

OFFSHORE RENEWABLES JOINT INDUSTRY
PROGRAMME (ORJIP) FOR OFFSHORE WIND



Quantification of mortality rates associated with displacement (QuMR)

Appendix – A

May 2025



ORJIP Offshore Wind

The Offshore Renewables Joint Industry Programme (ORJIP) for Offshore Wind is a collaborative initiative that aims to:

- Fund research to improve our understanding of the effects of offshore wind on the marine environment.
- Reduce the risk of not getting, or delaying consent for, offshore wind developments.
- Reduce the risk of getting consent with conditions that reduce viability of the project.

The programme pools resources from the private sector and public sector bodies to fund projects that provide empirical data to support consenting authorities in evaluating the environmental risk of offshore wind. Projects are prioritised and informed by the ORJIP Advisory Network which includes key stakeholders, including statutory nature conservation bodies, academics, non-governmental organisations and others.

The current stage is a collaboration between the Carbon Trust, EDF Energy Renewables Limited, Ocean Winds UK Limited, Equinor ASA, Ørsted Power (UK) Limited, RWE Offshore Wind GmbH, Shell Global Solutions International B.V., SSE Renewables Services (UK) Limited, TotalEnergies OneTech, Crown Estate Scotland, Scottish Government (acting through the Offshore Wind Directorate and the Marine Directorate) and The Crown Estate Commissioners.

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- Natural England
- Natural Resources Wales
- NatureScot
- Scottish Government's Marine Directorate

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Who we are

Our mission is to accelerate the move to a decarbonised future.

We have been climate pioneers for more than 20 years, partnering with leading businesses, governments and financial institutions globally. From strategic planning and target setting to activation and communication - we are your expert guide to turn your climate ambition into impact.

We are one global network of 400 experts with offices in the UK, the Netherlands, Germany, South Africa, Singapore and Mexico. To date, we have helped set 200+ science-based targets and guided 3,000+ organisations in 70 countries on their route to Net Zero.

Contents

ORJIP Offshore Wind.....	2
Acknowledgements	2
Who we are	3
List of Tables	5
List of Figures.....	5
Abbreviations	5
Introduction	1
Displacement, barrier effects and macro-avoidance.....	2
1. Displacement and mortality rates presented in assessments	2
1.1. Data gaps and uncertainty/precaution around displacement and mortality rates7	
1.1.1. Red-throated divers.....	8
1.1.2. Auks	9
1.1.3. Gannet.....	10
1.1.4. Gulls	10
2. Review of mortality rates	10
2.1. Carry over effects.....	11
2.2. Habitat quality.....	14
2.3. Density dependence	15
2.4. Seasonal differences in displacement	15
3. Review of tools and methods for estimating mortality	16
3.1. SNCB Matrix approach	16
3.2. SeabORD.....	17
3.3. Other approaches	18
4. Collation of relevant datasets	20
4.1. Evidence of displacement rates	1
5. References.....	7

List of Tables

Table 1. Displacement and mortality rates presented in offshore consent applications in the UK.....	2
Table 2. Summary of evidence for compensatory or depensatory density dependence for the key species (from Horswill & Robinson 2015).	15
Table 3. Displacement matrix for breeding season guillemots at Helgoland (Germany). From Busch & Garthe (2016).	19
Table 4. Sources of datasets with information potentially suitable for assessing consequences of seabird displacement.	21
Table 5. Sources of quantified estimated seabird displacement rates in Busch et al. (2015).	1
Table 6 Evidence of avoidance and attraction in Dierschke et al. (2016).....	3
Table 7 Quantification of displacement rates based on Dierschke et al. (2016) criteria.	3

List of Figures

Figure 1. Example of Matrix Approach from SNCB (2017) guidance.....	17
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Abbreviations

Term	Description
BACI	Before After Control Impact
BDMPS	Biologically Defined Minimum Population Scales
BTO	British Trust for Ornithology
CEH	Centre for Ecology & Hydrology
CWS	Canadian Wildlife Service
ECSAS	Eastern Canada Seabirds at Sea
EDB	EURING Databank
EE	Expert Elicitation
EIA	Environmental Impact Assessment
ENSO	El Niño Southern Oscillation
EOWDC	European Offshore Wind Deployment Centre
ESAS	European Seabirds at Sea
FAME	Future of the Atlantic Marine Environment

FMR	Field Metabolic Rate
GGOWL	Greater Gabbard Offshore Wind Farm
GLS	Global Location Sensor
GIS	Geographic Information System
GPS	Global Positioning System
HRA	Habitats Regulations Appraisal
MEDIN	Marine Environmental Data and Information Network
MERP	The Marine Ecosystem Research Programme
MSI	Marine Scotland Information
OBIS	Ocean Biodiversity Information System
ORD	Offshore renewable development
ORJIP	Offshore Renewables Joint Industry Programme
OWEZ	Offshore Windpark Egmond aan Zee
OWF	Offshore wind farm
PAWP	Prinses Amalia Wind Park
PBR	Potential Biological Removal
PINS	Planning Inspectorate
PVA	Population Viability Analyses
RSPB	Royal Society for the Protection of Birds
SEANSE	Strategic Environmental Assessment North Seas Energy
SNCB	Statutory Nature Conservation Bodies
SOSI	Seabird Oil Sensitivity Index
SPA	Special Protection Area
SPG	South Polar Gyre
SST	Sea Surface Temperature
STAR	Seabird Tracking and Research
TDR	Time Depth Recorders
WP	WP Work package

Introduction

ORJIP Offshore Wind launched its second stage with the objective of identifying, prioritising and selecting research to reduce consenting risk for offshore wind. The application of seabird mortality rates associated with predicted displacement from offshore wind farms was identified as an important area for research, as the mortality rate values currently used for displaced birds lack sufficient evidence base and poorly communicate any associated uncertainty, which reduces their defensibility. This project aims to review the ranges of mortality rates currently used for displaced birds and provide recommendations for their improvement.

The Joint SNCB (Statutory Nature Conservation Bodies) Interim Displacement Advice Note provides advice on how to present assessment information on the extent and potential consequences of seabird displacement from Offshore Wind Farm (OWF) developments (JointSNCB 2017). This advice requires assessments to use published indices of disturbance (e.g., Furness et al. 2013; Wade et al. 2016) to assign a range of displacement levels for each species individually, with consideration of modifications arising from emerging new evidence and discussions with SNCBs to agree appropriate levels of likely adult mortality associated with particular displacement levels, for each species individually (acknowledging that data are very limited at this time). Assessments should then use these two metrics (displacement rate and displacement mortality rate) to estimate displacement impacts. The advice specifies that this table should be presented from 0-100%, in 10% increments for displacement levels. Percentage increments for mortality should also be presented between 0-100% but including smaller increments at lower values (e.g., 0%, 1%, 2%, 5%, 10%, 20%, etc).

The estimation of displacement mortality rates is therefore a critical component of the assessment process, with large influence upon resulting offshore wind farm impacts on affected populations. However, there is very little empirical evidence upon which this rate may be based. Importantly, a recent Marine Scotland project, Scottish waters east region – regional sectoral marine plan - SEANSE, suggested that the use of an individual-based model, SeabORD (Searle et al. 2014, 2018), indicates mortality rates from displacement and barrier effects are likely to be higher than those used in the displacement matrix for Round 3 sites (Searle et al. 2020). The displacement matrix outputs are based on SNCB advice on, what are assumed to be, precautionary values. However, the outputs from SeabORD are based on “the latest available data and understanding of the ecology of seabirds”. Neither approach has been compared to empirical values of displacement or mortality as a consequence of displacement.

This report reviews the displacement mortality rates used to determine the mortality of birds displaced by offshore wind farms in the United Kingdom, the key factors influencing mortality rates from displacement, the tools and methods for estimating displacement mortality and identifies relevant datasets that could be used to estimate empirical values for the demographic consequences of displacement.

This study focuses on six key species considered to be at greater potential risk of displacement and displacement mortality in future offshore wind farm development in the UK:

- Black-legged kittiwake *Rissa tridactyla* (hereafter ‘kittiwake’),
- Common guillemot *Uria aalge* (hereafter ‘guillemot’),
- Razorbill *Alca torda*,
- Atlantic Puffin *Fratercula arctica* (hereafter ‘puffin’),
- Red-throated diver *Gavia stellata*, and
- Northern Gannet *Morus bassanus* (hereafter ‘gannet’).

Displacement, barrier effects and macro-avoidance

The terms 'displacement', 'barrier effects' and 'macro-avoidance' can all, to some extent, be considered part of the same effect. Displacement occurs when a bird that would have foraged within the area occupied by an offshore wind farm chooses not to due to the presence of the wind farm or the individual turbines. In this report 'displacement' is referring to the difference in the abundance of birds within an area of sea as the result of the presence of an operational offshore wind farm (rather than a wind farm under construction). Construction phase disturbance is a short-term (1–3 years) impact that is temporary, as it stops occurring following completion of construction. This is the disturbance caused by the construction activities within the wind farm which only occur at small spatial scales compared to the overall area that becomes occupied by the wind farm. Barrier effects are the effect of the presence of an operational wind farm on birds that decide to move around the wind farm, rather than through it, and are often considered synonymous with displacement. However, the consequences of barrier effects are likely to be different at an individual level. 'Macro-avoidance' is a behavioural response of birds to the presence of the wind farm that results in birds not entering the wind farm. Displacement is assumed here to refer to both birds in flight and on the sea.

1. Displacement and mortality rates presented in assessments

A review was undertaken to collate information on displacement and mortality rates presented in offshore wind farm applications in the UK. Information was primarily obtained through a review of recent assessments and advice from the relevant SNCBs and through searches of applications on the Planning Inspectorate (PINS) website (Table 1). It is important to note that the PINS website is not intended to be a searchable database of information, and it only applies to the wind farm application being considered. As such, the advice from the relevant SNCB applies specifically to that project and shouldn't be considered general guidance applicable to other wind farm applications.

Table 1. Displacement and mortality rates presented in offshore consent applications in the UK

Species	Offshore wind farm (OWF)	Development stage	Assumed displacement rate	Assumed displacement area	Assumed mortality rate of displaced birds
Kittiwake	Firth of Forth Alpha & Bravo	Operation	9.90%	OWF (no buffer)	1%
Gulls (kittiwake, great blackbacked gull (<i>Larus marinus</i>), lesser blackbacked gull (<i>L. fuscus</i>), herring gull (<i>L. argentatus</i>))	Hornsea ONE	Operation	25%	OWF (no buffer)	Breeding = 2%, Nonbreeding = 1%

Gulls (lesser black-backed gull, herring gull)	Neart na Gaoithe	Construction/operation	50%	1 km radius around OWF	Not assessed
Gulls (little gull (<i>Hydrocoloeus minutus</i>), great blackbacked gull)	Neart na Gaoithe	Construction/operation	25%	1 km radius around OWF	Not assessed
'Commic' tern	Norfolk Boreas	Construction	100%	2 km radius around construction vessels	10%
Arctic tern (<i>Sterna paradisaea</i>)	Neart na Gaoithe	Construction/operation	25%	1 km radius around OWF	Not assessed
Guillemot	Hornsea ONE	Operation	30%	1 km radius around OWF	Breeding = 2% Post-breeding = 2% Nonbreeding = 1%
	Hornsea TWO	Operation	30%	2 km radius around OWF	Breeding = 10% Nonbreeding = 1%
	Thanet Extension	Construction	OWF = 67%, 500m buffer = 25%	1 km radius around OWF	1 - 5%
	Thanet Extension	Construction	OWF = 79%, 500m buffer = 25%	1 km radius around OWF	1 - 5%
Razorbill	Hornsea ONE	Operation	40%	1 km radius around OWF	Breeding = 2% Post-breeding = 2% Nonbreeding = 1%
	Thanet Extension	Construction	OWF = 89%, 500m buffer = 25%	500 m radius around OWF	1 - 5%
	Thanet Extension	Construction	OWF = 95%, 500m buffer = 25%	500 m radius around OWF	1 - 5%
Puffin	Hornsea ONE	Operation	40%	1 km radius around	Breeding = 2%

				OWF	Nonbreeding = 1%
	Hornsea THREE	Operation	40%	2 km radius around OWF	Breeding = 2 - 10% Nonbreeding = 1%
Razorbill and puffin	Hornsea TWO	Operation	40%	2km radius around OWF	Breeding = 10% Nonbreeding = 1%
Auks (guillemot, razorbill)	Norfolk Boreas	Construction	100%	2 km radius around construction vessels	1 - 10%
	Norfolk Boreas	Operation	50 - 70%	2 km radius around OWF	1 - 10%
	East Anglia ONE	Construction	100%	2 km radius around construction vessels	1 - 10%
	East Anglia ONE	Operation	30 - 70%	2 km radius around OWF	1 - 10%
	East Anglia TWO	Construction	100%	2 km radius around construction vessels	1 - 10%
	East Anglia TWO	Operation	30 - 70%	2 km radius around OWF	1 - 10%
Auks (guillemot, razorbill, puffin)	Norfolk Vanguard	Construction	100%	2 km radius around construction vessels	1 - 10%
	Norfolk Vanguard	Operation	30 - 70%	2 km radius around OWF	1 - 10%
	East Anglia THREE	Construction	100%	2 km radius around construction vessels	Not assessed
	East Anglia THREE	Operation	30 - 70%	2 km radius around OWF	1 - 10%

	Firth of Forth Alpha & Bravo	Operation	16.90%	OWF (no buffer)	1%
	Neart na Gaoithe	Construction/operation	50%	1 km radius around OWF	Not assessed
Red-throated diver	Norfolk Vanguard	Construction	100%	2 km radius around construction vessels	1 - 10%
	Norfolk Vanguard	Operation	80%	4 km radius around OWF	1 - 10%
	Norfolk Boreas	Construction	100%	2 km radius around construction vessels	1 - 10%
	Norfolk Boreas	Operation	90%	4 km radius around OWF	1 - 10%
	East Anglia ONE	Construction	100%	2 km radius around construction vessels	1 - 10%
	East Anglia ONE	Operation	100%	4 km radius around OWF	1 - 10%
	East Anglia TWO	Construction	100%	2 km radius around construction vessels	1 - 10%
	East Anglia TWO	Operation	100%	4 km radius around OWF	1 - 10%
	East Anglia THREE	Construction	100%	2 km radius around construction vessels	10%
	East Anglia THREE	Operation	100%	4 km radius around OWF	10%
	Hornsea THREE	Construction	100%	2 km radius around construction vessels	1 - 10%
	Thanet Extension	Construction	82%	4 km radius around OWF	1 - 5%

	Thanet Extension	Operation	OWF = 73%, 500m buffer = 25%	4 km radius around OWF	1 - 5%
Fulmar	Hornsea TWO	Operation	30%	2 km radius around OWF	Breeding = 2%, Nonbreeding = 1%
	Hornsea THREE	Operation	1 - 10%	2 km radius around OWF	Breeding = 2%, Nonbreeding = 1%
	Hornsea ONE	Operation	30%	OWF (no buffer)	Breeding = 2%, Nonbreeding = 1%
Gannet	Norfolk Vanguard	Operation	60 - 80%	2 km radius around OWF	1%
	Norfolk Boreas	Operation	60 - 80%	2 km radius around OWF	1%
	East Anglia ONE	Operation	60 - 80%	2 km radius around OWF	1%
	East Anglia TWO	Operation	60 - 80%	2 km radius around OWF	1%
	East Anglia THREE	Operation	60 - 80%	2 km radius around OWF	0-1%
	Hornsea ONE	Operation	70%	OWF (no buffer)	Breeding = 2% Nonbreeding = 1%
	Hornsea TWO	Operation	70%	2 km radius around OWF	Breeding = 2% Nonbreeding = 1%
	Hornsea THREE	Operation	1 - 10%	2 km radius around OWF	Breeding = 2% Nonbreeding = 1%
	Thanet Extension	Operation	100%	OWF (no buffer)	1 - 5%
	Neart na Gaoithe	Construction/operation	100%	1 km radius around OWF	Not assessed

1.1. Data gaps and uncertainty/precaution around displacement and mortality rates

Seabirds vary in the extent to which they are disturbed by the presence of construction vessels (e.g., export cable installation, wind turbine construction and associated vessel traffic) and operational infrastructure (e.g., wind turbines, offshore project substations and met masts) as well as to the maintenance activities that are associated with an operational wind farm (particularly ship and helicopter traffic). Garthe and Hüppop (2004) presented a scoring system for such disturbance factors, which has been used widely in offshore wind farm EIAs. Definitive displacement rates and mortality rates associated with displaced birds around offshore wind farms, are not known and precautionary estimates have to be used in assessments. Although evidence is limited, some empirical studies have provided evidence of displacement rates, particularly for red-throated divers, gannets and auks. Rates estimated by empirical evidence are often lower than those recommended by SNCB guidance, as guidance tends to be precautionary.

Some bird species are more susceptible to disturbance than others. Gulls are not considered susceptible to disturbance, as they are often associated with fishing boats (e.g., Camphuysen 1995; Hüppop and Wurm, 2000) and have been noted in association with construction vessels at the Greater Gabbard offshore wind farm (GGOWL 2011) and close to active foundation piling activity at the Egmond aan Zee (OWEZ) wind farm, where they showed no noticeable reactions to the works (Leopold and Camphuysen, 2007). However, species such as divers and scoters have been noted to avoid shipping by several kilometres (Mitschke et al. 2001 from Exo et al. 2003; Garthe and Hüppop, 2004; Schwemmer et al. 2011). There are a number of different measures used to assess bird disturbance and displacement from areas of sea in response to activities associated with an offshore wind farm. Garthe and Hüppop (2004) developed a scoring system for such disturbance factors. Furness and Wade (2012) developed this further, with disturbance ratings for particular species, alongside scores for habitat flexibility and conservation importance. These factors were used to define an index value that highlights the sensitivity of a species to disturbance and displacement. Dierschke et al. (2016) reviewed all available evidence from operational offshore wind farms on the extent of displacement or attraction of seabirds in relation to these structures. They found strong avoidance of operational offshore wind farms by great crested grebe (*Podiceps cristatus*), red-throated diver, black-throated diver (*G. arctica*) and gannet. They found weak avoidance by long-tailed duck (*Clangula hyemalis*), common scoter (*Melanitta nigra*), fulmar, Manx shearwater (*Puffinus puffinus*), razorbill, guillemot, little gull and Sandwich tern (*Thalasseus sandvicensis*). They found no evidence of any consistent response by eider (*Somateria mollissima*), kittiwake, common tern (*S. hirundo*) and Arctic tern, and evidence of weak attraction to operating offshore wind farms for common gull (*L. canus*), black-headed gull (*Chroicocephalus ridibundus*), great black-backed gull, herring gull, lesser black-backed gull and red-breasted merganser (*Mergus serrator*), and strong attraction for shags (*Gulosus aristotelis*) and cormorants (*Phalacrocorax carbo*). Dierschke et al. (2016) suggested that strong avoidance would lead to some habitat loss for those species, while attracted birds appear to benefit from increases in food abundance or foraging or resting opportunities within operational offshore wind farms. Recent breeding season monitoring of a Scottish wind farm near a seabird breeding colony has further supported these results, with gannet showing strong avoidance but other species, including guillemot, razorbill and kittiwake showing evidence of no, or little, avoidance of turbines (MacArthur Green 2021).

For recent wind farm assessments in English waters, the recommended displacement and mortality rates from Natural England has differed from at least some of the empirical evidence available (for examples, refer to sections 2.1.1 – 2.1.2 below). While there is empirical evidence that shows low or moderate rates of displacement for most species, the number of studies is small and there remains uncertainty about displacement rate and there is no empirical evidence on the mortality consequences for displaced birds. This is reflected in precautionary guidance from SNCBs, which advises use of relatively high rates. Natural England's advised approach is to sum displacement effects estimated for different seasons to obtain an annual total effect. This should then be assessed in relation to both the largest of the individual seasonal

Biologically Defined Minimum Population Scales (BDMPS; Furness, 2015), and also the biogeographic population. In advising this approach Natural England has acknowledged there is a risk this incorporates double counting of individuals (i.e., some individuals may potentially be present in more than one season), and that the BDMPS is almost certainly under-estimates the population from which they are drawn (which must be at least this size and is likely to be considerably larger as a consequence of turnover of individuals). However, at present there is no agreed alternative method for undertaking assessment of annual displacement and therefore the above approach is presented, albeit with the caveat that the results are anticipated to be precautionary. The level of precaution is likely to be relatively small (Searle et al. in press).

1.1.1. Red-throated divers

Recent advice on the displacement and mortality rates to be used in the assessment of impacts on red-throated divers have been from cases in England. Natural England has advised that during construction, a 100% displacement rate and a 1 to 10% mortality rate should be used for red-throated divers displaced by cable laying vessels. During operation, Natural England has advised in the past that displacement will occur at a constant level to a distance of 4 km and that within this area, 100% of birds will be displaced and mortality of displaced birds will be between 1% and 10%. In more recent advice have started that assessments should assume 100% displacement from within the wind farm, but that this should decrease, linearly, to 0% at 10 or 12 km. This is assumed to be a precautionary approach as it combines high values for three aspects of the assessment: the distance over which birds will be affected (10 to 12 km), the rate of displacement within the area (0 - 100% across the whole buffer) and the mortality rate of displaced individuals (1 - 10%). Recent wind farm assessments have provided estimates for red-throated diver displacement derived from spatial modelling which reported peak levels of displacement within the wind farm of around 40 - 50% which declined to zero by 8 km. Monitoring of operational UK wind farms in areas of red-throated diver (such as London Array) have found similar levels of displacement (around 55%) with declines extending as far as 11 - 12 km, while studies conducted in the German Bight have reported statistically detectable effects for distances up to 20 km.

It therefore appears that displacement effects in this species are not static and probably reflect different spatial and temporal features (e.g., the German studies reflect the situation in spring, while the UK ones use mid-winter data).

Studies at Kentish Flats and Thanet have provided evidence that red-throated divers are displaced to a decreasing extent with increasing distance from wind turbines (Percival, 2013, 2014). Percival (2014) reported that at Kentish Flats, while displacement within the wind farm boundary was around 80% (compared to pre-construction), this declined to 10% at 1 km from the wind farm and was 0% from 2 km. A similar within wind farm reduction in density was reported at Thanet, but there was no detectable displacement beyond the wind farm boundary (Percival, 2013). Displacement rates of 60% to 80% were reported for OWEZ (Leopold et al., 2011) and the review by Dierschke et al. (2016) also suggested a figure in this range.

There is no empirical evidence that birds displaced from wind farms suffer mortality as a consequence of displacement (see Section 2). Any mortality due to displacement would be most likely a result of increased density in areas outside the affected area, resulting in increased competition for food where density was elevated (Dierschke et al. 2017). A review of evidence undertaken by a panel of experts brought together by JNCC concluded that mortality associated with displacement of red-throated divers may well be zero (Dierschke et al. 2017) and is certainly very unlikely to be as high as 10%. This conclusion is also supported by modelling of individual energy budgets by Topping and Petersen (2011), who predicted little change in population size even though there were clear displacement effects.

A review of available evidence for red-throated diver displacement was submitted for the Norfolk Vanguard assessment (MacArthur Green 2019a) and this concluded that the limited evidence suggested

that there would be little or no effect of displacement on diver survival. That review advocated an evidence-based displacement rate of 90% extending 2 km from the wind farm boundary with a consequent maximum mortality rate of 1%.

It is clear that there remains considerable uncertainty about a generally applicable displacement rate for red-throated diver, most critically with respect to consequences and this is reflected in the precautionary stance adopted by SNCBs. It is also important to note that Natural England's concerns for the populations of red-throated divers in SPAs have not been that there are impacts on the conservation objective to maintain or restore, "the population of each of the qualifying features" but that the impacts are to the objective to maintain or restore, "the distribution of the qualifying features within the site".

In response to this review Joint SNCB Interim Advice was shared on the site characterisation and impact assessment for offshore wind farms. This recommends that a 10 km buffer is used for site characterisation and impact assessment, but notes that empirical evidence shows a decline in the displacement rate with increasing distance from studies wind farms. Rather than provide generic advice on the change in displacement from the wind farm boundary to the 10 km buffer, the guidance recommends that this change is discussed with the relevant SNCB on a case-by-case basis. Note that at the time of writing this advice note was not publicly available and was provided confidentially.

1.1.2. Auks

Across recent wind farm assessments UK SNCB's have often advised that an estimated 1 - 10% mortality rate should be used for auks displaced from wind farms. Compared with baseline auk mortality rates, this covers a very wide range of mortality rates and includes, at its upper end, a large change in baseline mortality.

There is little empirical data on displacement of foraging seabirds from offshore wind farms with the consequence that assessment of the amount of displacement arising from developments is somewhat speculative. Available pre- and post-construction data have yielded variable results but indicate that auks may be displaced to some extent by some wind farms, but this is partial, and apparently negligible in some sites (Dierschke et al., 2016).

Common guillemots at Blighbank (Vanermen et al., 2012) were displaced only in a minority of surveys at two Dutch wind farms (OWEZ and PAWP; Leopold et al., 2011; Krijgsveld et al., 2011) but were not significantly displaced at Horns Rev (although the data suggest that slight displacement was probably occurring; Petersen et al., 2006) or Thornton Bank (Vanermen et al., 2012). Reanalyses of guillemot distribution data using robust spatial statistics (Leopold 2018) reported that spatial abundance of guillemots at OWEZ and PAWP was very variable from survey to survey and displacement effects were inconsistent. Razorbills were displaced in one out of six surveys at two Dutch wind farms (OWEZ and PAWP; Leopold et al., 2011, Krijgsveld et al., 2011), but not at Horns Rev (Petersen et al., 2006), Thornton Bank or Blighbank (Vanermen et al., 2012). Vallejo et al. (2018) found that there was no displacement of guillemots from Robin Rigg, and while there were instances of statistically significant decline in parts of the wind farm following construction, there were also instances of statistically significant increase in the wind farm. It appears in this instance that guillemots were changing their relative spatial distribution across the survey area with time, and this was independent of the wind farm. The reanalysis reported by Leopold (2018) stated that "a very weak displacement was found for Robin Rigg" through using a different statistical approach. Most recently, initial reports from the Beatrice offshore wind farm have shown evidence of no response of guillemots, razorbills and puffins to turbines, and so no displacement effect (MacArthur Green (2021). Peschko (2020) reported a strong "avoidance" of wind farms in the German Bight by guillemots breeding on the island of Helgoland. That study used GPS loggers to examine patterns of use by tagged birds, but the study was only undertaken after the construction of the wind farms, so changes to behaviour are unknown.

A review of available evidence for auk displacement was submitted for the Norfolk Vanguard assessment (MacArthur Green 2019b) and this concluded that precautionary rates of displacement and mortality from operational wind farms would be 50% and 1% respectively. These figures are also considered suitably precautionary for the potential displacement around construction vessels.

Current advice provided by UK SNCB's on auk displacement has been assumed to be precautionary and at present there are publications showing displacement occurring and not occurring in both the breeding season and non-breeding season. Most studies have reported results for guillemot and far fewer have reported results for other auks. Methods have often been very different with some sites using a Before After Control Impact (BACI) approach (e.g., Vanermen et al., 2012), others looking at wider spatial patterns (e.g., Vallejo et al. 2018) and others using responses to turbines (e.g., MacArthur Green 2021).

1.1.3. Gannet

A very wide range of displacement effects have been presented in assessments of gannets, with values spanning the whole range from 1% to 100%. However, mortality rates have typically been low, with most at 1% and a few above this at 2 – 5%. The key impact from offshore wind farms to gannets has generally been assumed to be from collisions with turbines, rather than displacement. Mortality rates likely reflect the often very long foraging ranges of gannets from breeding colonies (e.g., Wakefield et al. 2013), so the relative loss of habitat of gannets were displaced have been assumed to be small. However, there is increasing evidence that gannets have high macroavoidance rates (Rehfishch et al. 2014, MacArthur Green 2021), so are at low risk from collisions. Depending on the distance from the wind farm boundary that avoidance behaviour occurs there is a strong possibility that gannets are at risk from displacement and that this displacement rate is high. Whether there is a mortality risk from this displacement effect will depend on the cumulative effective habitat loss within the foraging range of breeding birds. Given that foraging ranges are large, though very variable between colonies (Wakefield et al. 2013), it seems likely that mortality effects would be relatively small.

1.1.4. Gulls

The displacement rate presented for assessments of gulls seems to be quite variable, with values from 10% to 50%. However, mortality rates have been relatively low (1–2%). Among the gulls, kittiwake has been a key species in assessments and one of only two species (including gannet) where both displacement effects and collision effects are recommended to be assessed. Little empirical evidence was found for kittiwake displacement, with evidence of no, or little, displacement occurring (Dierschke et al. 2016, Vanermen et al. 2015, MacArthur Green 2021). Among the large gulls there is some evidence of attraction into some wind farms (Vanermen et al. 2020, Dierschke et al. 2016) and no response to others (Thaxter et al. 2018).

2. Review of mortality rates

A literature review to identify and assess the consequences of displacement from offshore wind farms on vital rates, and associated variability and uncertainty, was carried out primarily using Google Scholar. Google Scholar has the best coverage of books, conference proceedings, 'grey' literature and reports. A search of 'grey' literature reports such as Statutory Nature Conservation Bodies (SNCB) Commissioned Research Reports, Marine Scotland Science Reports, ORJIP reports, and BTO Research Reports that are available and searchable online was also completed.

These reviews found no empirical evidence of the mortality of seabirds that have been displaced from offshore wind farms. It appears likely that this has not been studied to date, rather than not reported. There are studies of the consequences of disturbance or displacement of other groups of birds, particularly shorebirds (e.g., see Goss-Custard et al. 2020), but these were not reviewed here. There were some published empirical studies found of displacement of seabirds from offshore wind farms. Displacement studies of the key species were reported from the UK, Belgium, Netherlands, Germany, Denmark and Sweden (see Dierschke et al. (2016) and the references therein). A more recent study from the UK has not been completed or published yet but provided useful insight to possible breeding season displacement effects and a novel analytical methodology ([https://marine.gov.scot/sites/default/files/bowl_pre-](https://marine.gov.scot/sites/default/files/bowl_pre-construction_aerial_surveys_report-redacted.pdf)

[construction_aerial_surveys_report-redacted.pdf](https://marine.gov.scot/sites/default/files/bowl_pre-construction_aerial_surveys_report-redacted.pdf)). There have also been several studies reporting displacement of red-throated divers in Germany and the UK (Humphries et al. 2020, Vilela et al. 2020, Webb et al. 2016). There is ongoing research in the energetic consequences of displacement of wintering red-throated divers from offshore wind farms (<https://jncc.gov.uk/our-work/rtd><https://jncc.gov.uk/our-work/rtd-project/project/>) which should provide useful information on the likely consequences of displacement. Similarly, there is ongoing work that has deployed time-depth-recorders (TDRs) on guillemots at two North Sea and two west Scotland colonies and is investigating seasonal variation in time and energy budgets of those birds, funded by Vattenfall through the European Offshore Wind Deployment Centre (EOWDC) and by Marine Scotland. That work is likely to report findings during 2022. Proposed monitoring at the Forth and Tay offshore wind farms in Scotland should also provide both useful measures of displacement and their consequences

(https://marine.gov.scot/sites/default/files/ftrag-o_discussion_doc_mar_2016.pdf) when these projects are reported. Monitoring at offshore wind farms in the Moray Firth are also likely to provide further information on the displacement of seabirds, but are less focused on the consequences of displacement (e.g., https://marine.gov.scot/sites/default/files/minutes_2.pdf).

2.1. Carry over effects

Carry-over effects are the effects of decisions an animal makes in one season influencing their fitness in a subsequent season (e.g., Norris 2005). This has been demonstrated in many species, for example American redstarts (*Setophaga ruticilla*) that winter in higher quality habitat in the neotropics arrive earlier at their breeding sites in temperate North America and have higher breeding success than birds that winter in lower quality habitats (Marra et al. 1998).

There have been many published studies on carry over effects in seabirds. Body mass, as a measure of condition, was found to have a carry-over effect from winter to the breeding season in little penguins (*Eudyptula minor*), with female birds with a higher body mass breeding earlier and males with a higher body mass breeding more successfully (Salton et al. 2015). Female Magellanic penguins (*Spheniscus magellanicus*) arrived earlier to the breeding colony when they experienced better winter conditions, and these females laid larger eggs when they arrived earlier and were in better condition (Rebstock et al. 2018). However, there was no carry over effect found for males in the study. Similarly, common terns (*Sterna hirundo*) were shown to have a greater likelihood of recruitment when primary productivity was higher in their wintering range (Szostek & Becker 2015). Conditions in the non-breeding season were shown to affect body mass and wing length in black-vented shearwaters (*Puffinus opisthomelas*) in the California Current System. Winter foraging behaviour was shown by Daunt et al. (2014) to have carry over effects into the breeding season for European shags. That study showed that shorter foraging times were associated with earlier and more successful breeding.

Carry over effects from one breeding season to the next have been shown in Cory's shearwater (*Calonectris borealis*), where experimentally manipulated early breeding failure resulted in earlier return to

the colony for male birds and was associated with a greater probability of reproductive success (Gatt et al. 2021). In Manx shearwaters (*Puffinus puffinus*), Fayet et al. (2016) also showed carry over effects from one breeding season to the next through experimental manipulation of reproductive effort. This also resulted in less time spent at the wintering grounds, a reduction in time spent resting daily and a delayed start of breeding with lighter eggs and chicks.

There are many examples of published studies of carry over effects in the seabird species of importance to offshore wind farm displacement impact assessments.

Several studies have demonstrated the presence of carry over effects in kittiwake populations in the North Atlantic, North Pacific and Arctic oceans. Some of these studies have examined the carry over effects of winter conditions on the breeding season, while others have looked at the opposite effect. Most studies have reported the effects on survival and/or productivity, and a few have examined the mechanisms for these carry over effects.

Bogdanova et al. (2011) showed the breeding kittiwakes that were unsuccessful in their breeding attempt left their breeding sites earlier, dispersed more widely and travelled further to nonbreeding locations. Female birds that were unsuccessful also remained longer in these nonbreeding locations than female birds that were successful. Despite this, successful and unsuccessful birds returned to the breeding colony in the following season at the same time. Female kittiwakes during chick-rearing have a higher metabolic rate (Fyhn et al. 2001) and energy expenditure (Jodice et al. 2002) than males. So, Bogdanova et al. (2011) hypothesised that *“breeding outcome in females may produce a stronger carry-over effect on migration strategy than in males”*.

Effects from the non-breeding areas may result in important carry over effects into the following breeding season. Reiertsen et al. (2014) showed that 52% of the temporal variation in adult survival of kittiwakes breeding on Hornøya (Norway), on the coast of the Barents Sea, was explained by prey densities in two wintering areas (the western Atlantic in mid-winter and the Barents Sea in the pre-breeding period). Frederiksen et al. (2012) showed that many kittiwakes winter in the west central South Polar Gyre (SPG) and Hátún et al. (2016) showed that the strength of the SPG affected the abundance of *Calanus finmarchicus* within the gyre. Hátún et al. (2017) then showed that this affected the breeding success of kittiwakes nesting on the Faeroe Islands in the following summer.

Food supplementation experiments on kittiwakes nesting on an artificial colony in Alaska have shown that fed birds that nested successfully left the colony earlier than unfed successful breeders, they also foraged over a smaller area during breeding and had a smaller winter range than unfed birds (Whelen et al. 2020). It was also shown that recruits in fed nests had earlier age of first breeding than birds recruiting on to unfed nests (Vincenzi et al. 2013). However, Renner et al (2014) showed that breeding success of kittiwakes breeding on St George’s Islands and St Paul Island (Alaska) were better explained by past breeding success than any environmental parameters. However, they did conclude that, *“Adult condition and foraging conditions during the non-breeding season may be important datasets for understanding drivers of kittiwake and murre reproductive success at the Pribilofs”*. An earlier study by Zador et al. (2013) of the same population found that higher local abundances of age-1 walleye pollock *Theragra chalcogramma* were linked to higher kittiwake productivity the following year. North Pacific kittiwakes have also been shown to have higher egg laying success when the El Niño Southern Oscillation (ENSO) index is positive (McKnight et al. 2020).

Harris et al. (2020) compared carry over effects between individuals classified having either “shy” or “bold” personalities of kittiwakes breeding on Svalbard. Shy personalities were those birds that minimised risk taking behaviours that maximised survival, while bold personalities chose to increase current reproduction at the cost of survival probability. They found that negative carryover effects were stronger in shy individuals than in bolder individuals. There were also sex specific differences, with males that spent more time foraging during the non-breeding season arriving later back to the colony the following spring, started breeding later and had lower chick survival. Female kittiwakes that spent more time in flight

had later colony arrival, later egg laying and lower chick survival, while time spent foraging had a positive effect on chick survival.

Experimental manipulation of the stress hormone corticosterone was applied to kittiwakes breeding on Svalbard (Schultner et al. 2014). Breeding adult birds were treated with corticosterone, a hormone related to food shortages, and their migration was studied with GPS loggers. A difference between the sexes was found; treated females left the breeding site earlier and spent more time in wintering areas compared with treated males or untreated birds. The treated females did not arrive back at their breeding colonies any later than untreated females, nor did they have longer migrations. This study showed that stress during breeding resulted in carry over effects into the migration and wintering behaviour of female kittiwakes.

Oro and Furness (2002) also found carry over effects from the end of one breeding season to the next breeding season. Adult birds with a higher body mass at the end of the breeding season had higher survival to the following breeding season. Survival, as well as productivity, was also found to be positively related to the availability of Group 0 sandeels.

There were far fewer published studies found on any of the other key species. Several studies have been published on carry-over effects in auks. The frequency of sabbatical periods for breeding adult guillemots was found by Reed et al. (2015) to be higher during the season following higher sea surface temperatures (SST). This carry over effect was hypothesised to be more likely under future climate change scenarios, though the authors noted that the demographic effects of this may be subtle if the frequency remains low.

Studies on puffins have focused on carry over effects on female egg production and on the effects of the costs of breeding. Corticosterone levels in feathers grown in their post-nuptial moult explained the variation in egg size of female birds in the following breeding season (Kouwenberg et al. 2013). Bond & Diamond (2010) noted the importance of understanding where nutrients in eggs are derived when understanding the source of contaminants in eggs, and that unlike the other species of seabirds they studied (including guillemot and razorbill) puffins incorporated at least some nutrients gained in winter or migration stop over locations.

Daunt et al. (2020) found a strong relationship between body mass at the end of the breeding season and survival to the following breeding season in puffins, but evidence was less strong in kittiwake, guillemot and razorbill.

Brood manipulation studies on puffins have found that the parents of supplementary fed broods had offspring in the following breeding season with higher body condition (Wernham & Bryant 1998) and parents of birds that had broods swapped to manipulate the costs of breeding (i.e., parents with younger chicks were swapped with parents with older chicks) showed a relationship between adult body mass and survival to the following year (Erikstad et al. 2009).

No studies on carry over effects could be found on razorbills or red-throated divers. However, an ongoing study by JNCC and the University of Liverpool is studying this in wintering red-throated divers to determine whether displacement from offshore wind farms in winter has carry over effects on the following breeding season (<https://jncc.gov.uk/our-work/rtde-project/>).

Studies on gannets have found no apparent carry over effects of migratory distance (Pelletier et al. 2020) or non-breeding foraging strategy (Grecian et al. 2019) on breeding season demography or body mass. However, Fairhurst et al. (2017) found physiological carry over effects which were apparently related to an oil spill event in their non-breeding range.

Consideration of carry over effects are likely to be very important in the assessment of the consequences of displacement on individuals and therefore on populations. Methods to empirically derive the consequences of displacement on demographic rates will need to be carefully designed so that carry over effects are identified and assessed against appropriate populations. It is important to note that the

application of this evidence is needed within the legal framework of EIA and HRA. Thus, demographic consequences are only significant if they have a significant effect on regional or national/international populations, or adverse effects on the integrity of Special Protection Areas (SPAs).

2.2. Habitat quality

Hypothetically, habitat quality could have an effect on the consequences of displacement. If offshore wind farms are placed in locations of higher quality habitat, *and* this is a constraint to populations, then there will be greater consequences to displacement than location where habitat quality may be lower. Seabird often forage on patchy and ephemeral food sources that can be unpredictable in the spatial and temporal availability. However, these patterns can be complex and dependant on the spatial and temporal scales being considered (Weimerskirch 2007).

It seems likely that the effects of habitat quality on the consequences of displacement will differ for the key seabird species between the breeding season and non-breeding season, as there are likely to be different constraints on individuals. In the breeding season the key species are central place foragers, having to leave their nest site to forage at sea. Energetic constraints and the need to provide food to the nest result in breeding adult seabirds foraging within a certain distance of their nest site. This distance varies from species to species (Woodward et al. 2019). However, central place foraging can also result in local food depletion around the colony as the breeding season progresses (Ashmole's halo hypothesis; Ashmole 1963). However, the presence of this effect among the key species here has only been shown in gannet (Lewis et al. 2001), though it has been shown in other seabird species and may apply to the other species of interest (other than red-throated diver as this is not a colonial nesting seabird).

In the non-breeding season colonial nesting seabirds are not constrained through central place foraging and many of the key species here migrate long distances to spend the winter in other areas of sea (e.g., Frederiksen et al. 2012, Fort et al. 2012). However, it is clear that non-breeding season constraints do occur for many seabirds and that these can have carry over effects in the breeding season (see 3.1). It is possible for displacement from offshore wind farms in the nonbreeding season to result in constraints on seabirds that have the potential to affect their survival or breeding success. The only species that is a focus of this study that is *only* a concern in the nonbreeding season is red-throated diver. Non-breeding populations of red-throated diver tend to be found in relatively shallow, often coastal, waters (Vilela et al. 2020). Since recent wind farms have also tended to be in shallow coastal waters there was a potential for a constraint occurring on diver populations. Several studies have shown strong displacement effects on red-throated divers in Germany (Vilela et al. 2020) and the UK (Humphries et al. 2020, Irwin et al. 2019, Webb et al. 2017). While there are no published empirical estimates on the consequences of displacement, there is ongoing research in this field (<https://jncc.gov.uk/our-work/rtde-project/>). In addition, Topping & Petersen (2011) used an agent-based model to assess the impact of displacement from four areas around offshore wind farms in Danish waters on the red-throated diver population. Their models predicted minimal impacts on population size despite clear displacement effects, but authors highlighted that there were several important un-tested assumptions in their model, so results should be interpreted with some caution.

In general, it is difficult to draw conclusions on the effects of habitat quality on the consequences of displacement as published studies have mostly reported results at larger spatial scales than is typified by single offshore wind farm developments. As offshore wind farms become more numerous, the spatial scale of cumulative effects will be more closely matched to the spatial scale that published studies report.

2.3. Density dependence

Compensatory density dependence occurs when population decline results in reduced competition for resources in the remaining animals, which can have increased survival or productivity as a result, slowing or reversing the population decline (Horswill & Robinson 2015). If displacement from an offshore wind farm results in negative demographic effects on those individuals, compensatory density dependence may occur in the individuals that are unaffected by this displacement effect.

Densatory density dependence occurs when the population falls rapidly as a result of the loss of benefits from birds occurring above a certainty threshold density. Among seabird species this has often been reported as reduction in productivity as a result of the loss of colony vigilance in reducing predation of eggs and/or chicks (Horswill & Robinson 2015), but densatory density dependence is likely to occur when colony size falls to very small numbers, so mostly affects populations that are at risk of local or regional extinction.

The review by Horswill & Robinson (2015) found good evidence of density dependent processes occurring across a wide variety of seabirds. However, they noted that, “...there is not a simple mechanism of density-dependence that can be applied uncritically in all situations. Rather the influence of density-dependence relates to a complex interaction between resource availability, colony size and other local factors, such as predation.”. Evidence was found for both compensatory and densatory density dependence occurring among most of the key species considered here (Table 2). A variety of demographic processes were found to be affected by density dependence.

Table 2. Summary of evidence for compensatory or densatory density dependence for the key species (from Horswill & Robinson 2015).

Key species	Compensatory	Densatory
Kittiwake	Yes	Yes
Gannet	Yes	No evidence
Guillemot	Yes	Yes
Razorbill	Yes	No evidence
Puffin	Yes	Yes
Red-throated diver	No evidence	No evidence

Density dependence is particularly relevant if displacement were to result in a significant increase in density of a species in the remaining habitat. In such circumstances it is likely that competition may increase and therefore have an impact on body condition or survival of affected birds. While such a scenario can be envisaged for a seabird with limited available habitat (such as perhaps redthroated diver), it is much less likely for a seabird that can live over large areas of sea with apparently little constraint from habitat (such as guillemot, razorbill, kittiwake, gannet).

2.4. Seasonal differences in displacement

There may be differences in the displacement effects of offshore windfarms on the same species in different seasons. For instance, studies from the southern North Sea have found relatively high levels of

displacement of auks from operational offshore wind farms during the nonbreeding season (see Section 2), while other studies have found no displacement effects on auks in the breeding season (Vallejo et al. 2017). Initial survey results from the Beatrice offshore wind farm in the Moray Firth, Scotland, have also shown no displacement of auks in the breeding season from

the wind farm

(https://marine.gov.scot/sites/default/files/bowl_preconstruction_aerial_surveys_report-redacted.pdfhttps://marine.gov.scot/sites/default/files/bowl_preconstruction_aerial_surveys_report-redacted.pdf).

There is evidence of strong displacement of gannets from offshore wind farms in the breeding season (Peschko et al. 2021, Garthe et al. 2017) and during migration (Rehfisch et al. 2014). No published evidence could be found on the displacement of gannets during winter (when there are few gannets in regions with offshore wind farms), though it appears likely to be the same.

Using a Before After Control Impact (BACI) approach, Vanermen et al. (2015) described no significant change in kittiwake abundance inside Belgian offshore wind farms, predominantly in winter. The authors noted that, “flocks of black-legged kittiwakes were repeatedly observed foraging inside the wind farm boundaries. Strikingly, the percentage of kittiwakes displaying active foraging behaviour (pecking or diving for food) inside the wind farm (5.8%) was much higher than in the control area (0.7%) ($\chi^2 = 163.5$, $df = 1$, $P < 0.001$)”. Similarly, at Robin Rigg offshore wind farm in the Solway Firth, Canning et al. (2013) found no change, or an increase, in the number of kittiwakes inside the wind farm between the pre-construction and post-construction (year three) phases of the development. Kittiwakes occurred in the wind farm year-round but predominantly occurred in the breeding season.

A potential seasonal difference in displacement effects is not relevant to red-throated divers, as they are largely a winter feature at nearshore offshore wind farms in the UK, particularly the Outer Thames estuary and Liverpool Bay. In the breeding season, red-throated divers occur on freshwater bodies and many fly to the nearest coastal marine habitats to forage. These coastal marine habitats that are used by breeding red-throated divers in the UK are not proposed for offshore wind farm development.

3. Review of tools and methods for estimating mortality

There are two primary approaches used for the assessment of displacement mortality for offshore wind farm EIA or HRA in the UK: the matrix approach and SeabORD.

3.1. SNCB Matrix approach

The matrix approach is a simple matrix of estimated number of birds predicted to be displaced from the wind farm being assessed across a range of displacement rates from 0% to 100%. This is compared with a range of subsequent mortality levels from 0% to 100%. Guidance on the use of the matrix approach, including the values used to parameterise the matrix has been provided by the UK SNCBs (SNCBs 2017). Input to the metric is the “mean seasonal peak population estimates based on several years data”, though typically there is not more than two seasons of survey data. The mean peak population estimate is based on the abundance of birds both on the water and in flight in the wind farm and a suitable buffer around the wind farm (which is species specific). Assessments are completed for the breeding season and non-breeding season separately. A range of displacement values are determined from published indices of species sensitivity to disturbance and a range of mortality levels are determined from published indices of species habitat flexibility. The matrix is based on displacement levels varying in 10% increments while

the mortality levels are based on 1% increments from 0% to 5% and 10% increments from 10% to 100%. An example matrix is provided in the guidance (Figure 1). Note that this example is based on a seasonal mean peak population estimate of 5000 birds inside the wind farm and buffer area, with a range of displacement from 10% to 30% and a range of mortality from 1% to 80%. Thus, the range of predicted mortality of birds is from five to 1200 birds, with a 'realistic' range from 20 to 500 birds being killed as a result of displacement from the wind farm.

It is important to note that to date the displacement rate and mortality rate have been based on recommendations from SNCB's based on the indices described above and not on empirical measures of displacement or mortality, largely because these have been lacking.

Figure 1. Example of Matrix Approach from SNCB (2017) guidance.

Species (season)		Mortality Level (% of displaced birds that die)													
Displacement Level (% of all birds on site)		0%	1%	2%	3%	4%	5%	10%	15%	20%	30%	50%	80%	100%	
	0%	0	0	0	0	0	0	0	0	0	0	0	0	0	
	10%	0	5	10	15	20	25	50	75	100	150	250	400	500	
	20%	0	10	20	30	40	50	100	150	200	300	500	800	1000	
	30%	0	15	30	45	60	75	150	225	300	450	750	1200	1500	
	40%	0	20	40	60	80	100	200	300	400	600	1000	1600	2000	
	50%	0	25	50	75	100	125	250	375	500	750	1250	2000	2500	
	60%	0	30	60	90	120	150	300	450	600	900	1500	2400	3000	
	70%	0	35	70	105	140	175	350	525	700	1050	1750	2800	3500	
	80%	0	40	80	120	160	200	400	600	800	1200	2000	3200	4000	
	90%	0	45	90	135	180	225	450	675	900	1350	2250	3600	4500	
	100%	0	50	100	150	200	250	500	750	1000	1500	2500	4000	5000	

3.2. SeabORD

SeabORD is a tool to estimate the cost to individual seabirds, in terms of changes in adult survival and productivity, of displacement and barrier effects resulting from offshore wind farms (Searle et al. 2018). It was developed for guillemot, razorbill, puffin, and black-legged kittiwake in the Forth and Tay region of Scotland during the chick-rearing period. Its application to date has been limited to offshore wind farm EIA/HRA in the Forth and Tay region.

The tool uses a simulation model to predict the time/energy budgets of breeding seabirds during the chick-rearing period and translates these into projections of adult annual survival and productivity for each individual and at the population level. The model simulates foraging decisions of individual seabirds under the assumption that they are acting in accordance with optimal foraging theory, minimising time away from offspring whilst maximising energy gain. In the model, foraging behaviour of individual seabirds is driven by prey availability, travel costs, provisioning requirements for offspring, and at-sea density of conspecifics. The model estimates productivity and adult survival, the latter resulting from estimates of adult mass at the end of the breeding season. To determine wind farm effects, baseline scenarios are compared with scenarios containing one or more wind farms.

The model estimates the demographic fate of individual birds, partitioned into different categories of affected individuals, including those that experience only displacement, only barrier effects, both or neither (i.e., those that never interact with a wind farm). The model also quantifies the impact on observed birds; it looks at the relationship between the number of birds seen in a "snapshot" at-sea survey in the wind farm footprint and the mortality associated with the subsequent development. This provides a

mechanism for translating at-sea survey data from wind farm footprints into population-level demographic consequences.

The model was parameterised from empirical values for time activity budgets, adult mass change during chick-rearing, chick growth and chick survival from studies of these or closely related species from long term studies of seabirds on the Isle of May or from published studies elsewhere. In some instances, parameter values were based on expert opinion because relevant empirical data did not exist.

The tool requires the user to input a range of information on wind farm footprints, displacement and barrier rates, colony locations, colony population size, bird foraging distribution and density, and prey distribution and density. Users also specify the proportion of the total species population to include in simulations, and the number of matched pairs of baseline and wind farm simulations, both of which affect assessments of uncertainty in model outputs. Users are advised to identify a range of median prey densities over which to run multiple paired simulations to provide a range of estimated wind farm impacts, which are then synthesized into a single value with associated uncertainty for each impact metric.

Local tracking data represents the 'gold standard' for estimating bird densities for use with the tool. The method in which these data are analysed to derive estimated foraging densities may have an impact on effect sizes. This is particularly the case in terms of whether the statistical analysis has included or removed flight locations from GPS tracking data prior to estimating bird densities but is also important in terms of whether non-flight fixes have been partitioned into foraging and resting, whose distributions may differ.

SeabORD is the only current means of estimating mortality from empirically derived inputs (with the exception of the displacement rate) and thus provides a more defensible estimation of mortality for any given displacement rate than the matrix approach, at least as these methods are applied to impact assessments in the UK. It has, however, been limited in its application to date to the wind farms in the Forth and Tay region. The requirement for high quality tracking data of the type and amount available from the long-term studies on the Isle of May combined with the need for prey density estimates appear to have been the primary cause of the limited application of this tool. In addition, the estimates are very sensitive to the assumed relationship between breeding adult seabird body mass and subsequent survival, and that relationship is not well known, but most likely varies from colony to colony depending on a variety of factors.

3.3. Other approaches

Warwick-Evans et al. (2017) developed an individual based model (IBM) to predict the impacts of offshore wind farm development on breeding gannets at Les Etac, Alderney. Like the SeabORD IBM, this model required high quality tracking data, which was obtained from 63 birds across four seasons. The model incorporated direct interactions between birds and the environment, including the availability of prey and intraspecific competition. The model indicated that there were no changes in mortality rate, productivity or physiological state and negligible mortality, if gannets avoided the offshore wind farms that were assessed cumulatively. Concerns that in years of poor prey availability, wind farms would have increased impact on gannets, were not supported by the model outcomes. It is important to note that this study assumed a displacement rate (and macroavoidance rate) of 64%. Recent evidence suggests that there is almost total displacement of gannets from offshore wind farms, so this was likely to be an underestimate. However, the model also assumed that there would be collisions as a result of birds flying through turbine rotors, which if almost total avoidance occurs, is unlikely to be the case.

A method that combined the SNCB matrix approach with seasonal potential biological removal (PBR) estimates of allowable take was developed by Busche & Garthe (2016). The matrix is very similar to that recommended by the UK SNCBs, but rather than estimating a possible mortality level based on indices of habitat flexibility, the mortality is compared with a range of PBR values. This has the advantage that the

level of mortality as a result of displacement required to exceed an estimate maximum take of birds from the population above which the population would be a risk of decline can be shown. This allows either the level of displacement needed for any given level of acceptable additional mortality, or the level of mortality needed to exceed any given level of displacement to be shown. In the example shown in Table 3, the predicted allowable take, according to the PBR assessment, from the population being studied was 19 – 20 birds per annum. From this matrix it can be estimated that if the displacement rate was 50%, mortality would need to be 40% or higher to result in a significant impact on the population. An alternative explanation would be that for a mortality from displacement of 20% the displacement rate would need to be 100% to result in a significant effect on the population. This allows the lack of knowledge of either the displacement rate or mortality rate as a result to be placed in the context of the level of additional mortality the population can withstand without significant effects.

Table 3. Displacement matrix for breeding season guillemots at Helgoland (Germany). From Busch & Garthe (2016).

Guillemot		Mortality (%)											
(colony attendance)													
Displacement level (%)		0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	
	0%	0	0	0	0	0	0	0	0	0	0	0	
	10%	0	1	2	3	4	5	6	7	8	9	10	
	20%	0	2	4	6	8	10	12	14	16	17	19	
	30%	0	3	6	9	12	15	17	20	23	26	29	
	40%	0	4	8	12	16	19	23	27	31	35	39	
	50%	0	5	10	15	19	24	29	34	39	44	49	
	60%	0	6	12	17	23	29	35	41	47	52	58	
	70%	0	7	14	20	27	34	41	48	54	61	68	
	80%	0	8	16	23	31	39	47	54	62	70	78	
	90%	0	9	17	26	35	44	52	61	70	79	87	
	100%	0	10	19	29	39	49	58	68	78	87	97	
Input data: peak population estimates during colony attendance period accounting for 1/3 of non-breeding adults associated with the colony (Amrumbank West 2012, Meerwind Süd/Ost 2011, Nordsee Ost 2010)													
Reference population: 5,744 Ind. (breeding adults, Helgoland colony 2011) (Dierschke et al., 2012)													
seasonal PBR figure ($f = 0.3$) for colony attendance season (4 months): 20 Ind.													

However, Cook & Robinson (2015) recommended that PBR is not used for offshore wind farm assessments in the UK. The authors stated that, “PBR considers only whether a pre-determined level of mortality is exceeded, rather than the biological impact of any additional mortality at a population level”. However, widely accepted Leslie Matrix population could be used to determine the level of additional mortality a population was predicted to sustain, within the constraints of the assumptions of the models. Thus, the method suggested by Busch & Garthe (2016) could still be useful if the sustainable level of additional mortality predicted by another population model was applied. This could be extended to compare the recommended SNCB approach, where the mortality is also estimated in the matrix, allowing the difference between the predicted displacement mortality and the level of predicted sustainable additional mortality could be compared. As described in Busch & Garthe (2016), it would be important that this was completed as a cumulative or in-combination assessment, as well as at an individual project level.

Van Kooten et al. (2019) presented an approach to assessment based on three separate modelling approaches. The spatial distributions of seabirds were predicted using a habitat preference modelling type approach to predict space use in un-surveyed areas. An individual-based energetics model was used to predict the mortality consequences of the placement of offshore wind farms within the spatial abundance predictions. Finally, a PVA was used to determine the effects of these results on populations.

4. Collation of relevant datasets

A search was undertaken to identify datasets which may contain information that can be used to estimate empirical values for the demographic consequences of displacement on seabirds. This was based on a general online Google search and a review of relevant peer-reviewed studies and grey literature which have utilised relevant seabird datasets for various investigative purposes. Results are listed below in Table 4. Where potentially useful data have been identified, the owners of the dataset would be contacted as part of WP2 or WP3.

Table 4. Sources of datasets with information potentially suitable for assessing consequences of seabird displacement.

Data Source	Description	Link	Relevant Information Obtainable
FAME (Future of the Atlantic Marine Environment) and STAR (Seabird Tracking and Research)	Twin projects in which RSPB, in collaboration with partners and a consortium of funders (including Marine Scotland, NatureScot and JNCC), have undertaken tracking of multiple species of seabirds from multiple colonies around the coast of the UK since 2010.	https://marine.gov.scot/information/fame-star-seabird-kittiwakes-guillemots-razorbills-and-shags-tracking-projects https://marine.gov.scot/information/fame-star-seabird-kittiwakes-guillemots-razorbills-and-shags-tracking-projects https://opendata-rspb.opendata.arcgis.com/datasets?sort=name&t=Tracking%20Data	At-sea distribution Foraging range
BirdLife International's Seabird Tracking Database	Contains tracking data provided by seabird researchers from around the world, including the FAME and STAR projects. A complete list of all seabird species currently recognized by BirdLife International can be found at the Data Zone section of the website. Raw data are shown on the website's mapping tool and some results of the application of analytical methods can be viewed in BirdLife's Marine E-atlas.	http://www.seabirdtracking.org/	At-sea distribution Foraging range

The European Seabirds at Sea (ESAS) database	A collaborative dataset with inputs from the Joint Nature Conservation Committee (JNCC) and other northwestern European organisations with the aim of collecting data on the distribution and abundance of seabirds in north-west European offshore areas. UK boat-based data and aerial data are available on JNCC's Resource hub.	https://hub.jncc.gov.uk/	At-sea distribution Foraging range
OBIS-Seamap website	Contains ESAS database among 212 worldwide seabird tracking datasets of georeferenced distribution, abundance, and telemetry data with tools to query and assess species.	https://seamap.env.duke.edu/	At-sea distribution Foraging range Environmental variables
SEATRACK	Presents data from GLS loggers of 11 seabird species (including puffin, guillemot and kittiwake) from 56 study sites. The application allows users to select results for different species, years, seasons, and colonies and display them on a map. The maps depict kernel distributions or probability density functions overlaid over all available data points that are based on the selection criteria.	https://seapop.no/en/seatrack/	At-sea distribution Foraging range

JNCC Seabird Monitoring Programme database	Holds results of an ongoing annual monitoring programme, established in 1986, of 25 species of seabird that breed regularly in Britain and Ireland. The programme aims to ensure that sample data on breeding numbers and breeding success of seabirds are collected, both regionally and nationally, to enable their conservation status to be assessed.	https://app.bto.org/seabirds/public/index.jsp	Colony location Number of breeding pairs Long-term population trends
The Marine Ecosystem Research Programme (MERP)	Aims to integrate existing and new marine data sets with current models of marine ecosystem services to further knowledge and understanding of the UK marine ecosystems. MERP undertook a major project to collate a large dataset of seabird observations in the north-east Atlantic. From this, density surface modelling for the 12 most common seabirds was produced. Species distribution models were used that took into account environmental variables likely to influence the biogeographical range of species.	https://www.marine-ecosystems.org.uk/	Foraging range At-sea distribution Environmental variables

Marine Scotland Information (MSI¹)	A web portal that provides access to information about the Scottish marine environment while providing links to datasets and map resources that are made available by Marine Scotland and Partners. MSI is part of the Marine Scotland Open Network which also includes MS Maps NMPi and MS Data.	https://marine.gov.scot/ maps.marine.gov.scot data.marine.gov.scot	Prey availability and distribution Environmental variables
World Seabird Union's Seabirds.net	A global seabird information portal containing the Seabird Information Network (S.I.N.) list of databases. Includes information on seabird colonies, population trends and productivity	https://www.seabirds.net/seabird_information_network/	Colony location Number of breeding pairs Productivity Foraging range
Seabird Maps and Information for Fisheries	Website is designed to help fisheries managers assess risk of seabird bycatch in geographic areas of interest. It can also be used to map seabird occurrence by region.	https://www.fisheryandseabird.info/	Foraging range At-sea distribution Environmental variables Prey availability and distribution
UK Centre for Ecology & Hydrology's (CEH) Environmental Information Platform	Contains datasets on seabird monitoring, including diet, productivity and dive times.	https://eip.ceh.ac.uk/	Foraging range Energy requirements Productivity

Movebank	An online platform that holds data on animal movements through worldwide tracking studies, including GPS tracking and bird ringing information on seabird species.	https://www.movebank.org	Foraging range At-sea distribution
The EURING databank(EDB)	Holds a high proportion of the ringing recovery data that have been gathered by bird ringing schemes throughout Europe.	https://euring.org/data-and-codes/euring-databankdatabank	Biometrics Survival rates Migratory movements
MEDIN portal	Contains information on over 15,000 marine datasets from over 400 UK organisations. Includes survey reports, fisheries information	https://portal.medin.org.uk/portal/start.php	Foraging range At-sea distribution
Red-throated Diver Energetics Project	Data from 2018, 2019 and 2021. Archival geolocator (GLS) and time depth recorder (TDR) tags were deployed and retrieved from red-throated divers breeding in Scotland, Finland and Iceland to quantify foraging behaviour and approximate nonbreeding season locations. Breeding birds that were tagged in Orkney, Shetland and Finland wintered in UK waters. See	https://jncc.gov.uk/our-work/rtde-project/	Foraging range At-sea distribution

	Thompson et al. (2020 ¹) for details.		
DIVER tracking study	Tracking study of divers within German Bight and wider North Sea. See Dorsch et al. (2019 ²) for details.	https://www.movebank.org/cms/webapp?wt_fragment=page=studies.path=study60771859	At-sea distribution

¹ Thompson, D.L., O'Brien, S., Ruffino, L., Johnson, L., Lehtikainen, P., Okill, D., Petersen, A., Petersen, I.K., Väisänen, R., Williams, J. & Williams, S. 2020. Red-Throated Diver Energetics Project - 2020 Field Season Report. JNCC Report No. 673, JNCC Peterborough, UK, ISSN 0963-8091.

² Dorsch, M., C. Burger, S. Heinänen, B. Kleinschmidt, J. Morkūnas, G. Nehls, P. Quillfeldt, A. Schubert, R. Žydelis (2019): DIVER – German tracking study of seabirds in areas of planned Offshore Wind Farms at the example of divers. Final report on the joint project DIVER, FKZ 0325747A/B, funded by the Federal Ministry of Economics and Energy (BMWi) on the basis of a decision by the German Bundestag.

JNCC Report: Review of evidence for identified seabird aggregations (Cook et al. 2015³)	Includes a review of peer-reviewed, grey literature and FAME project tracking data available to help determine locations and extents of seabird aggregations around the UK.	https://data.jncc.gov.uk/data/f94ea883-7de4-48eb-8a99-191d23840aa9/JNCC-Report-537-FINAL-WEB.pdf 7de4-48eb-8a99-191d23840aa9/JNCC-Report-537-FINAL-WEB.pdf	Foraging range At-sea distribution
CWS-EC Eastern Canada Seabirds at Sea (ECSAS) programme	Data on seabird abundance and distribution in Canadian waters. In addition, the biological, chemical, and physical data collected concurrently by oceanographers with the Department of Fisheries and Oceans provide the means to examine the linkages between seabirds and their marine habitats.	http://ipt.iobis.org/obiscanada/resource?r=c_ws_eastcoastseabirdsatc	Foraging range At-sea distribution Environmental variables
Seabird FMR Calculator	The field metabolic rate (FMR) is the sum of an animal's energy expenditure over a specified period. The Seabird FMR Calculator is a web-based app which can be utilised to generate estimates of FMR for any population of breeding seabird. Daily FMR estimates are based on the outputs of a model	https://ruthedunn.shinyapps.io/seabird_fmr_calculator/	Energy expenditure

³ Cook, Aonghais S.C.P., Still, David A., Humphreys, Elizabeth M. & Wright, Lucy J. 2015. Review of evidence for identified seabird aggregations. JNCC Report No 537. JNCC, Peterborough.

	exploring the large-scale determinants of seabird FMR during the breeding season. The app requires inputs of species, bird mass, colony latitude and breeding phase. In return it generates an estimate of daily FMR.		
JNCC Seabird Oil Sensitivity Index (SOSI)	A tool which aids planning and emergency decision making with regards to oil pollution. The SOSI report is accompanied by GIS which can be used to identify seabird sensitivity in specific key areas at specific times of the year.	https://jncc.gov.uk/our-work/seabird-oil-sensitivity-index-sosi/ https://jncc.gov.uk/our-work/seabird-oil-sensitivity-index-sosi/	At-sea distribution Environmental variables

4.1. Evidence of displacement rates

A literature review has been undertaken to gather evidence of studies where attempts have been made to quantify displacement rates of seabirds around offshore wind farms. Historically, little robust evidence has been available – for example at the JNCC/Marine Renewables Ornithology Group *Seabird Displacement Impacts from Offshore Windfarms* Workshop held in 2015, JNCC noted that consistent empirical evidence for displacement from offshore wind farms was relatively limited, due to both the inherent complexities of species distribution data and the fact that wind farm projects differ in scale, density and physical location. At that point, very few studies had presented results quantifying the rate and scale of displacement, and those that did indicated these rates are likely to be species and site specific.

As part of the workshop's outputs, Busch et al. (2015⁴) presented a literature review of displacement impacts of offshore wind farms, which contained the following information, based on results of post-construction monitoring, where displacement was quantified (Table 5). Note however, that this does not include the studies where no quantification was undertaken, or where no significant change in abundance was recorded (i.e., no, or no significant displacement effect).

Table 5. Sources of quantified estimated seabird displacement rates in Busch et al. (2015).

Species	Location	Displacement rate	Source
Red-throated diver	Nysted and Horns Rev, Denmark	100 % (wind farm footprint) 77 % (2 km buffer) 50 % (4 km buffer)	Petersen et al (2006 ⁵)
Red-throated diver	Gunfleet Sands	100 % (>1 km)	Baker (2011 ⁶)
Red-throated diver	Kentish Flats	89-94 % (> 3 km)	Percival (2009, 2010, 2014 ⁷)
Divers	OWEZ, PAWP Netherlands	significant decline in 3 of 8 surveys	Leopold et al. (2011)
Divers	OWEZ Netherlands	Significant decline	Leopold et al. (2013 ⁸)
Divers	Egmond aan Zee	68 %	Krijgsveld et al. (2011)
Gannet	Robin Rigg	Up to 50 %	Walls et al. (2013)

⁴ Busch, M., Buisson, R., Barrett, Z., Davies, S., Rehfish, M. (2015). Review of the Habitat Loss Method for Assessing Displacement Impacts from Offshore Wind Farms. JNCC Report 551, Peterborough.

⁵ Petersen, I.K., Christensen, T.K., Kahlert, J., Desholm, M. & Fox, A.D. 2006. Final results of bird studies at the offshore wind farms at Nysted and Horns Rev, Denmark. NERI Report, Commissioned by DONG energy and Vattenfall A/S.

⁶ Baker, R. 2011. Gunfleet Sands Gunfleet Sands 2 Offshore Wind Farms. Year 1 Post-construction Ornithological Monitoring. NIRAS Consulting Ltd, Cambridge.

⁷ Percival, S. 2014. Kentish Flats Offshore Wind Farm: Diver Surveys 2011-21 and 2012-13. Report to Vattenfall Wind Power. Ecology Consulting, Durham.

⁸ Leopold, M. F., van Bemmelen, R.S.A. and Zuur, A., 2013. Responses of local birds to the offshore wind farms PAWP and OWEZ off the Dutch mainland coast. Report C151/12, IMARES, Texel.

Gannet	OWEZ, PAWP Netherlands	"nearly total" (significant in 2 of 10 surveys)	Leopold et al. (2011)
Gannet	Blighbank, Belgium	Significant decline	Vanermen et al. (2012)
Gannet	OWEZ, PAWP Netherlands	Significant decline	Leopold et al. (2013)
Gannet	Bligh Bank, Belgium	85 % within wind farm	Vanermen et al. (2014 ⁹)
Gannet	Egmond aan Zee	64 %	Krijgsveld et al. (2011 ¹⁰)
Razorbill	OWEZ, PAWP Netherlands	50 % (significant in 1 of 6 surveys)	Leopold et al. (2011)
Razorbill	Blighbank, Belgium	Significant decline	Vanermen et al. (2012)
Razorbill	PAWP Netherlands	Significant decline	Leopold et al. (2013)
Razorbill	Bligh Bank, Belgium	64 % within wind farm	Vanermen et al. (2014)
Guillemot	OWEZ, PAWP Netherlands	50 % (significant in 2 of 11 surveys)	Leopold et al. (2011 ¹¹)
Guillemot	Blighbank, Belgium	Significant decline	Vanermen et al. (2012)
Guillemot	OWEZ, PAWP Netherlands	Significant decline	Leopold et al. (2013)
Guillemot	Bligh Bank, Belgium	71 % within wind farm	Vanermen et al. (2014)
Auks	Robin Rigg	30 %	Walls et al. (2013 ¹²)
Auks	Egmond aan Zee	68 %	Krijgsveld et al. (2011)
Kittiwake	OWEZ, PAWP Netherlands	none (significant attraction in 1 of 5 surveys)	Leopold et al. (2011)
Kittiwake	PAWP Netherlands	Significant decline	Leopold et al. (2013)
Kittiwake	Bligh Bank, Belgium	No avoidance	Vanermen et al. (2014)

Subsequent to the workshop in 2015, Dierschke et al. (2016) published a comprehensive review of post-construction studies of seabirds at 20 European offshore wind farms for evidence for displacement or attraction of 33 different seabird species. This provides a useful overview of the level of consistency of species' behaviour and how confidently displacement rates could be attributed for use in analysis of overall impacts of displacement.

⁹ Vanermen, N., Onkelinx, T., Courtens, W., Van de walle, M., Verstaete, H., and Stienen, E.W.M., 2014. Seabird avoidance and attraction at an offshore wind farm in the Belgian part of the North Sea. *Hydrobiologia*. 756 pp.51-61

¹⁰ Krijgsveld, K.L., Fijn, R.C., Japink, M., van Horssen, P.W., Heunks, C., Collier, M.P., Poot, M.J.M., Beuker, D. and Dirksen, S. (2011). Effect studies Offshore Wind Farm Egmond aan Zee: Final report on fluxes, flight altitudes and behaviour of flying birds.

NoordzeeWind report nr OWEZ_R_231_T1_20111114_fluxandflight, Bureau Waardenburg report nr 10-219.

¹¹ Leopold, M.F., Dijkman, E.M., Teal, L. & The OWEZ-Team 2011. Local Birds in and around the Offshore Wind FARM Egmond aan Zee (OWEZ). NoordzeeWind Rapport OWEZ_R_221_T1_20111220_local_birds. Imares / NoordzeeWind, Wageningen / IJmuiden.

¹² Walls, R., Canning, S., Lye, G., Givens, L., Garrett, C., Lancaster, J., 2013. Analysis of Marine Environmental Monitoring Plan Data from the Robin Rigg Offshore Wind Farm, Scotland (Operational Year 1): Technical Report. Natural Power Consultants, Dumfries and Galloway, Scotland, UK.

The review found that red-throated divers and gannets showed consistent and strong avoidance behaviour/displacement around offshore wind farms, whereas razorbill and guillemot showed less consistent displacement. Compared to pre-construction situations, razorbill and guillemot strongly decreased in some wind farms, but did not change or even increased in others. There were no recognisable consistent displacement or attraction effects recorded for kittiwake. No general picture could be obtained for puffin due to a relative lack of data, although it was considered strong avoidance appears to be unlikely. A summary of Dierschke et al. (2016) findings is presented in Table 6.

Table 6 Evidence of avoidance and attraction in Dierschke et al. (2016).

Species	Mean response score	Number of studies	Strong avoidance	Weak avoidance	No effect	Weak attraction	Strong attraction
Red-throated diver	1.3	7	3	2			
Divers	1.1	9	7	1			
Gannet	1.4	12	7	2	1		
Razorbill	2.0	8	2	4	2		
Guillemot	2.0	12	5	2	2		1
Razorbill/guillemot	-	4	1	2			
Kittiwake	2.7	12	2	2	5	1	1

Mean Response Score:

Strong avoidance (score 1-2): complete absence or very strong decrease in abundance in a marine area, which had been used by the species before the construction of the wind farm.

Weak avoidance (score 2-3): continued use of a marine area after the construction of the wind farm, but to a lesser degree or at a lower abundance.

In only a minority of studies reviewed by Dierschke et al. (2016) was there sufficient information to attempt some form of quantification of displacement rate. These are summarised below in Table 7.

Table 7 Quantification of displacement rates based on Dierschke et al. (2016) criteria.

Species	Location	Displacement rate	Sources
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Red-throated diver	Gunfleet Sands	non-significant decrease >80%	Barker, 2011
Divers	North Hoyle	non-significant decrease >80%	PMSS, 2006, 2007; May 2008
Divers	Kentish Flats	non-significant decrease >80%	Gill et al., 2008; Rexstad and Buckland, 2012; Percival, 2011, 2014; Banks et al., 2011
Divers	Thanet	significant decrease >50%	Ecology Consulting, 2012; Percival, 2013
Divers	Alpha ventus	significant decrease >50%	Sonntag et al., 2011; Mendel, 2012; Aumüller et al., 2013; Mendel et al., 2013, 2014, 2015; Hill et al., 2014; Welcker and Nehls, 2016
Gannet	Bligh Bank	significant decrease >50%	Vanermen et al., 2011, 2013a, 2015a, 2016
Gannet	Thorntonbank	significant decrease >50%	Vanermen et al., 2011, 2013a–c, 2015a, 2016
Gannet	Alpha ventus	significant decrease <50%	Sonntag et al., 2011; Mendel, 2012. Aumüller et al., 2013; Mendel et al., 2013, 2014, 2015; Hill et al., 2014; Welcker and Nehls, 2016
Razorbill	Robin Rigg	non-significant decrease >50%	Canning et al., 2013
Razorbill	Thanet	significant decrease <50%	Ecology Consulting, 2012; Percival, 2013
Razorbill	Bligh Bank	significant decrease >50%	Vanermen et al., 2011, 2013a, 2015a, 2016
Razorbill	Thorntonbank	non-significant decrease >50%	Vanermen et al., 2011, 2013a–c, 2015a, 2016
Guillemot	North Hoyle	significant increase >50%	PMSS, 2006, 2007; May 2008
Guillemot	Gunfleet Sands	non-significant decrease >80%	Barker, 2011
Guillemot	Bligh Bank	significant decrease >50%	Vanermen et al., 2011, 2013a, 2015a, 2016
Guillemot	Thorntonbank	significant decrease >50%	Vanermen et al., 2011, 2013a–c, 2015a, 2016
Guillemot	Egmond an Zee	significant decrease <50%	Krijgsveld et al., 2008, 2010, 2011; Leopold and Camphuysen, 2008; Leopold et al., 2011, 2013; Camphuysen, 2011

Razorbill/guillemot	Alpha ventus	significant decrease >50%	Sonntag et al., 2011; Mendel, 2012; Aumüller et al., 2013; Mendel et al., 2013, 2014, 2015; Hill et al., 2014; Welcker and Nehls, 2016
Kittiwake	Robin Rigg	non-significant increase >80%	Canning et al., 2013
Kittiwake	Gunfleet Sands	non-significant increase >50%	Barker, 2011
Kittiwake	Thorntonbank	non-significant decrease >80%	Vanermen et al., 2011, 2013a–c, 2015a, 2016
Kittiwake	Prinses Amalia	significant decrease <50%	Leopold et al., 2010, 2011, 2013; Camphuysen, 2011
Kittiwake	Alpha ventus	significant decrease <50%	Sonntag et al., 2011; Mendel, 2012; Aumüller et al., 2013; Mendel et al., 2013, 2014, 2015; Hill et al., 2014; Welcker and Nehls, 2016

In recent years, a study by Vanermen et al. (2015) found that gannet, guillemot and razorbill avoided the Bligh Bank Wind Farm area, and decreased in abundance by 85, 71 and 64%, respectively. Welcker & Nehls (2016) found that from survey data covering the first three years of operation of the alpha ventus offshore wind farm, Germany, there was evidence of displacement of divers (90% lower), gannets (79%) and auks (75%) from the wind farm compared to outside.

Vallejo et al. (2017) however found relative guillemot abundance remained similar within the Robin Rigg offshore wind farm footprint across the pre-construction, construction and operational development phases.

Peschko et al. (2020) studied the effects of three German offshore wind farms on seabirds covering 14 years before and 3 years post-construction. They found that guillemot density was highly significantly reduced by 63% in spring out to c. 9km, and by 44% in the breeding season within the OWFs (+3 km buffer). For kittiwake there was no significant difference in the spring, with density being reduced by a non-significant 10% in the OWF area. Kittiwake density was highly significantly reduced by 45% in the breeding season however, out to c. 20km. The study highlights the potential large-scale effects of displacement and seasonal variation in avoidance behaviour throughout the yearly cycle.

Recently, a study of year 1 post-construction monitoring of the Beatrice Offshore Wind Farm (MacArthur Green, 2021¹³) found broadly similar overall abundance (within the total study area) for all species compared to pre-construction surveys in 2015. Within the wind farm, guillemot, razorbill and kittiwake were (on average) more abundant in 2019 than 2015 and gannet and puffin were less abundant. Of the latter, gannet had the most marked difference, which is consistent with results from other wind farm studies. A robust assessment of overall wind farm effect was obtained from spatial models fitted to the before (2015) and after (2019) construction data. For gannet, the spatial model found no evidence for an overall change in abundance, but a very strong and significant spatial effect, with a decline centred on the wind farm, backing up the more simplistic observations of gannet avoiding the wind farm. Puffin

¹³ MacArthur Green (2021). Beatrice Offshore Wind Farm Year 1 Post-construction Ornithological Monitoring Report 2019.

abundance was not found to have changed in the study area, but an area of reduced abundance included the wind farm, plus a much larger area centred to the east of the site boundary.

There was a significant increase in the overall guillemot abundance, but no significant change in distribution. Razorbill had a significant increase in overall abundance across almost all of the survey area, including the wind farm. Kittiwake showed a significant redistribution effect, but no overall change in abundance. There was a significant increase centred on the northern edge of the wind farm, and overall distribution was considered more likely to reflect a change in prey distributions rather than effects of turbines.

Following review of this report several additional studies were recommended by UK SNCB's. Nelson et al. (2015) reported on the Year 5 results from monitoring at Robin Rigg offshore wind farm in the Solway Firth. This report focused on avoidance behaviour of seabirds, rather than displacement behaviour. However, the findings were no different to those of Canning et al. (2013), which are discussed above.

Vanermen et al. (2019) presented further analysis of displacement (and attraction) of seabirds at the Thornton Bank wind farm (Belgium) after six years of post-construction monitoring. The authors found significant avoidance of the wind farm area by gannet, guillemot and razorbill. However, attraction was shown for herring gull and great black-backed gull. This study used a BACI approach, and so results should be treated with caution, as it is clear from studies based on larger spatial scales that control sites are not effectively providing a contrasting baseline as the spatial scales are much smaller than the scale of use of the sea by highly mobile species.

Mendel et al. (2019) reported on changes in red-throated diver distributions in response to offshore wind farms and associated ship traffic. This study reported displacement as statistically significant to 16 km from the wind farms. Unlike the study by Vilela et al. (2020) this study used several survey platforms and compared data from boat-based and visual aerial survey platforms with data from digital aerial surveys. It is also important to note that the study by Medel et al. (2019) was a sub-set of the areas also studies by Vilela et al. (2020). The study by Mendel et al. (2019) also used a BACI approach, unlike the gradient approach using Bayesian spatial and spatiotemporal modelling used by Vilela et al. (2020).

A further study from the German Bight also reported strong displacement by red-throated divers through GPS tracking of tagged birds (Heinänen et al. 2020). This also reported statistically significant change at 10–15 km from offshore wind farms, but a gradient of effect was noted, with the effect declining from 5 km from the wind farms. The authors also noted smaller displacement distances at night and in poorer visibility, suggesting the effect is caused by visual disturbance.

Finally, a study by APEM (2021) that was not available at the time of writing, was recommended. This was a further study on red-throated divers, from the Outer Thames estuary, which reported displacement effects at 7 to 12 km.

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