OFFSHORE RENEWABLES JOINT INDUSTRY PROGRAMME (ORJIP) FOR OFFSHORE WIND

CARBON TRUST

WP1: Literature and data review

Improving understanding of distributional change for relevant seabird species (ImpUDis)

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orjip working to accelerate offshore consenting

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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.

For further information regarding the ORJIP Offshore Wind programme, please refer to the Carbon Trust website, or contact Ivan Savitsky (ivan.savitsky@carbontrust.com) and Žilvinas Valantiejus (zilvinas.valantiejus@carbontrust.com).

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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.

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1. Introduction

1.1. Context

For seabirds, the primary direct effects of offshore wind farm (OWF) developments are collision and distributional change. Distributional change involves shifts in habitat use of OWF areas where birds are either displaced from (i.e. avoid), or are attracted to, wind farm areas (Lamb et al. 2024). Understanding these distributional changes for different seabird species is key to assessing the environmental impact of OWF developments.

In assessing the potential impacts of offshore wind farms, developers are required to consider if the project is likely to affect sites within the UK National Site Network providing a Habitats Regulations Assessment or Appraisal (HRA). HRA is an iterative process and the emphasis is on understanding the potential for Likely Significant Effects (LSEs) and avoiding Adverse Effects On Integrity (AEOI) on these sites. If LSEs on the species which are features of the UK National Site Network, either alone or in combination with other plans or projects, cannot be ruled out after HRA screening, the HRA report provided with the application should enable the competent authority to then carry out an Appropriate Assessment (AA). The purpose of the AA is to ascertain whether or not there are any AEOI on the sites. These sites are classified as Special Protection Areas (SPAs) based on the size of the population of a species, or suite of species, that they hold and must be maintained in a favourable condition (i.e. species' population sizes should not decline below those set out in the conservation objectives for the site). There is substantial uncertainty associated with estimates of the rates underpinning assessment of displacement within HRA and AA, arising due to varied behavioural responses reported in relation to operational OWFs. The need to make precautionary assumptions in assessments (De Sadeleer 2009) means that this uncertainty reduces the likelihood that the examining authorities will be able to conclude that there are no AEOI in relation to protected sites.

With over 20 years of post-construction monitoring across different OWFs, there is an abundance of data on seabird distributional changes. Previous reviews of post-construction studies by Dierschke et al. (2016) and Lamb et al. (2024) have provided insights into the species which are likely to be displaced. They found evidence of displacement in divers, gannets, sea ducks and alcids, as well as some evidence of attraction in gulls and cormorants. However, there is still substantial uncertainty surrounding displacement rates, which is driven by factors such as the design of post-construction monitoring studies at early projects (MMO 2014; Lamb et al. 2024), the variability of the marine environment, the relatively small sample sizes and few years of monitoring in many studies, which contribute to low statistical power to detect changes (see Maclean et al. 2014; Vanermen et al. 2015b), and the use of analytical methods that are not able to account for features of 'messy' ecological data, such as zero-inflattion and spatial and temporal autocorrelation. There is a substantial volume of data available over many years from many different OWFs. This presents the opportunity to pool data across multiple sites and studies, offering the potential to boost sample size and increase statistical power. It is important that the data used in these analyses are robust, by removing data of insufficient qualify, which requires the identification of a subset of data sets collated.

Within this literature and data review, we: present available estimates on the extent and direction of seabird distributional change resulting from OWFs, assess the methods used for estimating distributional change, critically review the collated data related to seabird distributional change to identify a subset of studies for use in analysis, and extract key factors that induce variation in seabird distributional change. The priority species considered in this review are auks (Common Guillemot Uria aalge, Razorbill Alca torda, Atlantic Puffin Fratercula arctica), Northern Gannet Morus bassanus, divers (Red-throated Diver Gavia stellata, Black-throated Diver Gavia arctica, Great Northern Diver Gavia immer) and Black-legged Kittiwake Rissa tridactyla, reflecting species which data from operational OWFs suggest are most likely to be vulnerable to displacement, and highlighted as priorities by UK Statutory Nature Conservation Bodies (Dierschke et al. 2016; JNCC 2022). Also of interest as part of this review, but of lesser priority, are Manx shearwater Puffinus puffinus, storm petrels (European Storm-petrel Hydrobates pelagicus, leach's petrel Hydrobates leucorhous), species which are present in areas such as the Irish and Celtic Seas where extensive OWF development is planned as part of upcoming leasing rounds, but for which little information is available on their interactions with OWFs. Also of lesser priority are terns (Common Tern Sterna hirundo, Arctic Tern Sterna paradisaea, Sandwich Tern Sterna sandvicensis, Roseate Tern Sterna dougallii and Little Tern Sternula albifrons), species for which there is emerging evidence of potential behavioural responses to operational OWFs (e.g. Thaxter et al. 2024).

To ensure the information identified through this review can be put in the context of the assessment process, we provide a summary of current approaches to assessing displacement. However, a key starting point for this report is to outline how seabird distributional change is defined to ensure clarity and consistency concerning these definitions, both as part of this report, and in subsequent work packages.

1.2. Definitions of distributional change

At a broad level, seabirds may respond to OWFs in four ways:

- **Displacement** from the wind farm area, resulting in functional loss of habitat (Mendel *et al*. 2019b).
- **Attraction** to new habitat in the wind farm area (Thaxter et al., 2018)
- The perception of the wind farm as a **barrier** to movement (Thaxter *et al*. 2024)
- **Indifference** to the wind farm, resulting in no change in distribution

The range of potential responses has contributed to considerable uncertainty surrounding how these distributional changes should be assessed. Clarity surrounding definitions of these distributional changes is key to reducing this uncertainty (Masden *et al.* 2015), and describing the distributional changes that occur as birds interact with OWFs.

1.2.1. Displacement

Drewitt & Langston (2006) define displacement as:

"…the reduced density of birds occurring within or immediately adjacent to wind-power plants due to long-term disturbance leading to functional habitat loss"

Recent Statutory Nature Conservation Body (SNCB) guidance follows Furness *et al.* (2013) in defining displacement as:

"*a reduced number of birds occurring within or immediately adjacent to an offshore wind farm*" (JNCC 2022).

The guidance notes that displacement can occur both within the footprint of a wind farm, and in the area around it, influencing both birds in flight and on the water surface (JNCC 2022). It is further noted that:

"*The degree of displacement, both in terms of length of time and proportion of the original source population affected, may vary seasonally and between species*" (JNCC 2022).

Displacement has typically been assessed using boat or digital aerial surveys, and comparing pre- and post-construction distributions of birds (e.g. Vanermen *et al.* 2015; Vallejo *et al.* 2017; Heinänen *et al.* 2020). However, the growing availability of GPS tracking data means that this is also contributing to our understanding of seabird displacement from OWFs, often by comparing the use of wind farm footprints by individual birds to usage of surrounding habitat (e.g. Peschko *et al.* 2020, 2021). Across these studies, inter-specific differences in the propensity for birds to be displaced have become apparent. For example, gannets, auks, divers and sea duck have a tendency to be displaced by OWFs (Dierschke *et al.* 2016; Lamb *et al.* 2024), whilst other species, such as gulls and cormorants have shown no consistent response, or even potential attraction. May (2015) includes this potential attraction (effectively, negative displacement) in its definition of displacement.

As data have been collected, it has become apparent that several factors may drive displacement. These include:

Changes in the prey base within the wind farm footprint, meaning that it is no longer profitable for birds to forage within it (Perrow *et al.* 2011)

Disturbance by vessels associated with construction, operations and maintenance activities (Mendel *et al.* 2019b)

Behavioural avoidance of perceived collision risk (May 2015)

Disturbance from presence of turbines themselves through visual, noise and vibration impacts (Drewitt & Langston 2006).

The importance of these factors may vary between species, populations and individuals, but also between sites and seasons. For example, recent analysis of Sandwich Tern GPS data shows birds entering wind farms to forage, but not when commuting between foraging areas and their breeding colonies (Thaxter *et al.* 2024). Similarly, during winter birds have been observed altering their distribution in response to the vessel traffic associated with OWFs (Mendel *et al.* 2019b). However, during the breeding season, when species are constrained as central place foragers by the need to provision chicks, the potential to redistribute in a similar manner may be limited.

It is recognised that displacement may occur within a zone of influence beyond the boundaries of a wind farm (NatureScot 2023). However, this has presented challenges in comparing estimates across different studies which have estimated displacement from the wind farm area and buffers of different sizes (Cook *et al.* 2014). The size of buffer identified around a wind farm can impact both the magnitude and significance of any displacement impact estimated (Juliet Lamb *et al.* 2024). Appropriate sizes for these buffers will vary between species. A buffer of 2 km is recommended for all species, with the exception of divers and sea ducks where a 4 km buffer is recommended and red-throated diver where a 10 km buffer is recommended (JNCC 2022). Edge effects may complicate assessments of displacement if the number of birds within the buffer areas is inflated by birds that avoid entering the wind farm. The situation may be further complicated by the fact that wind farm footprints are defined with reference to the wind farm lease area, which may be larger than the wind farm footprint as defined based on the locations of turbines, which will more accurately reflect the wind farm as perceived by birds. Reflecting this, (Pollock *et al.* 2024) assessed displacement in relation to a minimum convex polygon around the outermost turbines within a wind farm.

For the purposes of this report, we define displacement as the reduction in density in birds within the footprint of a wind farm, as defined by a minimum convex polygon around the rotor sweeps of the outermost turbines, and appropriate species-specific buffer around the wind farm. This may be measured through comparison between pre- and post-construction monitoring data, or by comparing the observed distribution of birds with that recorded in the wider environment (e.g. using tracking data). Attraction and barrier effects are considered as distinct from displacement.

1.2.2. Attraction

In contrast to displacement, attraction would reflect active selection of the habitat within a wind farm and would be manifested by an increase in the number of birds within, or immediately adjacent to a wind farm. As data have been collected from operational OWFs, the potential for birds to be attracted to these sites has become evident (Dierschke *et al.* 2016). This effect has been most evident in cormorants and large gulls. Birds may be attracted both by the potential to use the turbine transition pieces to rest and perform other maintenance activities (Stienen *et al.* 2024), and by the foraging opportunities offered, as has been observed in grey seals (Russell *et al.* 2014). Birds may also nest on associated infrastructure, as is the case for kittiwakes nesting on Walney Two offshore substation (Peyton-Jones & Rounce 2023). There is additional evidence that birds may be attracted to the edge of wind farms by fishing vessels which aggregate there (Krijgsveld *et al.* 2011; Skov *et al.* 2018). This effect can complicate simple comparisons of birds inside and outside wind farms when attempting to quantify displacement if the number of birds on the edge of the wind farm is artificially inflated due to the presence of the fishing vessels. This effect is also likely to vary between sites; OWFs in UK waters are open to fishers, whereas OWFs in German and Belgian waters are not open to fishers and OWFs in Danish and Dutch waters are only open to passive fishing activities. This variation may influence the ability to extrapolate findings in relation to distributional changes.

For the purposes of this report, we define attraction as the converse of displacement, an increase in the density of birds within the footprint of a wind farm, as defined by a minimum convex polygon around the outermost turbines, and appropriate species-specific buffer around the wind farm, taking into account the potential for potential attraction to any aggregated fishing vessels.

1.2.3. Barrier effects

As barrier effects are manifested by a reduction in the numbers and/or density of birds within a wind farm, they are typically considered a form of displacement (Drewitt & Langston 2006). However, we suggest that these two impacts should be distinguished between one another. In contrast to displacement, which may be thought of as functional loss of habitat (Drewitt & Langston 2006; May 2015), barrier effects are likely to be driven by the anticipatory avoidance of collision (May 2015). Whilst displacement reflects a response to habitat that a bird has actively selected, e.g. for foraging, resting or other maintenance activity, barrier effects reflect a response to habitat that a bird is not actively selecting, but is passing through as it reflects the shortest and/or most energetically efficient route between two points, e.g. the breeding colony and preferred foraging areas, or the start and end of migration routes. This is recognised in recent SNCB guidance which defines barrier effects as applying to:

"*Birds that would have previously passed through the footprint of the disturbance area to a more distant feeding, resting or nesting area, but now choose either to stop short or detour around the location*" (JNCC 2022).

It is noted that this definition will typically apply to birds in flight.

To date, the focus on the use of surveys as part of post-construction monitoring at wind farms has meant that the quantifying displacement and barrier effects separately has not been possible. However, the increasing use of tools such as radar and high-resolution GPS tracking means that we are able to gain detailed insights into the movements of birds as they approach OWFs using tools such as step-selection functions (e.g. van Bemmelen *et al.* 2024). Combining data from studies such as these, with data describing the energetic costs of flight will enable us to better understand the individual, and population-level costs of barrier effects (e.g. Masden *et al.* 2009, 2010), and how these compare to the costs associated with habitat loss associated with wind farms, particularly those overlapping with key foraging areas.

For the purposes of this report, barrier effects are defined as the alteration in the flight path of a bird as it approaches an OWF. This alteration is likely to have implications in relation to the energetic cost of flight.

1.2.4. Distributional change

As highlighted above (sections 1.2.1 & 1.2.3), the presence of an OWF has the potential to influence the distribution of seabirds at sea, either through displacement, or attraction. Building on the definitions above, the resulting changes apply to birds that have previously actively selected (or, potentially, avoided) the area under consideration. **For the purposes of this report, we describe such changes as distributional change, which refers to the active selection, or avoidance of, and area following the construction of an OWF. This definition does not extend to cover barrier effects.**

1.2.5. Macro-avoidance/macro-response

The term macro-avoidance has been used as a catch-all term to capture changes in the abundance and density of birds within a wind farm footprint following development, regardless of the drivers of that change. As highlighted above, and by Cook *et al.* (2014), the development of an OWF may lead to an increase in the numbers, meaning that the term macro-response, implicitly covering both attraction and avoidance, may be more appropriate. Cook *et al.* (2014) considers macro-responses to include both displacement and barrier effects, in addition to any potential attraction.

For the purposes of this report, the term macro-response will be used to refer to changes in bird numbers within the windfarm area resulting from the development of the windfarm site, through processes including, but not limited to, attraction, displacement and barrier effects.

1.3. Current approaches to assessing displacement in EIAs

Current SNCB guidance is that a buffer of 10 km should be applied around the OWF footprint for Red-throated Divers, 4 km for other diver species and sea ducks, and 2 km for other species. The guidance states that a single displacement rate should be applied to the OWF footprint, and any buffer out to 4 km, but that, reflecting evidence from post-construction monitoring in Germany (e.g. Mendel *et al.* 2019b), a gradient in the displacement rate can be applied for Red-throated Diver out to 10 km.

At present, there are two key approaches that have been applied to estimate the impact of displacement by OWFs on seabirds (Croll *et al.* 2022), the Matrix Approach (e.g. JNCC 2022) and an Individual Based Model (IBM) referred to as SeabORD (Searle *et al.* 2018).

1.3.1. The Matrix Approach

The matrix approach combines estimates of the proportion of birds displaced from an OWF with estimates of the expected mortality level amongst displaced birds to give an estimate of the number of adult birds at risk of mortality due to displacement in a given season. The number of birds at risk of mortality due to displacement is estimated for each species on a seasonal basis, with a minimum of two seasons (breeding and non-breeding), though additional seasons are considered where appropriate (e.g. for moult periods when auks are flightless). The input to the matrix approach is the mean seasonal peak abundance estimated from the baseline survey data.

Acknowledging the uncertainty associated with both displacement rates and the mortality arising as a result of displacement, in the matrix approach, the full range (i.e. 0-100 %) is presented for both values. From the resulting matrices, a range of most plausible values, informed by current understanding of species susceptibility to displacement (e.g. Dierschke *et al.* 2016) and potential sensitivity to that displacement (e.g. Furness *et al.* 2013), can be highlighted and taken forward for further assessment.

At present, the matrix approach considers only adult, and not juvenile or immature, mortality, and does not consider potential sub-lethal impacts (e.g. reduced productivity) (JNCC 2022).

1.3.2. SeabORD

SeaBORD is an IBM which predicts the time-energy budgets of seabirds during the chick-rearing period, and translates these into projections of productivity and survival at both an individual, and population-level (Searle *et al.* 2018). The model has been parameterised using empirical values for time activity budgets, adult mass change during chick-rearing, chick growth and chick survival, largely obtained from long-term studies by UK CEH on the Isle of May, supplemented values from elsewhere in the literature and expert opinion where necessary.

Seabird distributions in the absence of a wind farm are estimated by simulating the movement of individuals parameterized by GPS tracking data, or through the use of distance decay functions from known breeding colonies. The distribution of seabirds is then re-estimated for a scenario including the presence of OWFs, with reference to estimated displacement rates and distances. In combination with assumptions surrounding prey distribution, the consequences of this redistribution on adult and chick survival is then estimated. The approach has been developed for use with Common Guillemot, Razorbill, Atlantic Puffin and Black-legged Kittiwake in the Forth-Tay region during the chick-rearing period.

However, extensions of this approach to cover additional species, the incubation period and the non-breeding season have been identified as being of high priority (Searle *et al.* 2022).

2. Literature and Data Review

2.1. Methodology

Building on existing reviews of seabird distributional change in relation to OWF developments (Cook *et al.* 2014, 2018; Dierschke *et al.* 2016; Lamb *et al.* 2024), we systematically review the literature to identify and extract available estimates on the extent of distributional change resulting from OWF developments. Following (Lamb *et al.* 2024), we searched Google Scholar for papers and reports using the following terms:

> (*Avian* OR *birds* OR *seabirds*) AND
> ("*offshore wind*" OR "*offshore wind farm*" OR "*offshore wind energy*" OR "*marine wind*" OR "*marine wind farm*") AND
> ("*displacement*" OR "*attraction*" OR "*avoidance*")

Given that the most recent review (Lamb *et al.* 2024) covered studies up to 2022, the focus for our search was on studies published from 2022 onwards. However, we carried out an initial exploratory search, and cross-referenced this with the studies considered in (Lamb *et al.* 2024), to ensure no studies were overlooked. Noting that many relevant studies may not appear in the peer-reviewed literature, we additionally searched online repositories, including the Crown Estate Marine Data Exchange, and solicited information from the members of the ORJIP Offshore Wind Steering Group.

2.2. Results

2.2.1. Identified studies

We identified 76 studies that investigated seabird distributional change in relation to OWF developments, published between 1998 and 2024. Of these studies, 50 are additional to those included in the Dierschke *et al.* (2016) review, and 23 are additional to those included in the Lamb *et al.* (2024) meta-analysis. See Appendix 1 for a list of the identified studies.

Of the studies identified, 22 used boat-based surveys, 15 used GPS telemetry, 7 used digital aerial surveys, 6 used radar, 5 used visual aerial surveys, 5 used visual observations from fixed points (e.g. the shore and meteorological masts) and 2 used radar-camera systems. A further 14 studies used combined survey methods, which were primarily combinations (up to three) of boat-based, visual aerial, digital aerial, visual observer and radar surveys. See section 2.2.6 for analysis of method use over time. 46 out of the 76 studies included data from both pre-construction and post-construction periods. The mean number of years of data collection for all studies was 5.3 years.

The studies were conducted at 35 OWF developments in Europe. Some wind farms have had more surveys conducted at them than others, a bias in effort that must be addressed for valid inference about more general displacement. Out of the 76 studies identified, 6 were conducted at Horns Rev wind farm and 6 were conducted at Nysted wind farm. 4 studies were conducted at Kentish Flats wind farm and 3 at Egmond aan Zee, Tuno Knob and Alpha Ventus wind farms. One or two studies were conducted at the remaining (29) wind farms. The overrepresentation of some earlier wind farms, particularly Horns Rev and Nysted, may have a disproportionate impact on perceptions of avoidance behaviour.

2.2.2. Direction of distributional change in key species

The studies reviewed included assessment of distributional change in 29 seabird species, along with 10 species groups (alcids, divers etc.) (see Table 1).

For most species, there is more evidence of displacement from, or macro-avoidance of, OWF developments compared to evidence of attraction to these developments. For all species and species groups combined, 33% of studies indicted a statistically significant displacement or macro-avoidance effect, 8% of studies indicated a statistically significant attraction effect and the remaining 59% of studies did not show a statistically significant change in distribution. Therefore, 41% of studies indicated a statistically significant distributional change (either displacement/macro-avoidance or attraction). Not all studies formally tested statistically for distributional change, and those studies with non-significant results may also have suffered low power. Coupled together, there were many studies that, while statistically inconclusive, were at least suggestive that distributional change exists. In such cases, a meta-analysis or similar pooling approach may offer a firmer view.

Species that show a clear pattern of displacement from, or macro-avoidance of, OWF developments include the Northern Gannet, Common Guillemot, Common Scoter, Little Gull, Razorbill, Red-throated Diver and Common Eider. Species that show a clear pattern of attraction include the Great Black-backed Gull and Great Cormorant. A number of species, such as the Black-legged Kittiwake, Lesser Black-backed Gull, Herring Gull and Common Gull, show a more mixed pattern, with some evidence of displacement, some evidence of attraction and a number of studies indicating no significant distributional changes. This may indicate variability in behaviour between wind farms, due to factors such as varying wind farm characteristics, varying behaviour between populations or varying responses to environmental conditions.

A number of species showed no evidence of any significant distributional change. This may be due to lower sample sizes, for example for the Northern Fulmar, two out of the four studies recorded just a couple of individuals in the impact areas, meaning they lacked statistical power to detect significant changes. This highlights the value of using a pooled analytical approach to boost sample sizes and obtain greater confidence about any significant/non-significant distributional changes recorded.

The priority species for this Project are alcids/auks, gannets, divers and kittiwake. For alcids (Common Guillemot, Razorbill and Atlantic Puffin), out of the 46 studies reviewed, 22 (48%) found a significant displacement/macro-avoidance effect and no studies found a significant attraction effect. The remaining 24 studies (52%) found no significant change. This indicates the tendency of alcids to be displaced from OWF development areas. For gannets, out of the 31 studies reviewed, 14 (45%) found a significant displacement/macro-avoidance effect, one study (3%) found a significant attraction effect, and the remaining 16 studies (52%) found no significant change. This indicates the tendency of gannets to be displaced from OWF development areas. For divers, out of the 24 studies reviewed, 14 (58%) found a significant displacement/macro-avoidance effect and no studies found a significant attraction effect. The remaining 10 studies (42%) found no significant change. This indicates the strong tendency of divers to be displaced from OWF development areas. For kittiwake, out of the 26 studies reviewed, 6 studies (23%) found a significant displacement/macro-avoidance effect, 3 studies (12%) found a significant attraction effect, and the remaining 17 studies (65%) found no significant change. This mixed pattern indicates significant variation in the responses of kittiwake to OWF developments.

Table 1. Species (or species groups) included in the studies identified and the number of studies indicating statistically significant displacement/macro-avoidance and attraction for each species[1]. Priority species for this Project are shown in bold.

Species	Number of Studies	No. of studies indicating significant displacement / macro-avoidance	No. of studies indicating significant attraction
Northern Gannet	31	14	1
Black-legged Kittiwake	26	6	3
Lesser Black-backed Gull	24	4	2
Herring Gull	21	1	2
Common Guillemot	20	11	0
Great Black-backed Gull	16	0	5
Common Gull	14	1	4
Sandwich Tern	14	3	0
Little Gull	13	7	1
Razorbill	13	7	0
Common Scoter	12	5	1
Red-throated Diver	12	6	0
Divers (as a group)	12	8	0
Great Cormorant	12	1	5
Common Eider	10	6	0
Alcids (as a group)	10	4	0
Marine birds (all)	7	6	0
Black-headed Gull	4	0	0
Common Tern	4	1	0
Northern Fulmar	4	0	0
Long-tailed Duck	4	2	0
Atlantic Puffin	3	0	0
Gulls (as a group)	3	0	0
Terns (as a group)	3	2	0
Waterfowl (all)	3	2	0
Arctic/Common Tern	2	1	0
Great Skua	2	0	0
Large Gulls (as a group)	2	1	0
Manx Shearwater	2	1	0
Red-breasted Merganser	2	0	1
Small Gulls (as a group)	2	0	0

[1] Note that species (or species groups) with just one study are not included in this table.

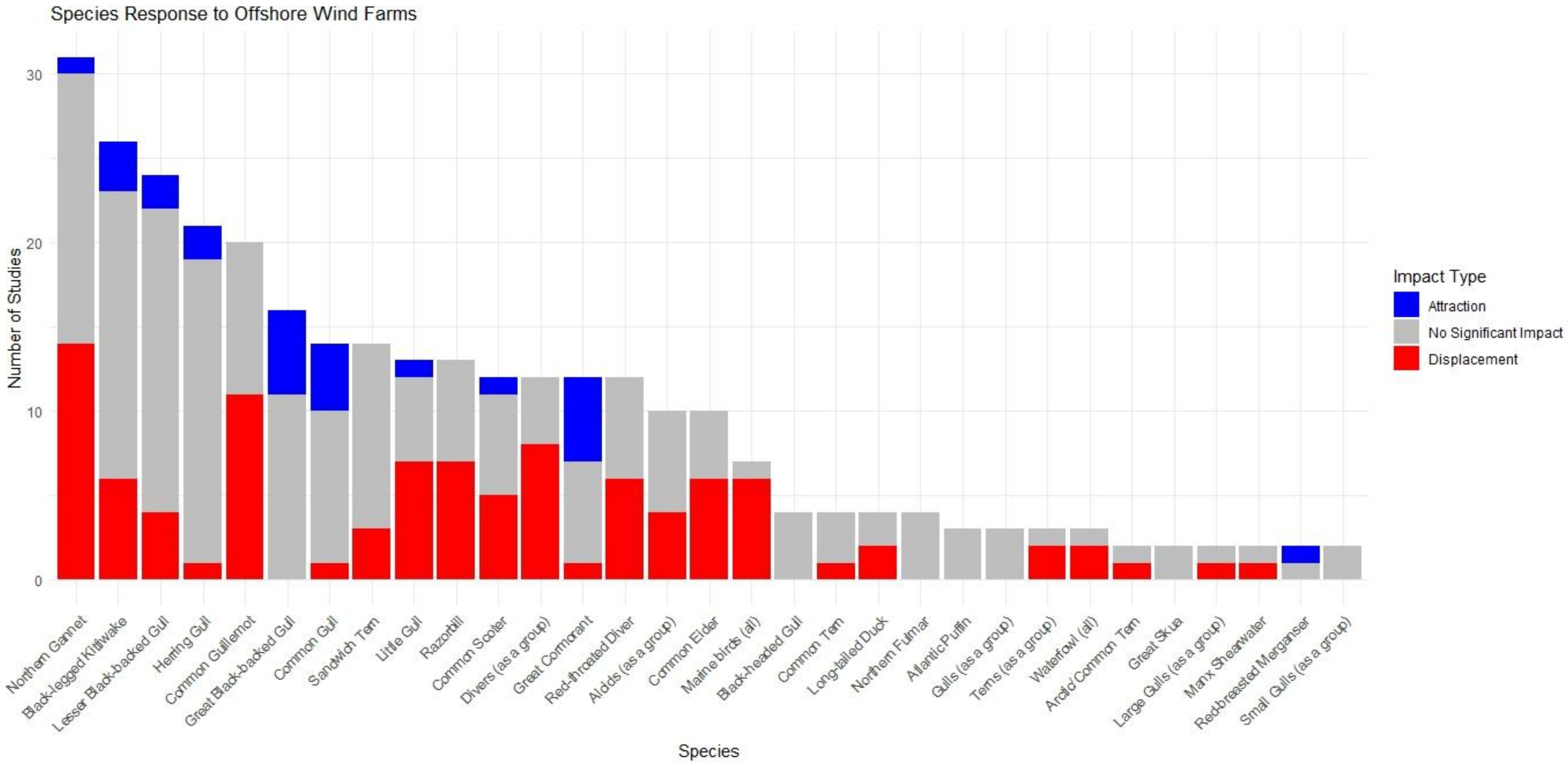

Figure 1. Number of studies indicating significant attraction or displacement/macro-avoidance effects, and those indicating no significant distributional change per species.

2.2.3. Magnitude of distributional change in key species

Whilst most, though not all, of the studies we identified attempted to quantify the extent distributional change in response to the presence of an OWF, drawing inferences about species-specific rates of displacement and/or attraction on the basis of the information presented in these studies is extremely challenging. There are several reasons for this. Firstly, species are often grouped together for analysis, particularly when only a few individuals of each species are present (Leemans *et al.* 2022), or in situations where species identification is challenging, or not possible, as in the case of data collected using radar (e.g. Petersen *et al.* 2006).

Differences in the methodologies used mean it is difficult to make meaningful comparisons between the results reported in different studies. For example, a study using boat-based surveys of OWFs in Belgian waters found that densities of Common Guillemot were 0.45 birds km^{-2} outside a wind farm compared to 0.35 birds km^{-2} inside a wind farm, an apparent displacement rate of ~22% (Vanermen *et al.* 2023). In contrast, a telemetry study of Common Guillemots in German waters found usage of OWFs was 63% lower than of surrounding areas (Peschko *et al.* 2020b). There are a number of possible explanations for these apparent differences:

- There is a genuine difference in the displacement rates between the wind farms concerned, arising as a result of differences in how the birds use the habitat within and outside the sites.
- The data reflect seasonal differences in the extent of any displacement given that the data presented by Vanermen *et al.* (2023) focus on the non-breeding season and Peschko *et al.* (2020b) focus on the breeding season.
- Differences are introduced by the data collection methodologies used. For example, telemetry data cover a much greater spatial scale than boat-survey data, meaning that they more accurately capture broader spatial patterns.
- Data may reflect different parts of the population. For example, seabird telemetry data are typically restricted to breeding individuals which are accessible to researchers whilst on their nests. In contrast, survey data may more accurately capture the population as a whole.
- Differences may be introduced through the analytical approaches used in the different study (point-process modelling for Peschko *et al.* (2020b) vs. comparison of density estimates for Vanermen *et al.* (2023)).

In the case of the first two explanations, these would reflect genuine ecological differences that must be taken into account when generating estimates of distributional change, and the variability associated with those estimates, for different species. However, the remaining explanations arise as a result of experimental design, and are likely to introduce uncertainty into estimates of distributional change that may be very challenging to quantify. Similar ranges are seen in other species considered in our review. For example, displacement rates in Northern Gannet range from 64% (Krijgsveld *et al.* 2011) to 99% (Vanermen *et al.* 2015a); in Black-legged Kittiwake from 32% (Welcker & Nehls 2016) to 86% (Vanermen *et al.* 2015a); in Red-throated Divers from 64% (APEM 2021) to 93.5% (Mendel *et al.* 2019b); and, in Razorbills from 21% (Leemans *et al.* 2022) to 64% (Vanermen *et al.* 2015a).

The challenge in generating species-specific displacement rates was recognised by Dierschke *et al.* (2016), who opted for a qualitative approach to defining species distributional changes in response to

OWFs. Subsequently, a number of new methods and approaches have been applied to quantifying seabird distributional change in response to the presence of OWFs. However, the challenges in combining the results from different studies to generate estimates for the rates of seabird distributional change identified by Dierschke *et al.* (2016) remain. These challenges highlight the value of analysing a high quality subset of the available data using a common analytical framework in order to quantify seabird distributional changes, and the uncertainty associated with those changes, in response to OWFs.

2.2.4. Impact of distance on estimates of distributional change

It is clear from the available data that species responses can vary with distance to OWFs. These responses can extend over a substantial spatial area, with impacts of OWFs on the distributions of Northern Gannets, Black-legged Kittiwakes and Red-throated Divers detected at up to 15 km, 20 km and 16 km respectively (Mendel *et al.* 2019b; Peschko *et al.* 2020a, 2021; Table 2). However, attempts to robustly define distances over which displacement may occur are confounded by the size of areas over which data have been collected. Current guidance is that the buffer around an OWF that should be surveyed during pre- and post-construction monitoring is 4-10 km (JNCC 2022). Most of the studies we identified pre-dated this guidance, and used buffer distances of 2-4 km, meaning that attempts to quantify the distances over which displacement may occur are confounded by the size of the study area considered. This challenge has been noted by Lamb *et al.* (2024), who found that the probability of detecting a significant distributional change was linked to the size of the survey area. As a consequence, the studies which have detected displacement impacts at the greatest distance have been those based on telemetry data (Peschko *et al.* 2021), or those that have pooled data across multiple surveys over a broad spatial area (e.g. Mendel *et al.* 2019b).

Table 2 Maximum distance at which a significant distributional change was detected for studies in which the total area considered exceeded this value

Species	Maximum distance at which displacement detected	Study
Red-throated Diver	11 km	APEM (2021)
	8 km	Webb et al. (2017)
	16.5 km	Mendel *et al.* (2019b)
Northern Gannet	15 km	Peschko *et al.* (2021)
	3 km	Webb et al. (2017)
Common Guillemot	9 km	Peschko *et al.* (2020b)
Black-legged Kittiwake	20 km	Peschko *et al.* (2020a)

2.2.5. Key knowledge gaps

There is much variation in the number of studies, and therefore extent of data, for each species (see Figure 1). Species with the most studies include the Northern Gannet, Black-legged Kittiwake, Lesser Black-backed Gull, Herring Gull and Common Guillemot. There are, however, many species (and species groups) with very few studies, including the European Shag, Little Tern, Skuas, Shearwaters, sea ducks (except scoters) and geese.

For the priority species (alcids/auks, gannets, divers and kittiwake), there are generally a relatively high number of studies for each. In total, there are 46 studies for alcids/auks, comprising 20 studies for Guillemot, 13 studies for Razorbill, 10 studies for alcids/auks as a group and 3 studies for Puffin. However, with just 3 studies for Puffin (none of which identified a significant distributional change), there is a knowledge gap for this species. For the remaining priority species, there are no major knowledge gaps. There are a total of 30 studies for the Northern Gannet, 24 studies for divers (primarily Red-throated Divers) and 26 studies for the Black-legged Kittiwake.

Species where no significant distributional change has been found include the Black-headed Gull, Northern Fulmar, Atlantic Puffin and Great Skua. Also, out of the 21 studies for the Herring Gull, only 3 found a significant distributional change (see Figure 1). It is unknown whether this indicates that these species do not (or rarely) react to the presence of wind farms, or whether this is due to other factors preventing a statistically significant change from being detected, such as study design, the variability of the marine environment or low statistical power due to small sample sizes and/or few monitoring years. By pooling high-quality data for each species from numerous studies, whilst incorporating appropriate covariates and applying robust statistical analytical methods, we aim to increase the statistical power to detect distributional changes for key species.

2.2.6. Survey methods used in the reviewed studies

The most frequently method used to explore seabird distributional changes in the identified studies was boat-based surveys, with results from 28 boat-based surveys reported in the studies we identified (Figure 2). Telemetry (18 studies), radar (14 studies), digital (14 studies) and visual (15 studies) aerial surveys were also widely reported. However, it should be noted that in many of these studies utilised overlapping datasets – for example the results of boat-based, visual aerial and digital aerial surveys of the German Exclusive Economic Zone are reported in Mendel *et al.* (2019a),Peschko *et al.* (2020a) and Garthe *et al.* (2023) – making it more challenging to gain a clear understanding about the number of surveys completed and the quantity of data available.

Of the methods used, boat-based surveys have been completed throughout the period we considered. In contrast, there has been a notable shift in aerial surveys, with digital methods replacing visual surveys around 2009. This pattern largely reflects an acknowledgement of the visual aerial surveys due to the potential for disturbing the target species and the need to fly at altitudes that would not be possible within operational wind farms (Avian Displacement Guidance Committee 2024). Whilst boat-based surveys also pose challenges in relation to the potential disturbance of target species, it is recognised that these remain of value due to the potential to collect complementary data on species behaviour and oceanographic variables that may explain species habitat preferences. An additional notable pattern has been the use of studies utilizing GPS and Satellite Telemetry to investigate species responses to, and interactions with, operational OWFs, which has increasingly become a key part of post-construction monitoring at operational wind farms since 2013 (e.g. Peschko *et al.* 2020b, 2021; Johnston *et al.* 2022; van Bemmelen *et al.* 2023; Pollock *et al.* 2024; Thaxter *et al.* 2024)

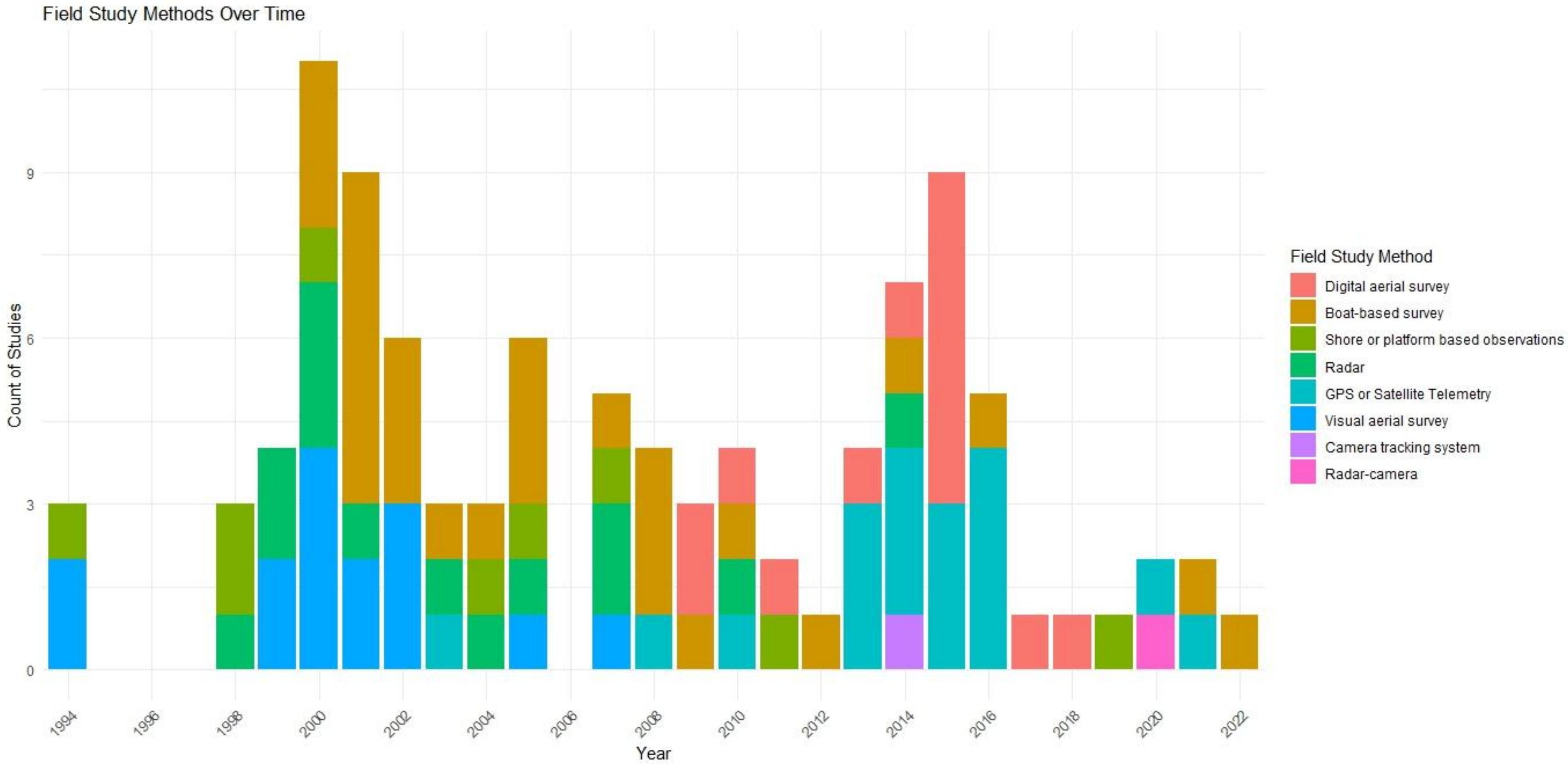

Figure 2. Number of studies conducted per year (based on first year of data collection), broken down by survey method.[2]

[2] Note that studies using multiple methods have been separated out into each method used. The peak from 2000 – 2002 is partially due to a number of studies using multiple methods being separated out.

2.3. Methods for estimating distributional change

2.3.1. Selectivity indices

Jacob's Selectivity Index has been widely used to assess the magnitude of displacement at OWFs, particularly in relation to earlier projects (e.g. Petersen *et al*. 2006; Vanermen *et al*. 2013). Jacob's Selectivity Index (*D*) is calculated as follows, for a region of interest within a study area:

$$D = \frac{(r - p)}{(r + p - 2rp)}$$

Where, *r* is the proportion of birds found within the region of interest, and *p* is the proportion of the study area this region covers. Values for the index range from -1 to +1, with a value of zero indicating the distribution that would be expected if birds were distributed evenly, values <0 indicating avoidance of an area and values >0 indicating attraction to an area.

The potential for distributional changes to have occurred is assessed by comparing changes in the estimates of *D* for the wind farm footprint between pre-construction, construction and post-construction phases of a project. A key advantage of Jacob's Selectivity Index is its relative simplicity. However, whilst the index can give an indication of the likely direction of any distributional change, it is difficult to assess both the magnitude and significance of any change. Furthermore, it is not possible to incorporate the environmental covariates, that help explain the factors driving variation in species distribution across the study area, and may improve quantification of, and reduce uncertainty associated with estimates of displacement.

2.3.2. Control-Impact

Control-Impact studies compare the distribution and/or behaviour of birds inside a wind farm to that in a control area outside a wind farm. For example, Welcker & Nehls (2016) make a comparison between the number of birds observed on a line transect within a wind farm to that observed on transects carried out to the North, South, East and West of the wind farm. The study found significant reductions in the numbers of several priority species (including gannets, kittiwakes, divers and alcids) within the wind farm, in comparison to transects outside. However, a criticism of such studies is that the dynamic nature of the marine environment means that some spatial variation in distribution is to be expected. Without data from the pre-construction period, it is more difficult to say conclusively that these differences relate to distributional change in response to the wind farm, rather natural variation in species distributions.

2.3.3. Before-After Control-Impact

Before-After Control-Impact (BACI) methodologies are a long-established approach for detecting environmental impacts following perturbation (Stewart-Oaten *et al*. 1986), and attempt to address criticisms of Control-Impact Studies by collecting data from both the control and impact sites pre- and post-construction. This emulates standard statistical design in controlled conditions, where a treatment effect (here perturbation) is made separable from natural changes through time, where no treatment is in effect (control). These approaches have been widely used as part of monitoring programmes for OWFs in the UK and elsewhere in Europe (e.g. MMO 2014; Vanermen *et al*. 2015a), though mostly based on data collected using boat-based surveys (e.g. Harwood *et al.* 2018). These data form the basis for much of which has been captured by previous reviews and our understanding of the potential for seabird distributional change in response to OWFs (e.g. Dierschke *et al.* 2016).

Features of seabird survey data, for example high natural spatial variability and consequent low signal-to-noise ratios, can make detection of impacts using BACI challenging due to low statistical power (e.g. Vanermen *et al.* 2015b). Furthermore, the use of BACI studies to investigate displacement from OWFs has been subject to criticism due to the challenges associated with selecting an appropriate control site (MMO 2014). The dynamic nature of the marine environment makes it difficult to identify a control site which is truly comparable in relation to the underlying environmental conditions (e.g. oceanography) and species present. As a result of this variation, it is argued that multiple control sites are required (Trendall *et al.* 2011; Methratta 2021). However, typically, only a single site has been used, often in close proximity to the project concerned, meaning that the possibility that the project is influencing species present within the control site cannot be excluded (MMO 2014).

2.3.4. Density Surface Models

Density surface models are increasingly used to assess the distribution of seabirds based on data collected using tools such as surveys and tracking. The availability of Generalized Additive Modelling (GAM)-based tools such as the MRSEA package (Scott-Hayward *et al.* 2021) or specialised spatial modelling such as Bayesian point pattern models fitted with INLA (Rue et al., 2009), has facilitated the uptake of these methods. At a most basic level, the distribution of birds within in region can be modelled with the presence of a wind farm included as an explanatory variable, allowing the significance, magnitude and spatial nature of any distributional change to be quantified (Burt *et al.* 2022). These are a modelling tool, so might be used to analyse BACI-derived data above or serve as the modelling basis for later methods.

2.3.5. Before-After Gradient

Before-After Gradient (BAG) analyses incorporate a temporal element into density surface models, accounting for construction phase, and potentially, time since construction was completed into models of bird distribution (e.g. Vallejo *et al.* 2017; APEM 2021). In addition to addressing some of the criticisms made in relation to traditional BACI, by modelling the distribution of birds in and around a wind farm footprint, BAG analyses can account for the fact that distributional changes associated with the development may attenuate with distance (e.g. Mendel *et al.* 2019). As a consequence, BAG offers greater inferential scope than BACI (Methratta 2021), but requiring larger survey areas (Ellis & Schneider 1997), and with the obvious loss of an explicit control, as difficult as they are to define. As digital aerial surveys increasingly replace boat surveys as the standard approach to baseline and post-construction data for OWFs, collecting data at the necessary spatial scale has become more feasible. In combination with a more strategic approach to post-construction monitoring, this has facilitated an uptake in the use of BAG analyses to quantify the distributional changes associated with OWFs.

2.3.6. Analyses of tracking data

As data collected using GPS tracking of the movements of birds in and around wind farms becomes available, these are increasingly used to investigate the potential for macro-responses to OWFs (e.g. Heinänen *et al.* 2020; Peschko *et al.* 2020, 2021; Johnston *et al.* 2022; Pollock *et al.* 2024; Thaxter *et al.*

2024; van Bemmelen *et al*. 2024). Analyses of these data compare the bird locations identified using GPS tracking to a series of random points generated using approaches such as point-process models (Peschko *et al*. 2021, 2021) and step-selection functions (van Bemmelen *et al*. 2023). These random points are treated as pseudo-absences, representing habitat potentially available to the birds which is not being selected. Potential macro-response rates can then be quantified and assessed by comparing the number of pseudo-absences and true bird locations within the wind farm, either using models (e.g. Peschko *et al*. 2021), or by estimating an avoidance-attraction index (Johnston *et al*. 2022). To date, analyses have indicated distributional changes including both possible attraction (Johnston *et al*. 2022) and displacement (Peschko *et al*. 2020, 2021). However, recent analysis of data collected for Sandwich terns indicate tracks of birds commuting between their breeding colony and foraging areas deviating around wind farms, indicating a potential barrier effect (Thaxter *et al*. 2024).

These analyses are providing valuable insights into the fine-scale movements of birds in and around OWFs. However, it is important to note the potential limitations of these data. The data are highlighting the potential for individual variation in response to OWFs (Peschko *et al*. 2021). However, obtaining a representative sample of birds can be challenging and is often restricted by factors including body size, the accessibility of nests and the ability to deploy sufficient tags to accurately characterise space use around a colony. Furthermore, the potential for device effects means that deployments are typically restricted to a few weeks during the breeding season, though one study on red-throated divers collected data during spring from birds captured at sea (Heinänen *et al*. 2020b).

2.3.7. Analyses of radar data

In addition to data from GPS tracking and surveys, radar has been used to collect information on birds' responses to OWFs. Whilst these approaches offer the potential to collect continuous data on the movements of birds at a broad spatial scale surrounding the wind farm, unless paired with cameras and/or human observers, identification of the species, and often the number of birds present, is usually not possible. For this reason, initially, much of the radar data was focussed on collecting information about migration intensity, often in locations where a limited number of species were likely to dominate data (Desholm & Kahlert 2005; Plonczkier & Simms 2012). As the focus was migrating birds, potential barrier effects were then assessed by comparing the number of tracks inside and outside the wind farm and/or between the pre-construction and operational phases of the project. Subsequent studies have attempted to assess the proportion of birds altering their flight trajectories as they approach developments, more clearly quantifying the numbers of birds actively responding to the projects, and accounting for those whose flight paths meant they were unlikely to enter the wind farm in the first place (Masden *et al*. 2009; Krijgsveld *et al*. 2011; Plonczkier & Simms 2012). More recently, attempts have been made to examine the response of local seabirds to the presence of OWFs using radar (Skov *et al*. 2018). Recognising that there may be differences in the areas covered by radar inside and outside a wind farm, for example due to shadow effects, these analyses have used a track-length density approach to compare bird distributions inside and outside a wind farm. Additionally, quantifying the impact of displacement has been complicated by the presence of fishing vessels, which attract birds, potentially inflating the numbers present, on the perimeter of projects (Krijgsveld *et al*. 2011; Skov *et al*. 2018). This effect is also likely to vary between sites depending on the fishing restrictions; complicating the issue further. For example, OWFs in UK waters are open to fishers, whereas OWFs in German and Belgian waters are closed to fishers. This is not solely an issue for radar.

2.3.8. Shore-based counts

Where wind farms have been built close to the coast, attempts have been made to quantify the number of birds present using shore-based counts (Rothery *et al.* 2009). Hourly estimates of the number of birds recorded flying within the wind farm were compared between pre- and post-construction periods using GLMs. Such approaches give useful insights into potential impacts of smaller projects close to shore, but are not appropriate for the commercial-scale projects planned at present. The spatial range of monitoring is relatively small, and the effective range is further reduced when accounting for falling detection probabilities with distance. Furthermore, whilst these approaches can capture changes between the pre- and post-construction periods, it can be challenging account for factors, other than the presence of the wind farm, that may be driving these changes.

2.3.9. Summary of methods for estimating distributional change

As data collection methodologies to assess species distributional changes in response to the presence of offshore wind farms have advanced, so too has experimental design and the analytical approaches applied to the resultant data. There has been a notable shift from simple approaches such as selectivity indices to analyse survey data collected over broad spatial scales (e.g. Petersen *et al.* 2006), to the use of BACI (e.g. Vanermen *et al.* 2015a), and latterly, BAG designs (e.g. Mendel *et al.* 2019a).

Data collected following BACI or BAG designs, or indeed any potential experimental design, can be analysed using a variety of different tools including GAMs, Generalized Estimating Equations and approaches based on spatial point pattern processes, such as INLA. For an appropriately designed survey, it would be expected that there would be no major differences in either the significance, or estimated effect sizes (e.g. Coelho *et al.* 2020). Of greater importance is understanding, and accounting for, differences in data collection methodology (e.g. digital aerial survey vs. GPS tracking), and ensuring that any modelling approach accounts for common features of at sea data, such as zero-inflation and autocorrelation.

2.4. Critical review of available data

Of the methodologies used in the studies identified above, the data collected using boat-based and aerial (both visual and digital) surveys are considered most appropriate for consideration in relation to further analysis. Of the other methodologies considered, radar data lack the species-level identification required to generate meaningful estimates of species distributional change. Data collected using Satellite or GPS telemetry appear to offer some potential. However, at present the number of relevant datasets available with which to investigate the response of the priority species – Northern Gannet, Common Guillemot, Razorbill, Atlantic Puffin, Black-legged Kittiwake and Red-throated Diver – is still limited, restricting our ability to make inferences about responses across multiple sites. Consequently, in this section we focus on criteria of relevance to data collected using line-transect methodologies.

Displacement necessarily requires a spatio-temporal view of species abundance/density, along with details of potential drivers, such as wind-farm development phases. A robust analysis will rely on the quality of data underpinning it to be generally high, with the existence of information describing both survey transects and observation data, consistent formats and generally free from demonstrable errors (e.g. incorrectly formatted date-time values, errors in the geographic project system used). This is set out in more detail below, drawing from experience of working with similar data (e.g. The Cumulative

Effects Framework for Key Ecological Receptors[3]). These aspects of the data set out the key requirements for ensuring any data obtained are usable for the purposes of modelling displacement, and for the purposes of prioritising datasets for inclusion in analysis.

2.4.1. Data formats

Data tends to be available in either spreadsheet (e.g. Excel) formats or in shapefiles, though in some cases is limited to summaries in pdf documents. Where data are only available in pdf documents, the complexity of digitising these data means it will not be possible to incorporate them in analyses as part of this project. For Excel and shapefiles, consistency is key to efficient and timely processing of the available data for analysis. However, formats may differ between projects, providers and platforms, despite efforts to standardise data reporting in recent years (e.g. Durning & Broderick 2019).

In the case of Excel files, contents can differ markedly in terms of variable names, coding of factor variables and formats. Observations and transect information, if present, is typically in separate spreadsheet tabs with some bespoke naming system. The spatial projections used vary, being usually one of decimal latitude/longitude, UTM (30N or 31N) or British National Grid. Some imprecision may arise as specifics of projections may be guessed at (WGS 84 is generally assumed). Generally, excel-based data will need to be considered on a detailed file-by-file basis, to ensure usability.

Shapefiles are the dominant data format, particularly in recent years. As with Excel formats, the contents of these, for example variable names, data formats and factor variable codes, can vary between surveys. However, time and location information is typically more standardised, with the spatial projection information generally integral to the file set. Projections are similarly variable, but conversions between projections are more easily achieved in this format. Consequently, bulk processing of shapefiles is more feasible than is the case for excel formats, but considerable care is still required.

2.4.2. Ambiguity of data

In some instances, data may be repeated across assessments and reports from multiple projects. For example, where wind farms are adjacent to one another (e.g. in the case of the West of Duddon Sands, Walney 1, Walney 2 and Walney Extension Projects), it is likely that monitoring data will also cover neighbouring sites. To ensure datasets used in any analysis are independent of one another, it will be necessary to work through these datasets and use metadata to determine whether they are truly independent of one another prior to including them in any analysis.

2.4.3. Effort information

Analysis requires that we know where surveying occurred and nothing was seen, as well as where animals were located. Typically, this requires survey track information as well as animal sightings. The track information is frequently missing, only presenting where animals were observed. This makes

[3] https://www.ceh.ac.uk/our-science/projects/cumulative-effects-framework-key-ecological-receptors

detailed modelling impossible, being particularly misleading when animals are sparse in certain regions – absence of animals and absence of effort are confounded.

In the case of Excel format data, data ought to consist of either: separate sheets for the locations/times of animal sightings and the track line of the survey platform, or markers within the sightings data that shows the start and finish of survey lines. It may be sufficient to have start-and-finish points of transects, if the track-lines can be assumed to be straight-lines.

In the case of shape-file data, there is typically a separate file for both the sightings/observations data and the survey track line. In cases where animals are dense, the tracks could be potentially inferred, but this is very imprecise and time-consuming. Generally, it should be assumed the data is unable to be modelled without survey path information. Survey providers would need to be approached in the absence of this data.

2.4.4. Detection probability

Many of the data sources require distance analysis to be useable e.g. any boat surveys and visual aerial will require some adjustment for detection probability, ideally including consideration of availability bias for diving species (Dunn *et al.* 2024), to get absolute abundances/densities. Arguably relative abundance could be used, but some data sources (digital aerial) would become incomparable or create temporal confounding.

For the analysis of visual data, two differences subsequently arise:

The data must contain distance information (the distance from the survey platform to the observation), or the means to calculate it and effort information. This is typically present in the data considered here, either as a precise distance from track-line, or a distance band, either of which suffices. However, track information is still essential.

The data needs to be subjected to distance analysis (Buckland et al, 2001) to determine the detection function. Without this adjustment, the estimates of abundance and/or density are at best relative, being generally an underestimate. These functions are usually required to be fitted for each species under consideration, as they are likely to have different detectabilities, although some pooling is possible in some cases. The detection functions are also platform specific and potentially site/condition specific. As a rough guide however, a detection function will be required for each visual survey style and species under consideration, at a site.

2.4.5. Prevalence of key species

The key species may occur infrequently in a survey, so may have little data to model and little power to detect change (Maclean *et al.* 2013; Vanermen *et al.* 2015b). There is no firm guidance about the amount of data required to achieve analysis goals, but 100s to 1000s seem likely depending on spatio-temporal scale. In the case of visual surveying, there needs to be sufficient data to calculate detection functions. At the modelling level, there are several factors that need to be contrasted and there needs to be sufficient numbers to separate signal from noise, and ideally, birds should be identified to species level. While power is currently unknown, greater quantities of data provide more precise estimates of model parameters, including impacts.

2.4.6. Paucity of data

Some data sources may have no real useable data. For example, in some cases data are restricted to reports, which contain some summary count information and maps of species counts. Such information cannot be analysed unless the underpinning data can be obtained.

2.5. Key factors inducing distributional change in seabirds

As the marine environment is highly dynamic, the inclusion of covariates in models can help account for any resulting variability, thus giving clearer understanding of the impact associated with OWFs.

There are three key reasons for considering covariates in these models:

1. To account for some of the underlying variation in seabird distribution in order to come up with more robust estimates of displacement;
2. To investigate how displacement rates may vary through time (e.g. seasonal wind farms, through time and to detect potential habituation);
3. To investigate how displacement may differ between sites.

Most studies have focussed on the first reason, surveying individual sites, but studies (e.g. Lamb *et al.* (2024) and van Bemmelen *et al.* (2023)) are starting to investigate the second and third reasons (see section 2.5.2).

2.5.1. Covariates used in the reviewed studies

In the studies reviewed, many different types of covariates, both biotic and abiotic, have been included and found to have had a significant effect on seabird distribution. These include temporal covariates such as year, season, month and time of day; weather-related variables such as wind speed, wind direction and visibility (rain, fog etc.); habitat-related variables such as bathymetry, salinity, chlorophyll-a and availability of food supply; spatial variables such as longitude and latitude, distance to coast and distance to colony; and anthropogenic variables such as shipping intensity and fishery activity. The most used covariates from the studies reviewed were season/month (20 studies) and water depth (17 studies), both of which were found to have a significant effect on seabird distribution in the majority of studies (80% and 77% respectively). Other covariates that generally had significant effect include time of day, wind speed, wind direction, visibility and shipping intensity (Table 3). Covariates included in studies are often a consequence of covariate data availability; however, in many studies (Burt *et al.* 2022; Nielsen *et al.* 2023; van Bemmelen *et al.* 2023) covariates such as thermal front probability, sea surface temperature, salinity, chlorophyll-a, availability of food supply and water depth were actively selected based on previous studies estimating seabird abundance and distribution, including (Wakefield *et al.* 2017; Fijn *et al.* 2022).

Table 3. Covariates included in the studies reviewed

Variable	No. of studies (no. in which effect was significant)	Direction of effect
Season/month	20 (16)	Season had a significant effect on resident bird abundance, migration intensity, flight direction and flight altitude, with effects varying between species (Blew 2008; Krijgsveld *et al.* 2011; Petersen *et al.* 2014). Season had a significant effect on time spent in OWFs, with birds using OWFs significantly more during the breeding season, specifically the early chick-rearing period (Thaxter *et al.* 2015; Lane *et al.* 2020; Vanermen *et al.* 2022).
Water depth (bathymetry)	17 (13)	Generally a non-linear relationship between depth and bird abundance, with the effect of depth varying between species (Webb *et al.* 2017; Trinder *et al.* 2019). Generally, abundance decreases at greater water depths. However, Petersen *et al.* (2014) found evidence of displacement of Common Scoter from shallower water to deeper water after construction of wind farms.
Time of day (day/night, start time, sun's angle)	8 (6)	Evidence of increased macro-avoidance at night: a significantly lower proportion of birds entered OWFs at night compared to day (Krijgsveld *et al.* 2011; Vanermen *et al.* 2022). Divers were significantly further away from OWFs during night compared to day (Heinanen *et al.* 2020). Evidence of reduced macro-avoidance at night: changes in flight orientation of migrating birds occurred significantly closer to OWFs at night than in the day (Petersen *et al.* 2006).
Distance to coast	8 (4)	Generally, abundance decreases with increasing distance to coast (Leopold *et al.* 2013; Trinder *et al.* 2019; Vanermen *et al.* 2020a).
Wind direction	7 (7)	Wind direction significantly affected migration routes, migration orientation and the probability that birds would enter the WF (Christensen and Hounisen 2005; Petersen *et al.* 2006; Kahlert *et al.* 2004). Direction of effects differed between studies/species. Migration fluxes were higher during tailwinds compared to headwinds (Pettersson 2005; Krijgsveld *et al.* 2011; Plonczkier and Simms 2012). In headwinds birds generally flew at lower altitudes than during tailwinds (Krijgsveld *et al.* 2011).
Longitude and latitude (x, y coordinates)	7 (3)	Significant effect of longitude and latitude on seabird densities/distribution. Note that significance of this covariate was not stated in 4 out of 7 studies.
Wind speed	6 (6)	Maximum migration fluxes occurred during wind speed of 4 Bft (Krijgsveld *et al.* 2011). Migrating birds generally increased flight height significantly with increasing wind speed (Blew 2008; Skov et al. 2012). Gull macro-avoidance of OWFs increased significantly at higher wind speeds (>10 m/s). However, diver displacement distance decreased significantly with increasing wind speed (Heinanen *et al.* 2020; Vanermen *et al.* 2022).
Year	6 (4)	Significant effect of year on bird numbers, flight height, activity, patterns of spatial overlaps with OWF areas, and max. displacement distance (Thaxter *et al.* 2015; Lane *et al.* 2020; Vilela *et al.* 2021; Thaxter *et al.* 2024). Direction of effects differed between studies/species.

Visibility (rain, fog, humidity)	4 (4)	During periods of poor visibility, there were significantly fewer migration flights and flight height was significantly lower in a number of species (Pettersson 2005; Plonczkier and Simms 2012; Skov et al. 2012). Migrating birds still showed macro-avoidance of wind farms during periods of poor visibility. However, displacement distance decreased with decreasing visibility in divers (Pettersson 2005; Heinanen *et al.* 2020).
Shipping intensity	4 (4)	Probability of presence decreased significantly with increasing shipping intensity (Rehfisch *et al.* 2016; Heinanen *et al.* 2020; Burt *et al.* 2022). Mendel *et al.* (2019) found a highly significant abundance decline of 31% for each additional ship in the spatio-temporal range of divers.
Availability of food supply (often indicated by seabed sediment type or grain size)	4 (3)	Abundance of sea duck and tern decreased significantly with decreasing prey abundance or availability (Guillemette *et al.* 1998; Perrow *et al.* 2006; van Bemmelen *et al.* 2023).
Individual/bird identity	4 (1)	Significant differences between individuals in the extent of offshore area usage and OWF area interactions (Thaxter *et al.* 2015).
Slope of seabed	4 (1)	Direction of effect not stated
Tidal force/height	3 (3)	Number of Lesser Black-backed Gulls inside the OWF area was expected to be 50% higher at low versus high tide. The OWFs were favoured during low tide and avoided during high tide (Vanermen *et al.* 2022).
Distance to colony	3 (3)	Area use decreased significantly with increasing distance to the colony (Peschko *et al.* 2020a; van Bemmelen *et al.* 2023).
Chlorophyll-a	3 (2)	In Red-throated Divers, the probability of presence increased significantly with increasing index (slope) of chlorophyll concentration (Heinanen *et al.* 2020).
Salinity	2 (2)	Probability of presence of Red-throated Divers increased significantly with increasing salinity. They have a preferred areas with salinities around 30–32 psu (Heinanen et al. 2020; Burt *et al.* 2022).
Sea surface temp	2 (1)	Significant effect on diver and alcid density. Direction of effect not stated.
Thermal front probability	2 (1)	Significant effect on diver density. Direction of effect not stated.
Bird sex	2 (1)	Female Gannets made longer foraging trips, flew higher and were in higher densities than males within wind farm sites. There was a significant effect of sex on maximum displacement distance (Lane *et al.* 2020).
Fishery activity	1 (1)	Strong and significant attraction effect of fishery activities in Lesser Black-backed Gulls (Vanermen *et al.* 2022).
Air pressure	1 (1)	Migrating Gannets and terns increased flight height significantly with increasing air pressure (Skov *et al.* 2012a).
Hourly status of turbines (rotating/not rotating)	1 (1)	Use of OWF area reduced significantly when turbines were rotating compared to not rotating (Peschko *et al.* 2020a).

2.5.2. Additional covariates

When pooling data across multiple sites and studies, additional covariates should be incorporated into models (Lamb *et al.* 2024; van Bemmelen *et al.* 2024). These should include wind farm parameters that influence the response of seabirds, such as the number of turbines, turbine density, turbine height, wind farm area and whether the wind farm is open to fishers. For example, van Bemmelen *et al.* (2023) found that Sandwich Tern avoidance rate of OWFs significantly increased with turbine density. Similarly, Lamb *et al*. (2024) found that the probability of observing significant changes in distribution increased with the size of the study area footprint, as well as with the ratio of study area footprint to wind farm footprint. Consequently, covariates should also include aspects of study design that influence the data collected, such as the wind farm buffer area, selection of control area and the number of years post-construction data available. Incorporating parameters such as these into models will help reduce uncertainty surrounding estimates of seabird distributional change by accounting for some underlying variation.

3. Conclusions

We identified that a substantial volume of data has been collected with which to assess the distributional change of seabirds in response to the presence of offshore wind farms. However, we encountered substantial challenges in accessing these datasets, particularly in the case of some of the older studies. In a number of cases, we found that projects had changed hands or that key personnel had moved positions and that as a consequence, links to the data had been lost. Access to data has improved for recent studies, through platforms such as The Crown Estate's Marine Data Exchange. However, even in relation to these studies, we found challenges relating to consistency of formats and the availability of effort data.

There was substantial variability in the quantity of data available for different species. In part, this reflects the overlap in the ranges of the species concerned with operational wind farms, with more data available for species such as gannets, kittiwakes, guillemots and razorbills than for species such as Manx shearwater and storm-petrels. Amongst the priority species there was a notable gap in relation to puffins. This is likely to, at least partially, reflect the locations in which the identified data were collected, with most sites located in the Southern North Sea.

As highlighted by previous reviews (Dierschke et al. 2016; Lamb et al. 2024), making direct comparisons between the results reported in different studies is challenging as a consequence of differences in study design. Differences in study design make it difficult to discern the extent to which reported differences in the magnitude and direction of reported distributional changes relate to genuine ecological differences as opposed to being artefacts of experimental design. Consequently, considerable uncertainty remains in relation to reported distributional changes by seabirds in response to the presence of offshore wind farms. The most effective means to address, and reduce this uncertainty, will be through the collation of available raw data for analysis using a common framework.

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Appendix 1: Table of studies of seabird distributional change

Windfarm	Years	Methodology	Construction Period	Key species & responses	Citation
Aberdeen	2020 – 2021	Radar-camera	Post-construction	• Black-legged Kittiwake: meso-avoidance • Herring Gull: meso-avoidance • Great black-backed Gull: meso-avoidance • Northern Gannet: meso-avoidance	Tjørnløv *et al.* 2023
Alpha Ventus	2011	Visual observations	Post-construction	• Northern Gannet: macro-avoidance • All marine birds: displacement	Aumuller *et al.* 2013
Alpha Ventus	2002 – 2011	Visual aerial survey	Pre-construction, post-construction	• All divers: displacement	Mendel 2012
Alpha Ventus	2010 – 2013	Boat-based surveys	Post-construction	• Northern Gannet: displacement • Little Gull: displacement • Common Gull: no response • Lesser Black-backed Gull: attraction • Herring Gull: no response • Great Black-backed Gull: attraction • Black-legged Kittiwake: displacement • All divers: displacement • All terns: displacement • All alcids: displacement	Welcker and Nehls 2016
Beatrice	2015 – 2019	Digital aerial survey	Pre-construction, post-construction	• Atlantic Puffin: no response • Black-legged Kittiwake: no response • Common Guillemot: no response • Northern Gannet: displacement • Razorbill: no response	Trinder *et al.* 2019
Beatrice	2015 – 2021	Digital aerial survey	Pre-construction, post-construction	• Northern Gannet: displacement/macro-avoidance • Common Guillemot: no response • Razorbill: no response • Atlantic Puffin: no response • Black-legged Kittiwake: no response	Trinder *et al.* 2024

Bligh Bank	2008 – 2013	Boat-based survey	Pre-construction, post-construction	• Black-legged Kittiwake: no response • Common Gull: no response • Common Guillemot: displacement • Great Black-backed Gull: no response • Great Skua: no response • Herring Gull: attraction • Lesser Black-backed Gull: attraction • Little Gull: no response • Northern Fulmar: no response • Northern Gannet: displacement • Razorbill: displacement	Vanermen *et al.* 2015
Blyth	1998 – 2003	Visual observations	Pre-construction, construction, post-construction	• Black-headed Gull: no response • Black-legged Kittiwake: no response • Common Eider: no response • Common Scoter: no response • Great Black-backed Gull: no response • Great Cormorant: macro-avoidance (summer) • Herring Gull: no response • Northern Gannet: no response • Sandwich Tern: no response	Rothery *et al.* 2009
Blyth Demonstration Site	2016 – 2018	Boat-based survey	Pre-construction, post-construction	• Northern Gannet: displacement • Herring Gull: no response • Black-legged Kittiwake: no response • Common Guillemot: displacement • Razorbill: displacement • Atlantic Puffin: no response	Percival 2019
Burbo Bank	2005 – 2009	Boat-based survey	Pre-construction, construction, post-construction	• Great Cormorant: attraction • All alcids: attraction	SeaScape Energy 2009
Egmond aan Zee	2007 – 2010	Visual observations and radar	Post-construction	• Black-headed Gull: no response • Black-legged Kittiwake: no response • Common Gull: no response • Common Scoter: macro-avoidance • Dark-bellied Brent Goose: macro-avoidance • Great Black-backed Gull: no response • Great Cormorant: no response • Herring Gull: no response • Lesser Black-backed Gull: no response • Little Gull: no response • Northern Gannet: macro-avoidance	Krijgsveld *et al.* 2011

				• Sandwich Tern: no response • All marine birds: macro-avoidance	
Egmond aan Zee and Princess Amalia	2008 – 2010	GPS telemetry	Post-construction	• Lesser Black-backed Gull: macro-avoidance	Campheysen 2011
Egmond aan Zee and Princess Amalia	2002 – 2012	Boat-based survey	Pre-construction, construction, post-construction	• Black-headed Gull: no response • Black-legged Kittiwake: displacement (Princess Amalia) • Common Guillemot: displacement • Common Gull: no response • Common Scoter: displacement (Egmond aan Zee) • Common Tern: displacement (Egmond aan Zee) • Great Black-backed Gull: no response • Great Cormorant: attraction • Herring Gull: no response • Lesser Black-backed Gull: displacement (Egmond aan Zee) • Little Gull: displacement (Princess Amalia) • Northern Fulmar: no response • Northern Gannet: displacement • Razorbill: displacement (Princess Amalia) • Sandwich Tern: no response • All divers: displacement (Egmond aan Zee)	Leopold *et al.* 2013
Greater Gabbard	2014	Digital aerial survey	Post-construction	• Northern Gannet: displacement	Rehfisch *et al.* 2014
Gunfleet Sands	2007 – 2013	Boat-based survey	Pre-construction, construction, post-construction	• Common Gull: attraction • Great Black-backed Gull: attraction • Herring Gull: attraction • Black-legged Kittiwake: attraction • Lesser Black-backed Gull: displacement • All divers: displacement • All alcids: displacement • All gulls: attraction	Mendez *et al.* 2015

Horns Rev	2004	Visual observations and radar	Post-construction	• Arctic/Common Tern: macro-avoidance • Common Scoter: macro-avoidance • Northern Gannet: macro-avoidance • Red-throated Diver: macro-avoidance • Sandwich Tern: no response • All gulls: macro-avoidance • All marine birds: macro-avoidance	Christensen and Hounisen 2005
Horns Rev 1	1999 – 2007	Visual aerial survey	Pre-construction, construction, post-construction	• All alcids: displacement • Common Eider: displacement • Common Scoter: attraction • Herring Gull: displacement • Little Gull: no response • All divers: displacement	Petersen and Fox 2007
Horns Rev 1 and 2	2010 – 2012	Radar	Post-construction	• Black-legged Kittiwake: macro-avoidance • Common Scoter: macro-avoidance • Northern Gannet: macro-avoidance • All small gulls: macro-avoidance • All large gulls: macro-avoidance • All divers: macro-avoidance • All terns: macro-avoidance	Skov *et al.* 2012a
Horns Rev 2	2005 – 2012	Visual aerial survey	Pre-construction, post-construction	• Common Scoter: displacement • All divers: displacement	Petersen *et al.* 2014
Horns Rev and Nysted	2005 – 2006	Visual observations and radar	Post-construction	• Common Scoter: macro-avoidance • Little Gull: macro-avoidance • Northern Gannet: macro-avoidance • Red-throated Diver: macro-avoidance • Common Eider: macro-avoidance • Great Cormorant: attraction • All swans and geese: macro-avoidance • All terns: macro-avoidance • All large gulls: macro-avoidance • All marine birds: macro-avoidance	Blew *et al.* 2008
Humber Gateway	2012 – 2019	Boat-based survey	Pre-construction, construction, post-construction	• Northern Gannet: macro-avoidance • Common Guillemot: macro-avoidance • Little Gull: macro-avoidance • Black-legged Kittiwake: macro-avoidance • Razorbill: macro-avoidance	Stone *et al.* 2023

Kentish Flats	2002 – 2007	Visual aerial survey	Pre-construction, construction, post-construction	• Great Cormorant: no response • All alcids: no response • All gulls: no response • All divers: no response • All marine birds: displacement • All sea ducks: no response	Gill *et al.* 2008
Kentish Flats	2002 – 2013	Boat-based survey	Pre-construction, construction, post-construction	• Red-throated Diver: displacement	Percival 2014
Kentish Flats	2001 – 2010	Boat-based survey	Pre-construction, construction, post-construction	• Common Gull: no response • Great Cormorant: no response • Herring Gull: no response • Lesser Black-backed Gull: no response • Red-throated Diver: no response	Rexstad and Buckland 2012
Kentish Flats Extension	2014 – 2017	Boat-based survey	Pre-construction, post-construction	• Red-throated Diver: displacement • Great Cormorant: no response • Common Gull: no response • Herring gull: no response • Great Black-backed Gull: no response	Percival and Ford 2017
Kriegers Flak	2022 - 2023	Boat-based survey	Post-construction	• Long-tailed Duck: no response	Nielsen et al. 2023
Lillgrund	2001 – 2011	Boat-based survey, visual aerial survey and radar	Pre-construction, post-construction	• Common Eider: displacement • Great Cormorant: no response • Herring Gull: displacement (boat surveys) / attraction (aerial surveys) • Long-tailed Duck: displacement • Red-breasted Merganser: displacement • All waterfowl: macro-avoidance	Nilsson and Green 2011
Lincs	2003 – 2016	Visual aerial and digital aerial survey	Pre-construction, construction, post-construction	• Red-throated Diver: displacement • Northern Gannet: displacement • Small Gulls: no response • Little Gull: no response • Common Gull: no response • Lesser Black-backed Gull: no response • Common Tern: no response • Sandwich Tern: no response • Common Guillemot: no response	Webb *et al.* 2017

London Array	2009 – 2016	Digital aerial survey	Pre-construction, construction, post-construction	• Red-throated Diver: displacement • Northern Gannet: inconclusive • Black-legged Kittiwake: inconclusive • Black-headed Gull: inconclusive • Common Gull: attraction • Lesser Black-backed Gull: inconclusive • Herring Gull: inconclusive • Great Black-backed Gull: attraction • All alcids: displacement	APEM 2021
Luchterduinen	2019 - 2021	Visual observations	Post-construction	• Lesser Black-backed Gull: no response • Black-legged Kittiwake: no response • Great Cormorant: attraction • Northern Gannet: macro-avoidance • Razorbill/Guillemot: macro-avoidance • Great Black-backed Gull: no response • Common Gull: no response • Common Guillemot: macro-avoidance • Herring Gull: no response • Sandwich Tern: macro-avoidance • Razorbill: no response	Leemans *et al.* 2022
Lynn/Inner Dowsing	2007 – 2010	Radar	Construction, post-construction	• Pink-footed Goose: macro-avoidance	Plonczkier and Simms 2012
Lynn/Inner Dowsing	2001 – 2010	Boat-based survey	Pre-construction, construction, post-construction	• Red-throated Diver: displacement • Northern Fulmar: no response • Northern Gannet: no response • Black-legged Kittiwake: no response • Common Gull: displacement • Lesser Black-backed Gull: inconclusive • Herring Gull: inconclusive • Great Black-backed Gull: no response • Sandwich Tern: no response • Common Tern: no response • Common Guillemot: inconclusive • All skuas: no response	Sansom *et al.* 2011
North Hoyle	2001 – 2005	Boat-based survey	Pre-construction, construction, post-construction	• Black-legged Kittiwake: attraction • Common Guillemot: no response • Common Scoter: displacement • European Shag: attraction • Great Cormorant: attraction • Northern Gannet: attraction • Razorbill: displacement	PMSS 2006

Norther	2013 – 2020	GPS telemetry	Pre-construction, construction, post-construction	• Lesser Black-backed Gull: displacement	Degraer *et al.* 2021
Norther and Borssele	2013 – 2021	GPS telemetry	Pre-construction, post-construction	• Lesser Black-backed Gull: no response	Vanermen *et al.* 2022
Nysted	2000 – 2003	Radar	Pre-construction, post-construction	• Waterfowl: macro-avoidance	Desholm and Kahlert 2005
Nysted	1999 – 2003	Radar	Pre-construction, construction, post-construction	• All marine birds: macro-avoidance	Kahlert *et al.* 2004
Nysted	2000 – 2005	Radar	Post-construction	• Common Eider: macro-avoidance	Masden *et al.* 2009
Nysted	2000 – 2007	Visual aerial survey	Pre-construction, construction, post-construction	• Long-tailed Duck: displacement	Petersen *et al.* 2011
Nysted and Horns Rev 1	1999 – 2005	Visual aerial survey and radar	Pre-construction, construction, post-construction	• All alcids: no response • All marine birds: macro-avoidance • Arctic/Common Tern: displacement • Common Eider: displacement (Nysted) • Common Scoter: displacement • All divers: displacement (Horns Rev 1) • Herring Gull: attraction (Horns Rev 1) • Little Gull: attraction • Long-tailed Duck: displacement • Northern Gannet: displacement • Red-breasted Merganser: attraction	Petersen *et al.* 2006

Ormonde	2008 – 2014	Boat-based survey	Pre-construction, construction, post-construction	• Manx Shearwater: inconclusive • Lesser Black-backed Gull: displacement • Common Guillemot: displacement • Northern Gannet: displacement • Black-legged Kittiwake: attraction	CMACS 2014
Race Bank	2006 – 2018	Digital aerial survey (and boat-based pre-construction)	Pre-construction, post construction	• Sandwich Tern: inconclusive	APEM 2022
Robin Rigg	2001 – 2015	Boat-based survey	Pre-construction, construction, post-construction	• Razorbill: no response • Common Guillemot: no response • Black-legged Kittiwake: no response • Herring Gull: no response	Nelson *et al.* 2015
Robin Rigg	2001 – 2012	Boat-based survey	Pre-construction, construction, post-construction	• Common Guillemot: no response	Vallejo *et al.* 2017
Scroby Sands	2002 - 2006	Boat-based survey	Pre-construction, construction, post-construction	• Little Tern: no response	Perrow *et al.* 2006
Sheringham Shoal	2009-2016	Boat-based survey	Pre-construction, construction, post-construction	• Razorbill: macro-avoidance • Common Guillemot: macro-avoidance • Northern Gannet: macro-avoidance • Little Gull: macro-avoidance • Great Black-backed Gull: attraction • Sandwich Tern: macro-avoidance	Harwood *et al.* 2018
Sheringham Shoal	Unknown	Visual observations	Pre-construction, construction, post-construction	• Sandwich Tern: macro-avoidance	Perrow *et al.* 2015

Thanet	2004 – 2013	Boat-based survey	Pre-construction, construction, post-construction	• Black-legged Kittiwake: displacement • Common Gull: attraction • Common Guillemot: displacement • Great Black-backed Gull: no response • Herring Gull: no response • Lesser Black-backed Gull: no response • Northern Gannet: no response • Razorbill: displacement • Red-throated Diver: displacement	Percival 2013
Thanet	2014 – 2016	Radar-camera	Post-construction	• Black-legged Kittiwake: macro-avoidance • Great Black-backed Gull: macro-avoidance • Herring Gull: macro-avoidance • Lesser Black-backed Gull: macro-avoidance • Northern Gannet: macro-avoidance	Skov *et al.* 2018
Thornton Bank	2005 – 2015	Boat-based survey	Pre-construction, construction, post-construction	• Black-legged Kittiwake: displacement • Common Gull: no response • Common Guillemot: displacement • Common Tern: no response • Great Black-backed Gull: attraction • Great Skua: no response • Herring Gull: no response • Lesser Black-backed Gull: no response • Little Gull: displacement • Northern Fulmar: no response • Northern Gannet: displacement • Razorbill: no response • Sandwich Tern: no response	Vanermen *et al.* 2016
Thornton Bank	2013 – 2017	GPS telemetry	Post-construction	• Lesser Black-backed Gull: displacement	Vanermen *et al.* 2020
Tuno Knob	1994 – 1997	Visual observations and visual aerial survey	Pre-construction, post-construction	• Common Eider: displacement • Common Scoter: no response	Guillemette *et al.* 1998
Tuno Knob	1998	Visual observations	Post-construction	• Common Eider: macro-avoidance	Larsen and Gullemette 2007

Tuno Knob	1998 – 1999	Radar	Post-construction	• Common Eider: macro-avoidance	Tulp *et al.* 1999
Walney	2008 – 2014	Boat-based survey	Pre-construction, construction, post-construction	• Manx Shearwater: displacement • Lesser Black-backed Gull: no response • Common Guillemot: no response • Black-legged Kittiwake: no response • Northern Gannet: no response	NIRAS 2015
Walney Extension and Burbo Bank Extension	2016 – 2019	GPS telemetry	Pre-construction, construction, post-construction	• Lesser Black-backed Gull: displacement	Clewley *et al.* 2021
Westermost Rough	2017	Digital aerial survey	Post-construction	• Black-legged Kittiwake: no response • Alcids (Razorbill, Atlantic Puffin, Common Guillemot): no response	Goddard *et al.* 2017
Multiple (Belgian OWF consession zone)	2021 – 2023	Boat-based survey	Post-construction	• Northern Gannet: macro-avoidance • Great Cormorant: attraction • Little Gull: macro-avoidance • Common Gull: attraction • Lesser Black-backed Gull: macro-avoidance • Herring Gull: inconclusive • Great Black-backed Gull: attraction • Black-legged Kittiwake: inconclusive • Sandwich Tern: inconclusive • Common Guillemot: inconclusive • Razorbill: inconclusive	Vanermen *et al.* 2023
Multiple	2011 – 2015	Digital aerial survey	Post-construction	• Common Scoter: macro-avoidance • Red-throated Diver: macro-avoidance	Burt *et al.* 2022
Multiple	2014	GPS telemetry	Construction	• Northern Gannet: macro-avoidance	Garthe *et al.* 2017

Multiple	2000 – 2017	Boat-based, visual aerial and digital aerial survey	Pre-construction, construction, post-construction	• All divers: macro-avoidance	Garthe *et al.* 2023
Multiple	2015 – 2017	Satellite telemetry and digital aerial survey	Post-construction	• Red-throated Diver: displacement	Heinanen *et al.* 2020
Multiple	2014 – 2019	GPS telemetry	Post-construction	• Lesser Black-backed Gull: attraction	Johnston *et al.* 2022
Multiple	2015 – 2019	GPS telemetry	Post-construction	• Northern Gannet: macro-avoidance	Lane *et al.* 2020
Multiple	2000 – 2017	Boat-based, visual aerial and digital aerial survey	Pre-construction, post-construction	• All divers: displacement	Mendel *et al.* 2019
Multiple	2016 – 2017	GPS telemetry	Post-construction	• Common Guillemot: displacement	Peschko *et al.* 2020a
Multiple	2000 – 2017	Boat-based and visual aerial survey	Pre-construction, post-construction	• Black-legged Kittiwake: displacement (breeding season) • Common Guillemot: displacement	Peschko *et al.* 2020b
Multiple	2015 – 2016	GPS telemetry	Post-construction	• Northern Gannet: displacement & macro-avoidance	Peschko *et al.* 2021

Multiple	2000 – 2003	Visual observations and radar	Pre-construction, construction, post-construction	• Common Eider: macro-avoidance • All waterfowl: macro-avoidance	Pettersson 2005
Multiple	2021	GPS telemetry	Post-construction	• Black-legged Kittiwake: attraction	Pollock *et al.* *"in review"*
Multiple	2002 – 2013	Boat-based, visual aerial and digital aerial survey	Pre-construction, construction, post-construction	• Red-throated Diver: no response • Unidentified alcids (Razorbill, Atlantic Puffin, Common Guillemot): displacement	Rehfisch *et al.* 2016
Multiple	2010 – 2012	GPS telemetry	Post-construction	• Lesser Black-backed Gull: attraction	Thaxter *et al.* 2015
Multiple	2014	GPS telemetry	Post-construction	• Lesser Black-backed Gull: meso-avoidance	Thaxter *et al.* 2018
Multiple	2016 – 2019	GPS telemetry	Pre-construction, construction, post-construction	• Sandwich Tern: macro-avoidance	Thaxter *et al.* 2024
Multiple	2016 – 2021	GPS telemetry	Post-construction	• Sandwich Tern: macro-avoidance	van Bemmelen *et al.* 2023
Multiple	2001 – 2018	Visual aerial and digital aerial survey	Pre-construction, construction, post-construction	• All divers: displacement	Vilela *et al.* 2021

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