.	2018	Thanet	England	0.797	SD 0.153	4
Vanermen et al.	2016	Thorntonbank	Belgium	0.990	n/a	4
		Bligh Bank	Belgium	0.820	n/a	4
Webb et al.	2016	Lincs	England	0.617	95% CI (25.9% - 100%)	3

2.3 Conclusions

Ten estimates of macro-avoidance were identified for potential application in CRMs, using methods and approaches described in Section 2. While the focus of this study is upon the use of macro-avoidance rates as a component part of overall avoidance rates for gannet used in CRM, more empirical data are needed to further develop displacement rates to assess impacts of habitat loss during EIA and HRA.

This review has identified multiple different approaches used to determine macro-avoidance rates. Unfortunately, it is unlikely that existing data from a relatively low number of OWFs will be representative or comprehensive enough to reveal sources of variation that might occur (e.g., diel, seasonal, annual). The inclusion of data collected during adverse weather may affect final estimates of macro-avoidance since wind direction and speed are likely to affect behaviour, highlighting the need for increased sampling during these periods (Skov et al., 2012; Furness et al., 2013; Goodale and Milman, 2020; Peshko et al., 2021).

Seasonality and associated variation in abundance is likely to affect calculated macro-avoidance rates. Lane et al. (2020) indicated gannet trip duration and distance varies seasonally, with marked differences during chick rearing, which could impact the number of birds in contact with OWF sites. Although the period of data collection was relatively long in some cases, the effect of seasonality was rarely a key objective, with many authors highlighting the need to include this in future assessment (Masden et al., 2010; Leopold et al., 2011, 2013; Mendel et al., 2014; Wade et al., 2016).

Habituation to the presence of OWFs has been observed. Although most prevalent for species such as cormorants and gulls (Vanermen et al., 2013, 2014), it is likely to also apply to gannet when considering their long life-histories and the timescale of operational OWFs. Skov et al. (2012) suggested habituation of gannet may be occurring at Horns Rev OWF, when comparing avoidance to Nysted OWF (86% compared to 99.1% respectively; Petersen et al., 2006). However, the large distance between these sites should be considered, since estimated avoidance rates have shown to be highly site-specific. Long-term monitoring at multiple sites will be necessary to determine if habituation is occurring, as it will ultimately alter avoidance rates through the life of the OWF. For gannets, this may be detrimental, since increased abundance within turbine arrays is likely to increase collision risk (Vanermen et al., 2021).

It is important to be able to take account of potential sources of variation in the macro-avoidance rates alluded to in many of these studies which may be used to find more appropriate overall avoidance rates used in CRM. By disentangling macro-avoidance from within-OWF avoidance rates, which are generally more difficult to collect during post-construction monitoring, it allows greater flexibility to apply different macro-avoidance or displacement rates to specific potential OWFs during the EIA and HRA process.

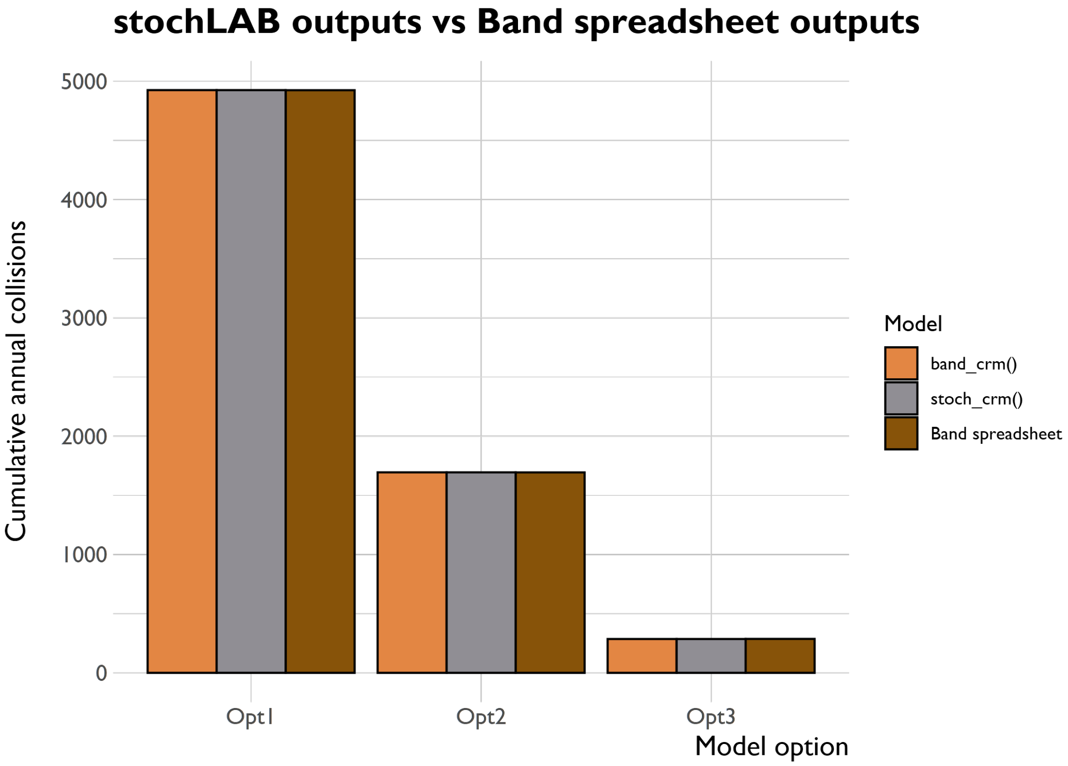
3 Investigating approaches to derive and account for macro-avoidance

Potential approaches to developing and incorporating macro-avoidance rates in the assessment process were developed and presented at a workshop on February 24th, 2022. The workshop was attended by representatives from APEM, BTO, HiDef, JNCC, MSS, Natural England, Natural Power, RSPB and Technical and Operated Assets (Appendix B). For the purposes of this work, barrier effects and displacement are not disentangled as there are few data available to be able to effectively discuss them separately. Here, the strengths and weaknesses of several options for deriving macro-avoidance rates are presented and discussed.

3.1 Options for deriving a macro-avoidance rate

All quantitative analyses were performed using v1.0.0 of the stochLAB package (https://www.github.com/HiDef-Aerial-Surveying/stochLAB; Caneco and Humphries, 2022) in R version 4.1.2. This package was developed by DMP statistics and HiDef Aerial Surveying Limited and contains functions to run the deterministic Band CRM (Band, 2012), and the stochastic collision risk model (sCRM) (Masden, 2015; McGregor et al., 2018). To demonstrate that the stochLAB package produces the same outputs as the Band spreadsheet, a sample collision risk scenario was run in the Band spreadsheet and then replicated using the band_crm() function. The stoch_crm() function (i.e., stochastic collision risk model) was also run with stochasticity removed (Figure 1).

Figure 1: Sample outputs between the band_crm function in the stochLAB package, the Band spreadsheet and the stoch_crm function (with stochasticity removed).



All data used in the simulations represent default biological (i.e., gannet) and wind farm parameters built into the sCRM package (Table 5). Approximate at-sea densities of gannet were obtained from HiDef digital aerial surveys and thus represent true estimates (Table 6). The actual magnitude of the data used in the simulations is not important, as mathematically, the collision risk models are linear (i.e., the data used in these simulations are simply illustrative, albeit based off true data).

Table 5: Biological and turbine/wind farm parameters used for simulations

Parameter type	Variable	Value
Biological parameters	Body Length	0.935m
	Wingspan	1.72m
	Flight speed	14.9m/s
	Nocturnal activity	0
	Proportion at collision risk height	30.00%
	Basic avoidance rate	98.79%
	Extended avoidance rate	92.61%
Turbine/wind farm parameters	Number of turbines	100
	Latitude	55.3
	Width	20km
	Tidal offset	-2m
	Number of blades	3
	Rotor radius	70m
	Upper blade height	175m
	Air gap	20m
	Blade width	6m
	Rotation speed	7m/s
	Pitch	10deg
	Mean wind speed	10m/s

Table 6: Monthly parameters used in the stochastic CRM simulations

Month	Mean and (standard deviation) of density (birds/km^2)	Operational time (%)	Mean downtime (%)
January	0.500 (0.014)	95	3
February	0.550 (0.011)	95	3
March	0.600 (0.050)	95	3
April	0.700 (0.153)	95	3
May	0.900 (0.151)	95	3
June	1.000 (0.170)	95	3
July	2.000 (0.300)	95	3
August	1.500 (0.189)	95	3
September	2.500 (0.300)	95	3
October	0.600 (0.083)	95	3
November	0.550 (0.097)	95	3
December	0.100 (0.007)	95	3

3.1.1 Options

Two options were identified for deriving a macro-avoidance rate:

Deriving an avoidance rate using published studies

> The literature review identified ten values of macro-avoidance (Table 4) on which to base a revised value upon. An updated macro-avoidance rate could be derived from the following approaches:
>
> 1. Use a mean and standard deviation and give to the stoch_lab() function as a stochastic process;
> 2. A weighted mean based on quality of study;
> 3. Pick a single value or range-based on relevance to the area; and
> 4. Pick the conservative estimate.

Deriving an avoidance rate via modelling or comparative exercises

> Two modelling approaches used to inform displacement analyses might be applicable to deriving estimates of macro-avoidance for gannet. These are:
>
> 1. Individual Based Models (IBMs) (e.g., seabORD)
> 2. Density surface models

A pre- and post-construction abundance estimate would also provide macro-avoidance rates in the case that such data were readily available.

Strengths and weaknesses of each method are summarised in Table 7.

Modelling and/or comparative exercises for deriving new avoidance rates fell out of scope for this work and thus only the derivation of avoidance rates from published studies (point 1 from above) was explored quantitatively.

Table 7: Strengths and weaknesses of options for deriving macro-avoidance rates for gannet

Method	Description	Strengths	Weaknesses
Deriving an avoidance rate using published studies			
Mean and standard deviation	Calculate the mean and standard deviation of existing macro-avoidance rates from all studies that report a value and apply them in the CRMs.	• Simple to implement • Captures information from all studies	• Standard deviation would be very high leading to large confidence intervals in stochastic models • Mean heavily influenced by any outliers (i.e., due to only ten macro-avoidance rates available) • Currently limited sample size • Does not acknowledge uncertainty or quality of the studies
Weighted mean	Calculate a weighted mean of the macro-avoidance rates from all studies that report a value. This could be done by expert opinion, or through quality scoring of the studies.	• Simple to implement • Captures information from all studies • Acknowledges uncertainty and/or quality of studies • Weighting towards conservative estimates balances precaution with less conservative estimates	• Expert opinion challenging in terms of finding agreement • Methods based on arithmetic operations with ordinal quantities can lead to errors (Shavykin and Karnatov, 2020) • Currently limited sample size

Method	Description	Strengths	Weaknesses
Single value or range	Select an avoidance rate from the literature for a site that best represents the site being assessed.	• Avoidance rate possibly more representative	• Disagreement on avoidance rate used more likely • Challenging to identify which site is most representative • Unlikely to be able to extrapolate to other sites • Limited sample size means there is unlikely to be a value that closely represents the site being assessed
Conservative value	Select the most conservative measure of avoidance (i.e., the lowest value).	• Simple to implement • Provides the highest amount of precaution	• Lowest value in the literature (0.617) is very low compared to other values (potentially too precautionary)
Deriving an avoidance rate via modelling or comparative exercises			
Density surface models	Density surface models run through tools such as MRSeaPower (github.com/lindesaysh/MRSeaPower) could be used. MRSeaPower has a function to redistribute birds through a survey area, and this could be leveraged to generate a displacement rate.	• Generally, accounts for environmental stochasticity through density surface models • Statistically robust • Allows for simulations and uncertainty	• Complex to implement • Method has not been developed for this purpose and would have to be explored • Requires statistical specialists

Method	Description	Strengths	Weaknesses
Individual-based model (IBM)	IBMs (e.g., seabORD; Searle et al., 2018) could be parameterised to a set of colonies where life history parameters (i.e., survival rates, etc.) are known. Using simulations, those models would be tuned so a displacement rate is calculated.	• Accounts for environmental stochasticity through density surface models • Statistically robust • Allows for simulations and uncertainty • Uses biological information (e.g., bioenergetics) to make inferences on mortality • Method is well developed	• Moderate to complex to implement • Most sophisticated models are only available for limited species / colony combination (i.e., those that have been tracked) • Requires statistical specialists
Pre- and post-construction comparison	When comparable survey data have been taken pre- and post-construction of a development area, the population estimates can be compared to calculate an avoidance rate.	• Simple and accessible to most stakeholders • Uses straightforward data collection techniques	• Directly comparable pre- and post-construction data not often available for public use • Snapshot surveys (e.g., aerial surveys) do not capture avoidance behaviour

3.1.2 Results

Within the scope and timeframe of this work, a mean value and a weighted mean could be calculated, which are described in Sections 3.1.2.1 and 3.1.2.2. The sample calculations for both sections are completed only for options 1 and 2 of the sCRM for illustration, noting that the findings would be identical for outputs from options 3 and 4 due to the linearity of the model mathematics.

Mean and standard deviation

From the ten values in Table 4, the mean macro-avoidance rate is 0.8564 with a standard deviation (SD) of 0.1334. The sCRM uses a beta distribution to create a range of values from which to draw avoidance rates. The upper and lower confidence limits of a beta distribution with a mean of 0.8564 (SD 0.1334) would have a 95% confidence interval range of 0.5349 to 0.9736. However, this mean is based on a combination of studies that have used different assessment methods at different locations and perhaps most importantly, within different seasons. There were only two studies that covered specifically the breeding season and a single non-breeding season study that provided empirical estimates of macro-avoidance. These studies resulted in mean avoidance rates of 0.945 (SD 0.055) during the breeding season and 0.950 (SD 0.000) during the non-breeding season. A mean macro-avoidance rate of 0.818 (SD 0.140) is estimated from only those studies with year-round data collection; this value is lower than the seasonal specific issues due to the low estimates (apparent outliers) from Krijgsveld et al. (2011) and Webb et al. (2016). Justification for using the unweighted mean approach is discussed in Paragraph 51 below.

Weighted mean

Calculating a weighted mean was agreed during the February 24th 2022 workshop to be a potential approach to calculating a macro-avoidance rate. A weighted mean approach makes use of available data in the literature while also acknowledging the quality of those studies. To generate a weighted mean, the quality scores from the literature review (Table 2) were used to generate normalised values. The normalised values were subtracted from 1 to ensure the lower QS (i.e., the studies with higher quality) were given more weight (equation 1). These baseline weights were then divided by the macro-avoidance rate to put further weight on the more conservative estimates which built in a level of precaution in the estimate (equation 2). These values are summarised in Table 8.

$$\text{base weights} = 1 - \left(\frac{\text{QS}}{\text{sum(QS)}}\right) \tag{1}$$

$$\text{final weights} = \frac{\text{base weights}}{\text{macro avoidance}} \tag{2}$$

Table 8: Weights calculated for the weighted mean approach for calculating a macro-avoidance rate for gannet

Study	Macro-avoidance	Quality score	Base weight	Final weight
Krijgsveld et al. (2011)	0.64	6	0.870	1.358
Mendel et al. (2014)	1.000	6	0.870	0.870
Nelson et al. (2015)	1.000	1	0.980	0.980
Peschko et al. (2021)	0.890	7	0.850	0.953
Rehfisch et al. (2014)	0.9502	6	0.870	0.920
Skov et al. (2012)	0.86	5	0.891	1.036
Skov et al. (2018)	0.797	4	0.913	1.146
Vanermen et al. (2016)	0.990	4	0.913	0.922
Vanermen et al. (2016)	0.820	4	0.913	1.113
Webb et al. (2016)	0.617	3	0.935	1.515

The final weighted mean (using the weighted.mean() function in the ‘stats’ package in R) was calculated to be 0.8330 (SD 0.1480). Using a beta distribution to sample avoidance rates, this gives an upper and lower 95% confidence limit of 0.4410 and 0.9959.

Correcting for macro-avoidance

For the parameters in Table 5 and Table 6, baseline collision risk estimates using within-site avoidance rates only for option 1 and 2 of the sCRM were 754 birds (95% CI 549 – 952) and 383 birds (95% CI 173 – 631) respectively. The baseline collision estimates were adjusted using macro-avoidance values of 0.5349, 0.8564 and 0.9736 (95% confidence limits and mean macro-avoidance values derived from the beta distribution with a mean and standard deviation of 0.8564 and 0.1334). For option 1, the lowest annual collision risk estimate (the lower confidence limit of the baseline adjusted by the upper confidence limit of macro-avoidances) was three birds, while the highest annual collision risk estimate (the upper confidence limit of the baseline adjusted by the lower confidence limit of macro-avoidances) was 508 birds. Using this method to correct collision risk estimates for option 1 would give a final annual collision risk estimate of 126 birds (95% CI 2 – 508; Table 9). Values for option 2 would be calculated in a similar way and in this case, the unweighted corrected annual collision rate for option 2 would be 55 birds (95% CI 4 – 293), the weighted corrected annual collision rate would be 65 birds (95% CI 1 - 336), while the baseline annual collision rate was 383 birds (95% CI 173 – 631;Table 10).

Table 9: Baseline collision estimates for option 1 of the sCRM corrected for macro-avoidance using unweighted and weighted means and respective 95% confidence limits calculated from beta distributions. Uncorrected scenario uses within-site avoidance rate only

Scenario		Mean	LCL*	UCL**	Correction
Uncorrected	Baseline	754	549	951	0
Corrected by unweighted mean and UCL/LCL from beta distribution	Baseline UCL	351	256	443	1 - 0.5349
	Baseline mean	108	79	137	1 - 0.8564
	Baseline LCL	20	15	25	1 - 0.9736
Corrected by weighted mean and UCL/LCL from beta distribution	Baseline UCL	402	293	508	1 – 0.4673
	Baseline mean	126	92	159	1 – 0.8315
	Baseline LCL	2	2	3	1 – 0.9944

**UCL: Upper Confidence Limit*
***LCL: Lower Confidence Limit*

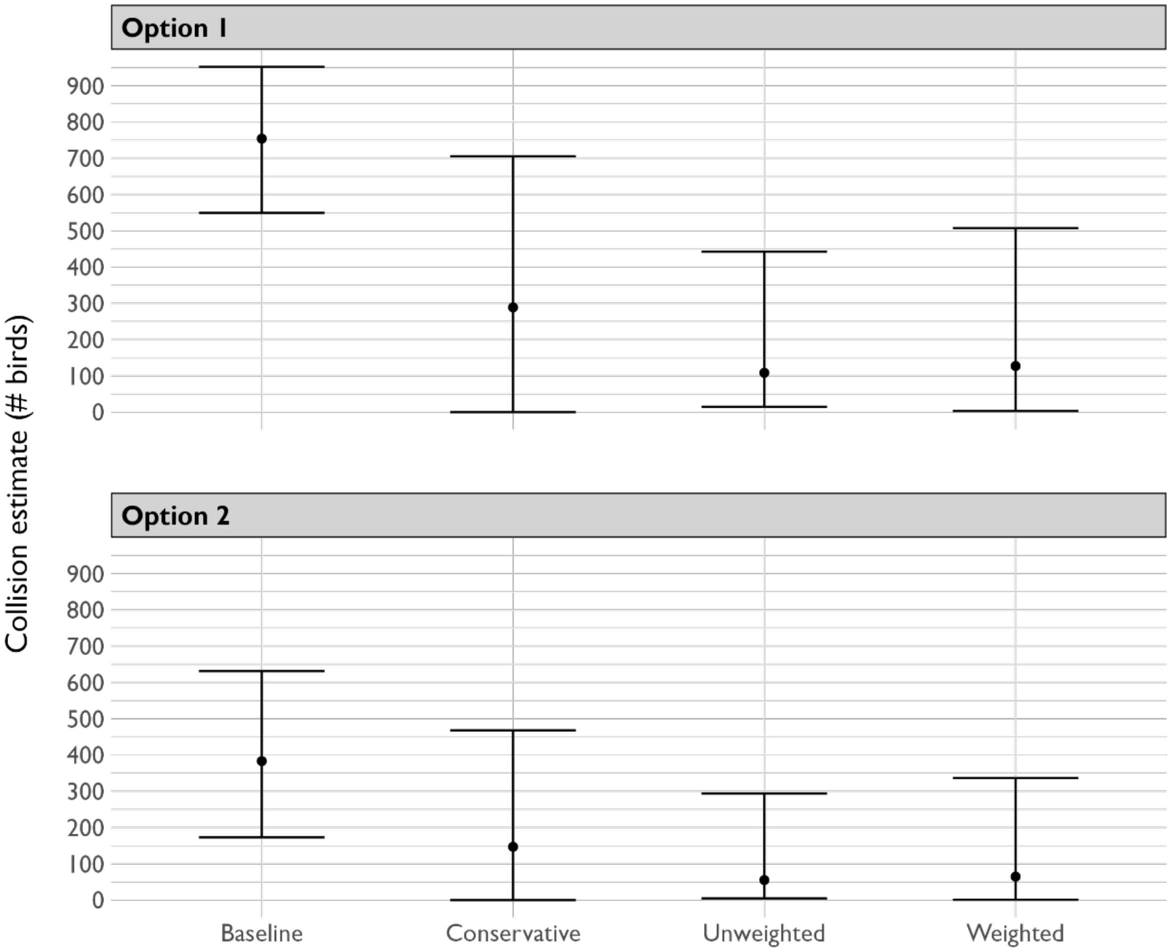
Table 10: Baseline collision estimates for option 2 of the sCRM corrected for macro-avoidance using unweighted and weighted means and respective 95% confidence limits calculated from beta distributions

Scenario		Mean	LCL	UCL	Correction
Uncorrected	Baseline	383	173	631	0
Corrected by unweighted mean and UCL/LCL from beta distribution	Baseline UCL	178	80	293	1 - 0.5349
	Baseline mean	55	24	90	1 - 0.8564
	Baseline LCL	10	4	16	1 - 0.9736
Corrected by weighted mean and UCL/LCL from beta distribution	Baseline UCL	204	92	337	1 – 0.4673
	Baseline mean	64	29	106	1 – 0.8315
	Baseline LCL	1	1	2	1 – 0.9944

Using the maximum and minimum possible corrected collision estimates with the unweighted and weighted means of macro-avoidance demonstrates little difference between both. The weighted mean is slightly more conservative than the unweighted mean with slightly higher uncertainty. The skewed confidence limits of the unweighted and weighted means are due to the non-linear nature of avoidance rates. The most conservative macro-avoidance estimate of 0.617 (Webb et al., 2016) had associated confidence limits of 0.259 and 1.000 and thus very large confidence intervals around the annual mean collision estimate (Figure 2).

A weighted mean approach was initially agreed with the project steering group and we have demonstrated by calculating unweighted and weighted means that they present little difference and therefore, that the weighted mean is not sensitive to the way in which quality has been scored. Nevertheless, given potential criticism of the weighted mean approach, whereby methods based on arithmetic operations with ordinal quantities can lead to errors (E. Masden, pers. comms.; Shavykin and Karnatov, 2020), we propose to use the unweighted mean approach when calculating a generic macro-avoidance rate for gannet.

Figure 2: Effect of correcting annual collision estimates by conservative (0.617; Webb et al., 2016), unweighted and weighted mean macro-avoidance rates and associated uncertainty for both option 1 and 2 of the sCRM

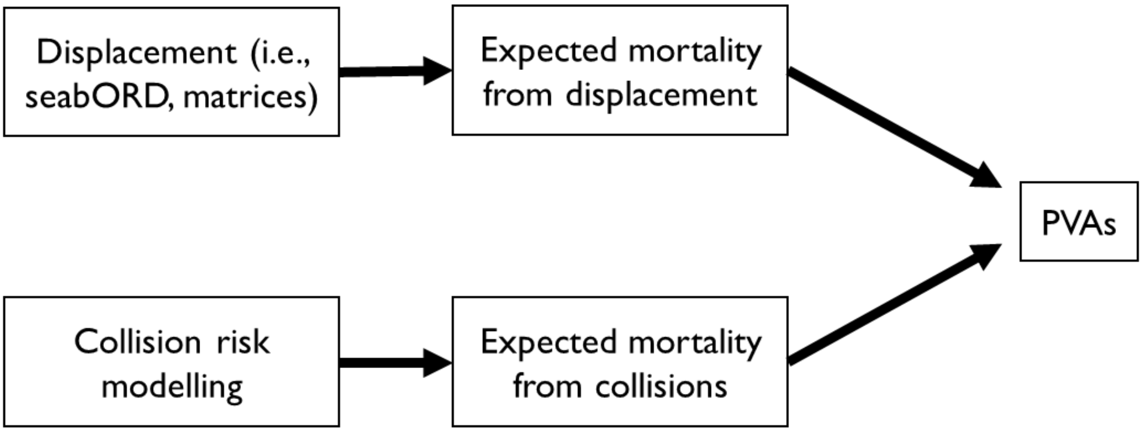


3.2 Options for accounting for macro-avoidance in assessment

3.2.1 Current assessment process

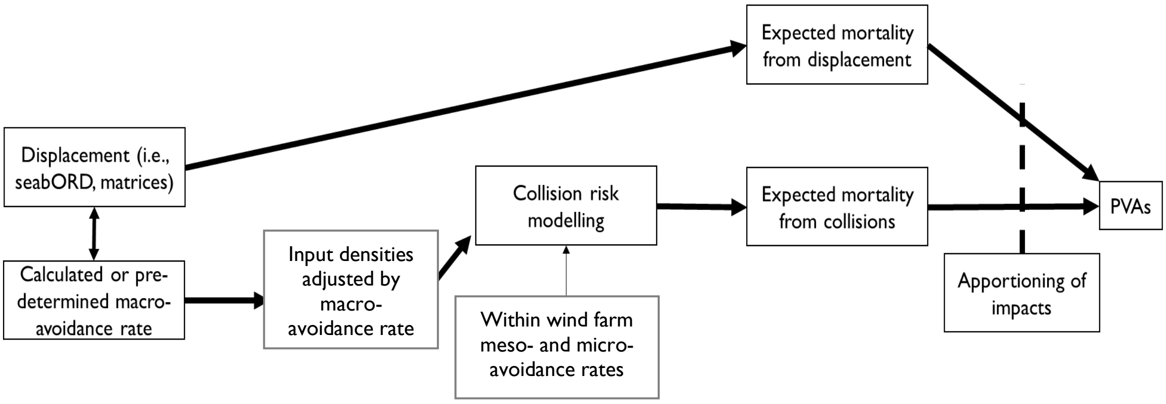
During the assessment process for gannet in its current format, population estimates for a site are fed into CRMs, or potentially used in displacement matrices. Mortality estimates from displacement and collision risk estimates are apportioned to colonies based on gannet foraging distance, then passed forward into population viability analyses to determine potential impacts of a proposed development. Currently, displacement and collision risk are performed as separate analyses (Figure 3).

Figure 3: Overview of impact assessment process for OWFs after population estimates



Displacement effects are an inherent part of macro-avoidance behaviour because macro-avoidance is a combination of both displacement and barrier effects. However, there are spatio-temporal mismatches in how displacement and collision mortalities are measured. Although this falls out of the remit of this work, it is important to note that this mismatch needs to be visited to better harmonise mortality estimates and reduce uncertainty. Figure 4 suggests a broad approach, where displacement rates are synergised to calculate a macro-avoidance rate that can be used to adjust input densities to collision risk models.

Figure 4: Suggested approach to the assessment process to better account for macro-avoidance for gannet (and other species)



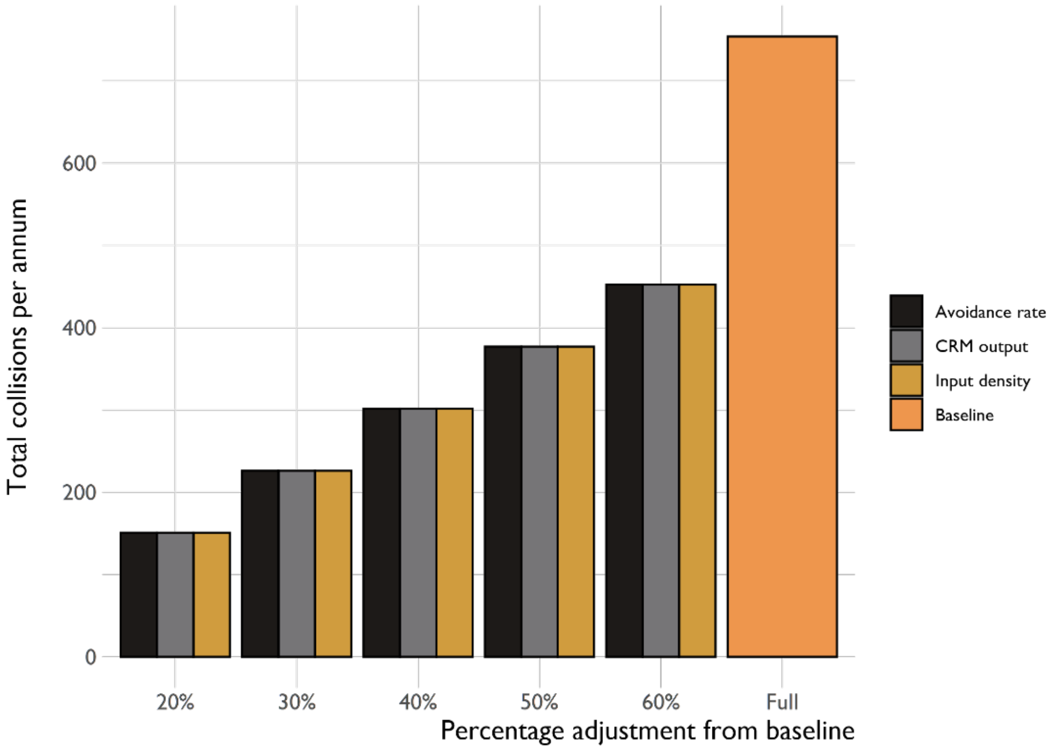
In lieu of the fact that this disconnect has yet to be addressed, it is suggested that the input densities for collision risk modelling should at the very least be adjusted by macro-avoidance rates.

3.2.2 Incorporation of macro-avoidance

Currently, macro-avoidance is not incorporated in CRMs. For gannets, guidance (SNCBs, 2017) is to use a value of 0.989 from Cook et al. (2014) which only incorporates micro and meso-avoidance rates (i.e., within OWF avoidance rate). The weakness of the current approach is that it limits the ability to take temporal effects into account (i.e., the possibility that macro-avoidance rates may differ throughout the year), and it does not follow the logical biological process (i.e., birds are first displaced, and then they may or may not collide with turbine blades). A more appropriate and logical way of incorporating macro-avoidance into collision risk modelling would be to apply the macro-avoidance rate prior to running a CRM, and then running a CRM with a within OWF avoidance rate only. Because of the linear nature of the collision risk model, it would be expected that applying the macro-avoidance in this proposed way would be straightforward and could be used to calculate updated collision estimates for sites that have currently been undergoing assessment.

This was tested by first generating a baseline collision risk scenario using the 0.989 avoidance rate (i.e., a collision rate of 1 – 0.989 = 0.011). For illustration, the avoidance rate was adjusted by macro-avoidance rates of 40, 50, 60, 70 and 80% (equating to 60, 50, 40, 30, and 20% decreases to the collision rates respectively) thus giving total avoidance rates of 0.9927, 0.9940, 0.9952, 0.9964 and 0.9976 respectively. The input densities and the output collision estimates for the 0.989 avoidance rate baseline were also decreased by 60, 50, 40, 30 and 20% (Figure 5).

Figure 5: Comparison of collision estimates when incrementally decreasing avoidance rates, input densities and CRM estimates



Due to the linear nature of the CRM, it was confirmed that incorporating macro-avoidance into the avoidance rate has the same effect as incorporating it into the input densities and output collision estimates.

To keep with the logic of the behaviour of birds, and the overarching goal of collision risk modelling (i.e., determining how many birds that are already in a OWF may collide with a turbine blade) it is recommended that macro-avoidance be incorporated into the input densities. This would require a slight alteration to the existing web-based sCRM in the form of a set of input boxes which allowed users to correct input densities by macro-avoidance rates.

Another strength of this recommended approach is that it would allow for macro-avoidance to consider possible temporal effects. Provided the data are available to do so, monthly mean estimates of flying bird densities could be altered by temporally adjusted macro-avoidance rates. If the data are not available, it would simply be a matter of adjusting all the input densities by the same macro-avoidance rate.

3.3 Approach for existing assessments

To date, due to a lack of inclusion of macro-avoidance in the collision risk modelling portion of environmental assessment, it is likely that collision predictions have been over-estimated. For example, when considering a theoretical single wind farm, a baseline of 754 annual gannet collisions was estimated to decrease to 108 collisions when adjusting by the unweighted mean avoidance rate of 0.8564 (Table 9). To illustrate the potential scale of impacts across multiple wind farms, the unweighted mean macro-avoidance rate was used, and adjusted collision estimates were calculated by multiplying the initial collision estimates by (1-0.8564) (Table 11). Initial collision estimates were modelled using parameters listed in Table 5 and Table 6. In the below hypothetical example, the cumulative annual total of 18,375 collisions estimated with unadjusted avoidance rate drops to 2,639 annual collisions when adjusted by the unweighted mean macro-avoidance rate (0.8564).

Table 11: Initial gannet collision estimates for three hypothetical wind farms adjusted by the unweighted mean macro-avoidance rate of 0.8564

Month	Wind Farm 1	Wind Farm 2	Wind Farm 3	Wind Farm 1 Adjusted	Wind Farm 2 Adjusted	Wind Farm 3 Adjusted	Total	Total Adjusted
Jan	492	544	854	71	78	123	1,890	271
Feb	978	163	571	140	23	82	1,712	246
Mar	136	904	387	20	130	56	1,427	205
Apr	439	578	214	63	83	31	1,231	177
May	721	239	914	104	34	131	1,874	269
Jun	151	920	827	22	132	119	1,898	273
Jul	106	219	525	15	31	75	850	122
Aug	66	60	247	9	9	35	373	54
Sep	921	660	937	132	95	135	2,518	362
Oct	498	93	725	72	13	104	1,316	189
Nov	900	312	902	129	45	130	2,114	304
Dec	362	106	704	52	15	101	1,172	168
Annual	**5,770**	**4,798**	**7,807**	**829**	**689**	**1,121**	**18,375**	**2,639**

3.4 Further issues to address

Although the recommended approach deals with some of the logical flow issues as reported, there are a couple of other issues that need addressing. The first is the temporal disconnect between the displacement assessment (e.g., displacement matrices) and collision risk modelling. Displacement assessments via displacement matrices make use of a single seasonal peak value that is applied. It assumes that the value used in the assessment is the total population within the OWF (and associated buffer), and a certain number of those individuals are displaced and die, which represents the mortality estimate for a season (seasonal estimates are combined for annual estimates). However, collision risk modelling is done at a monthly scale and assumes that each month represents a new population of birds that are available to collide with turbine blades. These issues of turnover should be addressed more clearly to ensure the assessment process is not under or over-estimating mortality.

The other important issue is the disentanglement of barrier versus displacement effects. Although both are the result of macro-avoidance behaviour, they have different implications on the biology of the animals. Current work focuses on displacement because it is somewhat easier to quantify, however, barrier effects should also be accounted for to ensure the modelling is assuming the correct number of available birds. Macro-avoidance as applied here and in current assessments is a broad-brush tool that somewhat captures these differences, but more focused work and data collection could help refine the overall process. Future work on individual-based models could be the way forward to address many of these issues.

4 Summary

Macro-avoidance is an important factor to take account of in any environmental assessment for OWFs. If macro-avoidance rates are not included in assessments, then there is a risk of over-estimating the number of collisions calculated in CRMs. For gannets, the within OWF avoidance rate proposed by Cook et al. (2014), Bowgen and Cook et al. (2018), and Cook (2021) uses the all-gull rate, but incorporation of macro-avoidance rates have not been explored.

The main objectives of this study were to:

- Collate, and appraise, all available evidence on gannet macro-avoidance behaviour from OWF's, considering survey and analysis methods, site-specific factors (e.g., array size and turbine spacing) and compatibility of results;
- Present the findings of the review, and a suggested approach to deriving a macro-avoidance rate, to the project panel at a workshop for discussion and agreement;
- Compare and evaluate different approaches to incorporating this macro-avoidance rate, and any associated uncertainty, during estimation of collision impacts;
- Detail the relative advantages and disadvantages of proposed methods and suggest which would be most appropriate for use in OWF impact assessments; and
- Suggest an approach or method for applying corrections to existing impact estimates for projects considered in cumulative and in-combination assessments.

In Section 2, the outcomes of the literature review are reported. The associated review database presents detailed notes on each study and can be easily queried while the quality scoring system allows the relevance of published gannet macro-avoidance rates to be examined.

The literature review found site-based variation in macro-avoidance rates. While some of this may come down to the method used to measure these rates, it is likely that there are temporal and other forms of variation that can only be accounted for in impact assessment if there is sufficient evidence to do so. This should be a focus for future post-construction monitoring projects at new OWFs.

In Section 3, several methods for determining macro-avoidance rates were compared (Table 7). Upon discussion with the project steering group, consideration of available approaches, consultation of published literature and expert opinion, it was concluded that a macro-avoidance rate for gannet should be calculated based on a simple mean approach. The mean macro-avoidance rate for gannet was calculated as 0.8564 (95% CI 0.5349 - 0.9736).

The incorporation of macro-avoidance was tested at several stages of collision risk modelling. It was determined that the most appropriate and logical way forward would be to alter the input densities of flying birds by a macro-avoidance rate and then run the CRMs using a within OWF only avoidance rate. This would address the possibility of including some sort of temporal factor to the macro-avoidance rates (as monthly densities could be altered individually). However, it was also shown that macro-avoidance could be accounted for at any stage of the process (e.g., altering the avoidance rates themselves, or the output collision estimates).

The literature review and associated quantitative measures presented here offer a straightforward and effective way to incorporate macro-avoidance across impact assessments for gannets. However, many of these concepts could also be applied to other species if the data are available to do so. These changes to the assessment process are simple to implement and will offer a logical and controlled stepwise approach as the push to build OWFs continues in the UK.

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Appendix A: Literature review search terms

Search terms used	
avoidance	Ireland
avoidance behaviour	Irish Sea
avoidance rates	macro-avoidance
barrier effects	mortality
Baltic Sea	Netherlands
Celtic Sea	North Sea
collision risk modelling	offshore renewable
displacement	offshore wind farm
Dutch	offshore wind farm impact assessments
England	Scotland
Europe	seabird
gannet	UK
Germany	Wales

Limited 1970 to present and searches of ‘grey’ literature and peer-reviewed publications.

Examples of multiple searches:

"gannet" offshore wind farm OR avoidance OR rates "macro-avoidance" North Sea

gannet avoidance OR displacement "collision risk"

"gannet" Scotland OR barrier OR rates "macro-avoidance"

Appendix B: Workshop minutes

Natural England/HiDef workshop on Gannet Macro-avoidance
24/02/2022 – 10:00-11:30am

Attendees

Grant Humphries (HiDef), Jaz Harker (HiDef), Katharine Keogan (HiDef), Richard Berridge (NE), Andrew Harwood (NE), Sophie Allen (NE), Aly McCluskie (RSPB), Jude Lane (RSPB), Tom Evans (MSS), Sean Sweeney (APEM), Rob Catalano (APEM), Aonghais Cook (BTO), Julie Black (JNCC), Michael Bailey, Chris Pendlebury (Natural Power), Neil McCulloch (Technical and Operated Assets), Rebecca Hall

Apologies: Kelly McLeod (HiDef), Tim Frayling (NE), Matthew Murphey (NRW)

Presentations from Jaz Harker and Grant Humphries

Discussion/Questions

How much attention was paid to post consent monitoring and displacement studies in literature review? A few studies from specific wind farms considered post consent monitoring, and these were included in the literature review. Pesco paper (reference?) and other similar papers may not give quantitative values but could be very helpful in providing qualitative information on avoidance. Action: Richard Berridge will point HiDef in the direction of further reports from grey literature.

Weighting of studies to calculate new avoidance rate from literature is a good idea, but not by putting to a vote by stakeholders. Should be done using a quantitative approach that is clearly pre-defined. HiDef have developed a scoring system to rate each study by quality which will be shared for review. Parallel JNCC project on micro and meso-avoidance has used one simple criterion – is there anything fundamentally wrong with the data that it shouldn’t be included in recalculations? If not, then it’s included. RSPB suggests digging out raw data and reanalysing in a way that’s agreed on by stakeholders. An IBM approach could be used to estimate avoidance rates.

Claim that not much evidence on seasonal variation between avoidance and displacement is contrary to APEM findings. APEM found quite a lot of variation consistently between datasets that were collected in the breeding season versus non-breeding season. Other research suggests there’s a lower rate of avoidance during the breeding season. Birds are more likely to take risks when there is greater pressure on their energy i.e.,during chick rearing. During non-breeding and migration there’s evidence that birds fly around the turbines. There should be a function in the SCRM that allows to change the densities/macro-avoidance across seasons.

Habituation to wind farms will occur over longer time scales – this could be factored in if an IBM approach was used. Habituation won’t happen at a uniform rate across the population because new recruits will join the population (turnover). This needs to be considered for incorporation into the modelling.

The assessment for barrier effects/displacement is very crude. The assumption is that the displacement matrices just account for birds that aren’t in the wind farm – but understanding the actual cause of mortality (i.e.,collision/barrier/displacement) would be better. Could an IBM be used to help validate our process – i.e.,instead of using it just to estimate avoidance rate & parameterise, use it to ask are we roughly getting things right?

Combining displacement and macro-avoidance agreed to be preferred method. If this is done then we need to either 1) make sure we have all the correct data to inform input parameters, or 2) agree that there are knowledge gaps and we need to make assumptions using the information that we have. Two separate questions: Are we broadly happy with the approach of combining macro-avoidance and within wind farm? That’s the approach that makes sense. Second, are we happy with the data that underpins macro-avoidance? That’s challenging – would probably find differences in displacement/avoidance rates depending on what data were used. We do need to do what we can with the data we’ve got, but it would be good to plug evidence gaps if necessary. These gaps will be more clear when excel sheets are presented by HiDef. We’re limited in what we can do with existing macro-avoidance rates.

Distinction between displacement and barrier effects. For a smaller development, the distinction isn’t important, but for cumulative impacts of many wind farms in combination, then it’s maybe more important. This could depend on where the farms are positioned in relation to each other, e.g.,if one behind the other in relation to a colony this may have a smaller impact than if two are side by side.

Was useful to see that incorporating macro-avoidance at different points doesn’t impact results. Applying macro-avoidance to initial densities is preferred, as this makes it more straightforward to change the advice on avoidance rates as more evidence becomes available. It’s the most direct change to make to guidance. New MSS tool (CEF?) gives this functionality, and they suggest adjusting densities using outputs from either an IBM or displacement matrix.

Avoidance rate is a correction factor that corrects between actual collisions and predicted collisions. Here we are assuming that this correction factor is taken into account by micro- and meso-avoidance rather than macro-avoidance. With macro-avoidance we are probably just thinking about the behaviour of the birds rather than predicted vs observed collisions. So in this study macro-avoidance is really avoidance behaviour rather than an avoidance rate.

Actions

1. Take a deeper look into literature. Is macro-avoidance just a combination of barrier or displacement effects or something different.
2. Weighted mean option – present based on qualitative assessment.
3. Clarify sensitivity analysis of removing different macro-avoidance rates.
4. Present more clearly the discrepancies between birds counted in displacement vs CRM through a sensitivity analysis (I think?).
5. Send round list of studies found so stakeholders can check if any have been missed. Include critical appraisal of data, so full spreadsheet.

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