OFFSHORE RENEWABLES JOINT INDUSTRY
PROGRAMME (ORJIP) FOR OFFSHORE WIND

CARBON TRUST

Final report

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

June 2026

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

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

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

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

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Who we are

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Glossary

Term	Description
OWF	Offshore Wind Farm
DAS	Digital Aerial Survey
DSM	Density Surface Model
ESAS	European Seabirds At Sea
BTO	British Trust for Ornithology
ImpUDis	Improving Understanding of Distributional Change for Relevant Seabird Species
DisNBS	(Effects of) Displacement from Offshore Renewable Developments in the Non-Breeding Season project
IBM	Individual-Based Model
BAG	Before After Gradient
BACI	Before After Control Impact
PVA	Population Viability Analysis
GA(M)M	Generalised Additive Model, or Generalised Additive Mixed Model
CRM	Collision Risk Model
WP	Work Package
INLA	Integrated Nested Laplace Approximations

Executive Summary

Offshore wind farms are a vital part of the transition to clean energy, but they can affect seabirds by causing them to avoid or be attracted to the wind farm area — a process known as distributional change or displacement. When regulators cannot be certain how much displacement is occurring, they must assume the worst, which can stall or complicate the consenting of new developments. The ImpUDis project was established to address this problem directly. Working with industry, regulators, and conservation bodies, the project reviewed the available evidence, developed a standardised set of methods for measuring displacement, tested those methods on real monitoring data from eight UK offshore wind farms, and engaged key stakeholders to validate the approach. Its central finding is that while displacement is real and measurable, the quality and consistency of monitoring data has historically been the main barrier to confident conclusions — and that addressing this data challenge is just as important as any statistical advance.

A review of 76 studies across 35 European offshore wind farms (WP1) confirmed that seabird distributional change is real but highly variable. Around 41% of studies reported statistically significant displacement or avoidance, with auks, gannets and divers tending to avoid wind farms and kittiwakes showing mixed responses. Reported displacement magnitudes varied enormously between sites and species, reflecting genuine ecological variability as well as major inconsistencies in survey design, spatial scale and analysis method. Critically, a large proportion of existing monitoring datasets were found to be unsuitable for robust analysis, due to missing effort data, inconsistent formats, poor metadata and ambiguous species identification.

Building on this evidence base, a formal guidance framework was developed (WP2) for estimating seabird redistribution in a consistent, transparent and reproducible way. The framework adopts a Before–After–Gradient (BAG) study design — the practical standard for OWF monitoring — and specifies detailed requirements for data structure, modelling approach, and reporting of outputs with quantified uncertainty.

This guidance was tested against real monitoring data from eight UK wind farms (WP3), with approximately 54 redistribution models fitted across sites and species. Results confirmed the framework is broadly workable. Where data quality allowed, functional distance and spatial models were more informative than simple inside–outside comparisons, and the framework produced outputs directly compatible with existing assessment tools. However, a very large proportion of available data could not be used due to the data quality issues identified in WP1, meaning many results must be treated as indicative rather than definitive.

A stakeholder workshop (WP4) brought together developers, regulators, statutory nature conservation bodies, NGOs and academics to scrutinise the methods and results. Participants validated the analytical approach and reinforced the need for better data standardisation, consistent metadata, and more prescriptive survey standards going forward.

The WP2 methodology is designed to be directly compatible with the existing UK consenting framework and can be integrated into assessments in three ways: redistribution estimates with confidence intervals can be applied directly within existing displacement matrices; gradient-based model outputs can underpin a modified matrix approach that distributes mortality spatially rather than applying a single rate; and density surface model outputs can be used as input layers in individual-based models such as SeabORD or DisNBS, enabling more evidence-based counterfactual scenarios.

Adopting this approach in future assessments would be expected to reduce uncertainty significantly. Where current assessments rely on a single precautionary displacement rate derived from the literature, the WP2 framework would instead produce a site-informed estimate with quantified uncertainty and a spatial gradient of effect. In cases where empirical displacement is lower than precautionary assumptions suggest, this is likely to result in more proportionate conclusions in Habitats Regulations Assessments and a reduced likelihood of concluding Adverse Effects on Integrity.

For this methodology to be routinely applied, the following next steps are required: development of a centralised, accessible repository of standardised pre- and post-construction survey data; formal adoption of the WP2 guidance by statutory bodies and industry as the expected standard for redistribution analyses; retrospective data recovery from existing monitoring programmes to expand the pool of usable analogous datasets; and further development of the approach for data-limited species, particularly puffin and divers.

Key recommendations

- The following recommendations are directed at developers, data holders, regulators and statutory nature conservation bodies:
- Future post-consent monitoring surveys must retain and share full effort data — survey tracks and sampled areas — alongside observation records. Without effort data, robust redistribution modelling is not possible, and data stored only as summaries in reports cannot be used.
- All monitoring datasets should adhere to consistent species coding conventions, machine-readable formats, defined spatial projections and a comprehensive data dictionary. OWF footprints should be defined using actual turbine locations, not lease areas.
- A coordinated programme to collate existing pre- and post-construction survey data into a shared, accessible repository should be initiated as a priority. This would substantially reduce the data recovery burden in future analyses and enable cumulative learning across sites.
- The BAG modelling framework set out in WP2, implemented through reproducible GAMM/GLMM-based density surface models, should be adopted as the standard approach for future displacement assessments, with outputs including quantified redistribution magnitude and uncertainty suitable for direct input into displacement matrices and individual-based models.
- Survey areas should extend well beyond the immediate OWF footprint — up to 10–20 km depending on species — to enable gradient-based models to capture the full spatial pattern of response.
- Regulators and statutory bodies should consider embedding more prescriptive survey and metadata standards in consent conditions, to ensure that future monitoring data are consistently fit for redistribution analysis from the outset.

1. Introduction

There is significant uncertainty surrounding the displacement rates of key seabird species due to varied behavioural responses reported across different offshore wind farms and inconsistent methodologies. This uncertainty complicates impact assessments and increases the likelihood of concluding Adverse Effects on Integrity, as decisions must be made 'beyond reasonable scientific doubt.'

The Improving Understanding of Distributional Change for Relevant Seabird Species (ImpUDis) project aimed to provide better parameter estimates for impact assessments, reducing prediction uncertainties and consenting risks by improving decision-making processes. The concept was to help minimize the need for additional precautionary measures in assessments and ensure that unnecessary compensation could be avoided. Establishing agreed-upon methods and sources of evidence is vital to enhance consistency in future assessments and post-consent monitoring approaches.

The project also aimed to enhance our understanding of seabird distributional changes by developing and applying standardized statistical methods using available data.

This project consists of several work-packages with goals that fed forward from one work package to the next:

- Work Package 1: Critically review how seabird distributional change from offshore wind developments is considered in impact assessments and calculated from post-consent monitoring.
- Work Package 2: Develop a standardised approach to quantifying seabird distributional change for future wind farms, clearly defining the ideal data requirements (inc. quality, quantity, and format) and approach to data processing and analysis.
- Work Package 3: Conduct a robust analysis in accordance with the agreed delivery plan.
- Work Package 4: Stakeholder engagement to discuss the interpretation of the results and their application to impact assessment.

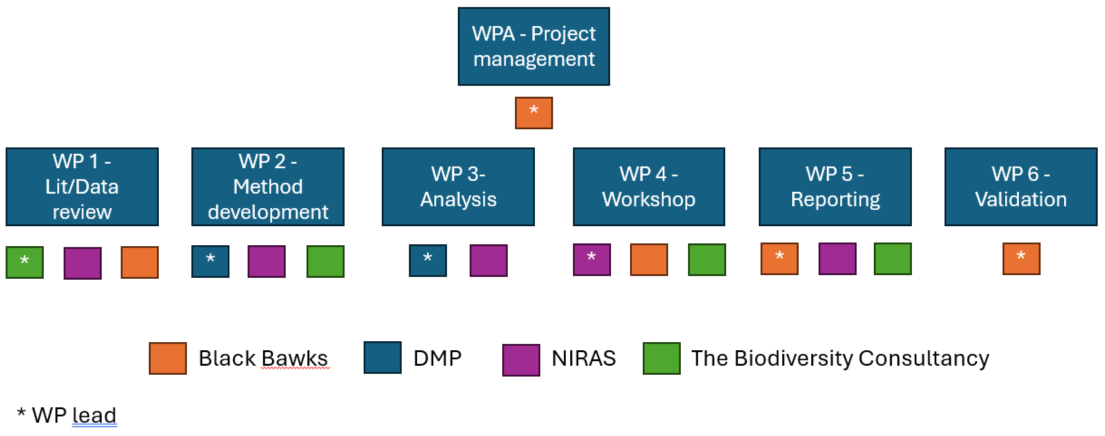

Figure 1. Organisational chart showing project leads and main consortium members involved in each work package.

For this final report of the ImpUDis project, we lay out the key findings of each work package and then conclude with statements on the importance of data standardization and a way forward regarding the use of the proposed methodology.

2. WP1 – Literature and Data Review

Work Package 1 (WP1) established the conceptual and empirical foundation for the ImpUDis project by reviewing how seabird distributional change around offshore wind farms (OWFs) has been defined, measured and interpreted, and by identifying and assessing the available data. The report emphasised that, alongside collision risk, distributional change is one of the two primary direct effects of OWFs on seabirds. This is particularly important for Habitats Regulations Assessments (HRAs), where uncertainty in displacement rates often forces precautionary assumptions, increasing the risk that authorities conclude adverse effects on protected sites.

With over 20 years of post-construction monitoring across different OWFs, the review found an abundance of data on seabird distributional changes. Previous reviews of post-construction studies by Dierschke et al. (2016) and Lamb et al. (2024) had provided insights into the species which are likely to be displaced. They found evidence of displacement in divers, gannets, sea ducks and auks, as well as some evidence of attraction in gulls and cormorants. However, those reviews pointed out that there is still substantial uncertainty surrounding displacement rates. This is likely to be 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 (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-inflation and spatial and temporal autocorrelation.

The WP1 review defined the four ways in which seabirds may respond to OWFs:

- **Displacement** from the wind farm area, resulting in functional loss of habitat (Mendel et al. 2019). Displacement was defined as **the reduction in density in birds within the footprint of a wind farm, as defined by a minimum convex polygon (i.e., the smallest polygon that encompasses all turbines) around the rotor sweeps of the outermost turbines, and appropriate species-specific buffer around the wind farm.**
- **Attraction** to new habitat in the wind farm area (Thaxter et al., 2018) with attraction defined 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.**
- The perception of the wind farm as a **barrier** to movement (Thaxter *et al*. 2024), with barrier effects defined as **the alteration in the flight path of a bird as it approaches an OWF.**
- **Indifference** to the wind farm, resulting in no change in distribution

The report next reviewed current approaches used in Environmental Impact Assessments (EIAs), with a focus on the Matrix Approach and the Individual-Based Model SeabORD (Searle et al. 2018), which are currently the most widely used in assessments. The Matrix Approach combines assumed displacement rates with assumed mortality rates to estimate adult mortality due to displacement, while SeabORD simulates how changes in foraging distributions affect energy budgets, breeding success and survival. WP1 highlighted that both approaches rely heavily on uncertain displacement parameters, making better empirical estimation of distributional change a key project need.

Given that the most recent review (Lamb *et al.* 2024) covered studies up to 2022, the focus for the WP1 review was on studies published from 2022 onwards. However, initial exploratory search was carried out and cross-referenced 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, other online repositories were searched (e.g., The Crown Estate Marine Data Exchange), and information solicited from the members of the ORJIP Offshore Wind Steering Group.

Searches identified 76 studies published between 1998 and 2024 across 35 European OWFs (Appendix 1). Of the studies identified, 22 used boat-based surveys, 15 used GPS telemetry, 7 used digital aerial surveys, 6 used radars, 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 with an average monitoring period of 5.3 years. Nearly half included both pre- and post-construction data, but **many were short in duration or spatially limited**.

Across all species, **33% of studies found significant displacement or macro-avoidance, 8% found significant attraction, and 59% found no significant change**, although **many non-significant results were likely under-powered**. Priority species for ImpUDis—auks, gannets, divers and kittiwakes (as determined by discussion with the project steering committee)—showed different tendencies. Auks (guillemot, razorbill, puffin) were displaced or showed macro-avoidance in nearly half of reviewed studies and were never clearly attracted. Divers showed even stronger tendencies towards displacement. Gannets also often avoided OWFs, though with some variability. Kittiwakes were more variable, with some studies showing displacement, some attraction and many no significant change, indicating strong site- or context-specific behaviour (Table 1).

Table 1. Table 1 from WP1 showing 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. 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

Species	Number of Studies	No. of studies indicating significant displacement / macro-avoidance	No. of studies indicating significant attraction
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

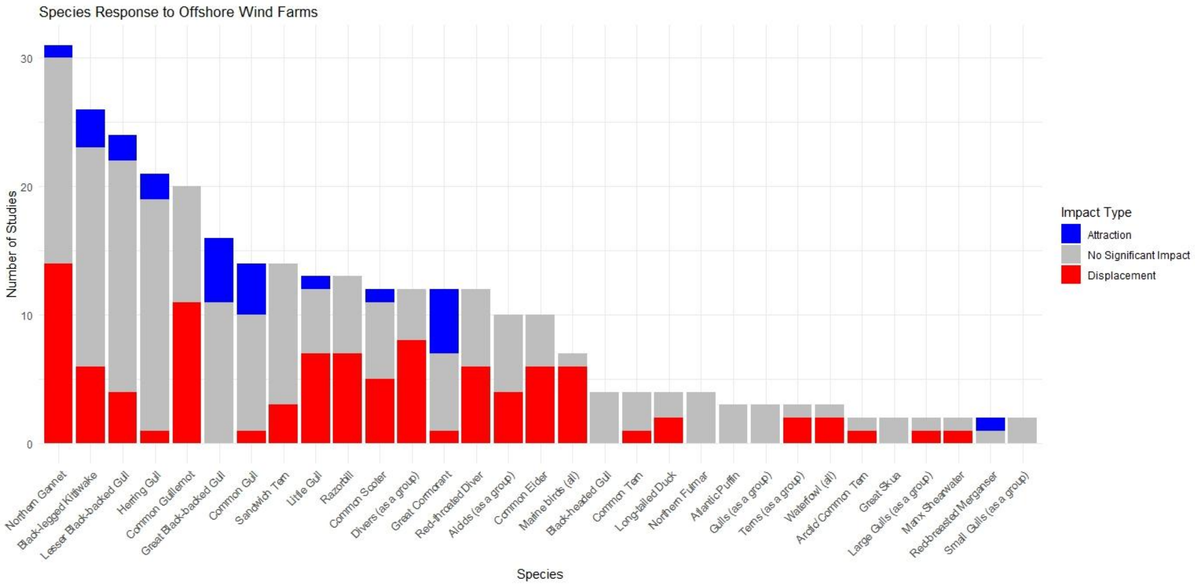

Figure 2 Figure 1 from WP1 showing the number of studies indicating significant attraction or displacement/macro-avoidance effects, and those indicating no significant distributional change per species.

WP1 also reviewed reported magnitudes of distributional change and found them extremely variable. For example, gannet displacement estimates ranged from around **64% to almost 99%**, kittiwake from about **32% to 86%**, and divers from about **64% to over 93%**. The report identified several 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, for example, 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).

The report then examined how distance from OWFs influenced estimates. There was a varying degree of buffer sizes around wind farms used across studies; from 2 km to 10 km, depending on species. This strongly affected both the magnitude and statistical significance of estimated displacement. WP1 highlighted that inconsistent buffer definitions and footprint definitions (lease area versus actual turbine locations) complicate comparisons across studies (Table 2).

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.* (2019)
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)

WP1 reviewed key knowledge gaps based on the identified studies and found that puffin were the only key species of interest to this project that lacked many relevant studies with only 3 identified of which none were able to determine any significant distributional change.

The review next elaborated on 8 methods for estimating distributional change which have evolved as data collection and analytical tools have improved. Early approaches, such as Jacob's Selectivity Index, provided a simple way to compare the proportion of birds in a wind farm area with the proportion of area it occupies, indicating avoidance or attraction, but could not test significance or include environmental drivers. Control–Impact studies compared bird numbers inside and outside wind farms, often finding fewer birds within developments, but without pre-construction data it was difficult to separate wind farm effects from natural spatial variability. The Before–After Control–Impact (BACI) design addressed this by collecting data at impact and control sites both before and after construction, allowing changes caused by the wind farm to be distinguished from background variation. However, BACI studies are often limited by high natural variability in seabird data, low statistical power, and the difficulty of identifying truly comparable control sites.

More recent methods use advanced spatial modelling and broader experimental designs. Density surface models, using tools such as Generalized Additive Models or Bayesian spatial models, relate bird distributions to environmental variables and the presence of wind farms, allowing estimation of the magnitude, significance, and spatial pattern of change. **Before–After Gradient (BAG) designs extend this by modelling how responses vary with distance from a wind farm and through time, providing greater inferential power but requiring larger survey areas**. In parallel, GPS tracking, radar, and shore-based counts provide complementary perspectives: tracking reveals fine-scale individual movements and potential barrier effects; radar captures broad-scale flight patterns but often lacks species identification; and shore-based counts are useful only for small, nearshore projects. Overall, the trend has been from simple descriptive indices to integrated, **model-based approaches that better account for environmental variation, survey design, and the complex ways birds respond to offshore wind farms**.

WP1 next critically reviewed the quality of available data. **Many datasets suffered from ambiguous formats, missing effort information, inconsistent species identification, and lack of detection**

correction. Species were often lumped into groups (e.g. “auk sp.” or “diver sp.”), making cross-site pooling problematic. The review concludes that boat-based and aerial (visual and digital) line-transect surveys are currently the most suitable data sources for analysing seabird displacement, while radar lacks species-level detail and telemetry data are still too limited for broad inference across sites. Robust displacement analysis requires high-quality, well-documented spatio-temporal data, including accurate survey tracks, observation records, consistent formats, and minimal errors. Data usability is often constrained by inconsistent formats (Excel vs shapefiles), ambiguous duplication across projects, missing effort information, lack of detection-probability correction, and insufficient sample sizes for key species. Visual survey data in particular require distance information and proper distance-sampling analysis to estimate true abundance. **Many datasets are unusable because they exist only as summaries in reports or lack essential metadata, meaning that only a subset of available data can realistically support reliable modelling of species displacement**.

The WP1 report continued to then report on key environmental factors related to distributional change that have been incorporated into past modelling exercises. 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 (See Table 3 from WP1). The report then continued to recommend the inclusion of other parameters such as the number of turbines, turbine density and height, wind farm area, and potential fishing activities.

WP1 concluded that, although there is a large volume of potentially useful data, **only a subset is suitable for robust redistribution analysis**. The report identified candidate datasets for further work, which were then taken forward into WP2 and WP3. It also identified key knowledge gaps, including **lack of long-term monitoring, inconsistent methods, poor metadata standards and limited integration of tracking and survey data**.

Overall, WP1 provided the scientific justification for the ImpUDis project. It demonstrated that distributional change around OWFs is real but highly variable, poorly quantified and methodologically inconsistent. It established the need for standardised analytical guidance and for systematic analysis of the best available extant data, which became the focus of the subsequent work packages.

3. WP2 – Redistribution Estimation Guidance

Work Package 2 (WP2) translated the findings of WP1 into formal guidance on how seabird redistribution around OWFs should be estimated in a way that is consistent, reproducible and useful for the consenting process. The final full version of this guidance can be found in the WP2 report "Guidance for estimating redistribution from OWF (WP2)" as prepared by DMP Statistics for the ImpUDis project.

The WP2 report focused on covering guidance for 4 elements of redistribution modelling:

- data collection and its treatment in terms of quality and preparedness for analysis,
- analysis methods,
- modelling outputs, and
- the treatment of data and analysis files for reproducibility and future utility.

The quantification of an effect in a fully controlled experiment would call for pre-treatment measures and a corresponding control throughout – the basis of the BACI design in ecological field experiments. Outside of OWF, establishing suitable control sites is difficult and frequently controversial. For this reason, previous studies and those going forwards are predominantly Before-After-Gradient analyses (BAG), which do not require a control site. This is at the cost of no contrast between impacted/unimpacted sites over time, giving less power to separate out confounding temporal changes. On balance, and in keeping with the bulk of research, WP2 therefore adopted a **Before–After–Gradient (BAG) study design as the practical standard**.

WP2 adopted the definition of distributional change from WP1: the active selection or avoidance of an area following OWF construction, through displacement or attraction. It recognised that most previous studies used transect surveys (e.g., digital aerial surveys) and that these would continue to dominate because of regulatory requirements, so the guidance focused primarily on transect data, with more limited advice on tracking and radar data.

The report next detailed recommendations on survey data requirements focused on survey design, effort/observation data, and data formats. Survey design recommendations in the report are not greatly addressed due to the nature of existing guidance in terms of design (Parker et al., 2022; NatureScot 2023; Natural Resources Wales, 2022). However, the report caveats that power analysis on survey designs to detect nuanced redistribution is likely to be low. Furthermore, although there were sufficient data for a power analysis, there is substantive complexity in how redistribution could be characterized and any such an analysis would be non-trivial. **The report recommends that digital aerial surveys and their design be in line with existing guidance.**

The report goes on to highlight the two key components for survey data to be analysed:

1. **Observations data**: locations and times that animals were seen. These should be identified to the lowest taxonomic level possible and be as spatiotemporally precise as possible. DAS typically provide precise individual-level recordings, whereas visual recordings will consist of estimated distances from survey platform and estimated group sizes when abundances are high.
2. **Effort/track data**: the spatiotemporal path of the survey platform from GPS.

The report then notes that effort data is often treated of secondary importance, but no robust analysis can be done without this, and imprecise effort data can lead to levels of uncertainty being passed forward through subsequent analyses. These effort data are required to make inference on where animals were absent as well as present (i.e., the "zero abundance" information). Thus, **for analyses to proceed, Observations and Effort data must be available and accessible.**

WP2 identifies three key elements of data formats that should be adhered to for any subsequent analysis:

1. **Formal representation of space and time data** - Survey data is inherently spatiotemporal and should be fundamentally treated as such. It is recommended the data be treated as per GIS, such that there is no ambiguity about time and location of observations and surveyed areas.
2. **Adherence to coding conventions and limit free form data** - Species coding should follow established conventions (e.g., ESAS or BTO) and free-form data collection/entry (e.g. spreadsheets) should be minimised to avoid entry errors.
3. **Data in files, not names** - Information ought not be solely recorded in filenames e.g. survey dates – these should be integral to the dataset itself.

WP2 next laid out guidelines for initial data treatment. Although this report is aimed primarily at redistribution modelling, this could also be applied to any spatial modelling exercise and draws heavily on that framework. The key points for noting here are:

1. Data must be provided in **usable digital formats** (Excel, CSV, shapefiles).
2. All files must include **clear metadata** (survey method, dates, projection, species codes).
3. Coordinates must have a **defined spatial projection**.
4. Dates and times must use a **standard, machine-readable format**.
5. Species and other factor codes must be **consistent across datasets**.
6. Data must include both:
    a. Where animals were seen (presences), and
    b. Where surveys occurred but no animals were seen (absences).

To summarise these: **Do not supply or store data in reports or PDF, always include effort data (survey tracks and/or sampled areas), and clearly define all codes, units and fields in a data dictionary.**

The guidance document then continues on to describe key points in combining effort and observation data:

1. Final modelling dataset must be a **single "tidy" table**:
    a. One row = one surveyed unit (segment, point, or cell).
    b. Includes counts, location, time, effort, and covariates.
2. **Zero counts must be included** where surveys occurred.

3. Continuous surveys may need to be **discretised into segments or grid cells**[1].

4. **Effort must be calculated** for each unit (e.g. area surveyed, swath width).

For stakeholders sharing data, **separate files for sightings and survey tracks should be provided (or some sort of linking data)**, **zero-count samples and coverage must be included**, **ensure there is detail to calculate surveyed area**.

WP2 highlighted the importance of derived variables. Key derived variables include **construction phase (pre, construction, post), distance to the realised OWF footprint (preferably based on actual turbine locations, not lease areas), and relevant environmental covariates such as bathymetry**. These are essential for separating development effects from confounding influences and should be provided by developers prior to any analysis.

For visual surveys, WP2 requires correction for detection bias using distance sampling. Without this, visual data can only be treated as relative abundance. For these kinds of data, analysis is required to be done for each combination of species and survey and can be far more onerous than typical analysis for digital aerial surveys. The guidance recommended reproducible, code-based distance analysis (e.g. using the R package Distance) rather than point-and-click software.

In terms of modelling, WP2 recommended regression-based approaches capable of handling count data, non-linear relationships and correlated errors. In practice, variants of Generalised Additive Models or Mixed Models, possibly with zero-inflated or over-dispersed error structures are most appropriate. **The report emphasises a non-prescriptive approach to the model framework selected**. In this context, the analyses in Peterson (2011, 2014), Trinder *et al.* (2019) and Garthe (2023) serve as exemplars, with general guidance in Mackenzie *et al.* (2013). Viewed from a spatial point process perspective, models based on Log-Gaussian Cox-Process (LGCP) might also be used, as fitted using INLA. Grundlehner *et al.* (2025) serves as an exemplar in the context of seabird OWF redistribution analysis.

Effective modelling of animal distributions around offshore wind farm (OWF) sites relies on selecting appropriate covariates that explain as much natural spatial and temporal variability as possible, so that changes linked to development can be isolated. The WP2 report recommends that at a minimum, models should include covariates such as:

- **Time (to capture seasonality)**
- **Spatial smooths (or spatial structure) and their interactions**
- **Terms representing development phase of the OWF**

Additional covariates such as bathymetry, distance to coast or breeding colonies, currents, habitat type, and proximity to other developments may be included where data allow. The choice of covariates is highly site-specific and constrained by data quality and resolution, but variables that change alongside OWF development are especially important to avoid confounding redistribution effects with unrelated environmental change.

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[1] Unless analysis is ultimately to be via point-process models.

Redistribution effects are estimated by **contrasting animal distributions before and after construction**. This requires clear encoding of development phases, ideally using simple categories (e.g. pre- vs post-construction) to retain statistical power. Two main approaches are proposed: complex models that fit separate spatial smooths for pre- and post-construction and then compare them, and simpler models that use predefined spatial blocks such as the turbine footprint and buffer zones. The more complex approach gives a detailed, spatially continuous picture of redistribution, while block-based methods provide targeted, easily interpreted contrasts. Choice between them depends on data quantity and clarity, but detailed **post-construction turbine locations should always be used when calculating distances or buffers.**

Temporal contrasts must be carefully designed so that pre- and post-construction periods are comparable, avoiding obvious confounding such as comparing different seasons. Pooling data into broader temporal categories, such as **seasons rather than months, may be necessary** to increase sample sizes and produce meaningful contrasts. Models must then be thoroughly checked using standard diagnostics to assess fit, error structure, and potential over- or under-fitting. Model selection should aim for justified simplicity, removing uninformative terms and controlling complexity of smoothers, using established criteria and methods appropriate to the modelling framework.

The modelling outputs indicate whether redistribution is detectable and, if so, its magnitude, extent, and spatial pattern. **These results can feed into secondary analyses, such as estimating population-level consequences through mortality displacement matrices or individual-based models**. Outputs such as proportions displaced, changes with distance from OWFs, and redistribution maps—along with their uncertainty—are directly useful for impact assessment and mitigation evaluation. However, results must be documented in a fully reproducible way, from raw data to final model. **Key limitations remain, especially low statistical power to detect subtle effects and the risk of confounding from unmeasured environmental changes or coincident shifts in survey methods, meaning that failure to detect redistribution does not necessarily imply no effect**.

WP2 continued to discuss how tracking and radar studies form an important minority of research on animal responses to OWFs, providing fine-scale, repeated location data on individuals or flocks. However, unlike transect surveys, tracking studies show little consistency in methods, design, or analysis, and most focus primarily on collision risk rather than large-scale redistribution. Radar has major limitations for redistribution studies because it covers only small areas, lacks reliable species identification, and mainly detects flying birds, so it is **currently not suitable for estimating redistribution at the scale of whole developments**. GPS tagging provides detailed individual movement data but requires animal capture, resulting in small sample sizes and **potential biases due to non-random sampling or behavioural effects of tags**.

WP2 emphasized that study design is critical if tracking data are to inform redistribution. Most existing studies are post-construction only, but robust inference requires pre- and post-construction data, ideally in a BACI- or BAG-style design. Statistical power should be considered when deciding how many animals to tag, using power analyses tailored to redistribution questions. In terms of modelling, there is no agreed standard approach, but methods should aim to estimate proportions displaced, changes with distance from OWFs, and spatial redistribution maps with uncertainty. Generalised Additive Mixed Models applied to space-use data, and kernel density estimation of utilisation distributions, are both promising approaches, especially when combined with pre/post contrasts and OWF-related covariates. **Major limitations remain, including small sample sizes, high**

individual variability, difficulty tracking the same individuals long-term, and risks of sampling and tagging bias, all of which reduce precision and complicate interpretation.

The guidance also stressed reproducibility. All data treatment, modelling and outputs should be fully transparent, version-controlled and reproducible, with clear documentation of assumptions, diagnostics and limitations. This was seen as essential for regulatory confidence and for future reuse of data. WP2 also provided guidance on outputs and reporting, emphasizing that results should include clear numerical estimates, functional relationships (e.g. curves of effect versus distance), and maps of spatial redistribution where appropriate.

Overall, WP2 created the analytical blueprint for the project. It defined what good redistribution analysis should look like, from data collection through modelling to reporting, and it provided the framework that was then tested and refined in WP3.

At the conclusion of WP2, a stage gate meeting was held on March 10th, 2025 to identify and agree on a series of questions to address in WP3:

1. Is there evidence of redistribution of the species in response to OWFs?
2. What is the quantifiable extent of this redistribution?
3. Which candidate analysis methods are practically superior for modelling redistribution based on types of data from WP1?
4. What level of displacement granularity can be estimated/supported given types of data and methods?
5. What modelled covariates are important drivers of seabird distributions around OWF developments/within monitoring surveys, outside development effects?
6. Can developments' data be pooled for estimation of redistribution, or does evidence support site-specific effects?

Approval from the steering committee was then given to continue into WP3 and the analysis.

4. WP3 – Analysis of Existing Data

Work Package 3 (WP3), applied the WP2 guidance to real, extant datasets from UK offshore wind farms to test feasibility, refine methods and answer the project's core research questions identified in WP2 during the stage gate.

Studies identified in WP1 (See Appendix 1) were queried in WP2 to determine if they met the criteria identified in WP2. After an extensive data collection exercise, a long-list was established that fulfilled the following criteria:

- **Identified** – a preference was shown for data sources from the UK, with further preference for any associated with a published investigation into redistribution.
- **Obtainable** – any sources that proved very difficult obtain were necessarily excluded
- **Contrasting** – sources were required to contain data collected in both the pre-installation and post-installation periods.
- **Adequate** – sources were required to be well-documented and formatted, without loss of critical attributes (such as effort tracks)
- **Quality** – data were briefly checked for inconsistencies and those that displayed a gross lack of quality assurance were excluded.

After extensive data triage and quality assurance, datasets from eight OWFs between 2001 and 2021 were selected. Steps to the data triage and a full summary can be found in the WP2 analysis plan with more specific notes linked in supplementary material (https://www.dropbox.com/scl/fi/b2h16drfjt33v8y1olcp1/ImpUDis-Data-Summary-V1.1.docx). These data came from five regions around the UK with two wind farm clusters (Gwynt y Mor/North Hoyle and Lincs/Lynn/Inner Dowsing). Figure 3 (also Figure 1 in WP3) shows a full map of the distribution of the wind farms and survey effort. Furthermore, the Github repository for this work package (https://github.com/dmpstats/impudis-wp3) contains an interactive data map. Access to this repository can be granted on request. The temporal coverages of the data are found in an online html document (https://www.dropbox.com/scl/fi/g047zpq23r3hf8b9e9ffs/ImpUDis_high-level-survey-coverage.html). We note however that the estimates generated in this work are not time varying as the temporal terms have been estimated and separated out in the modelling.

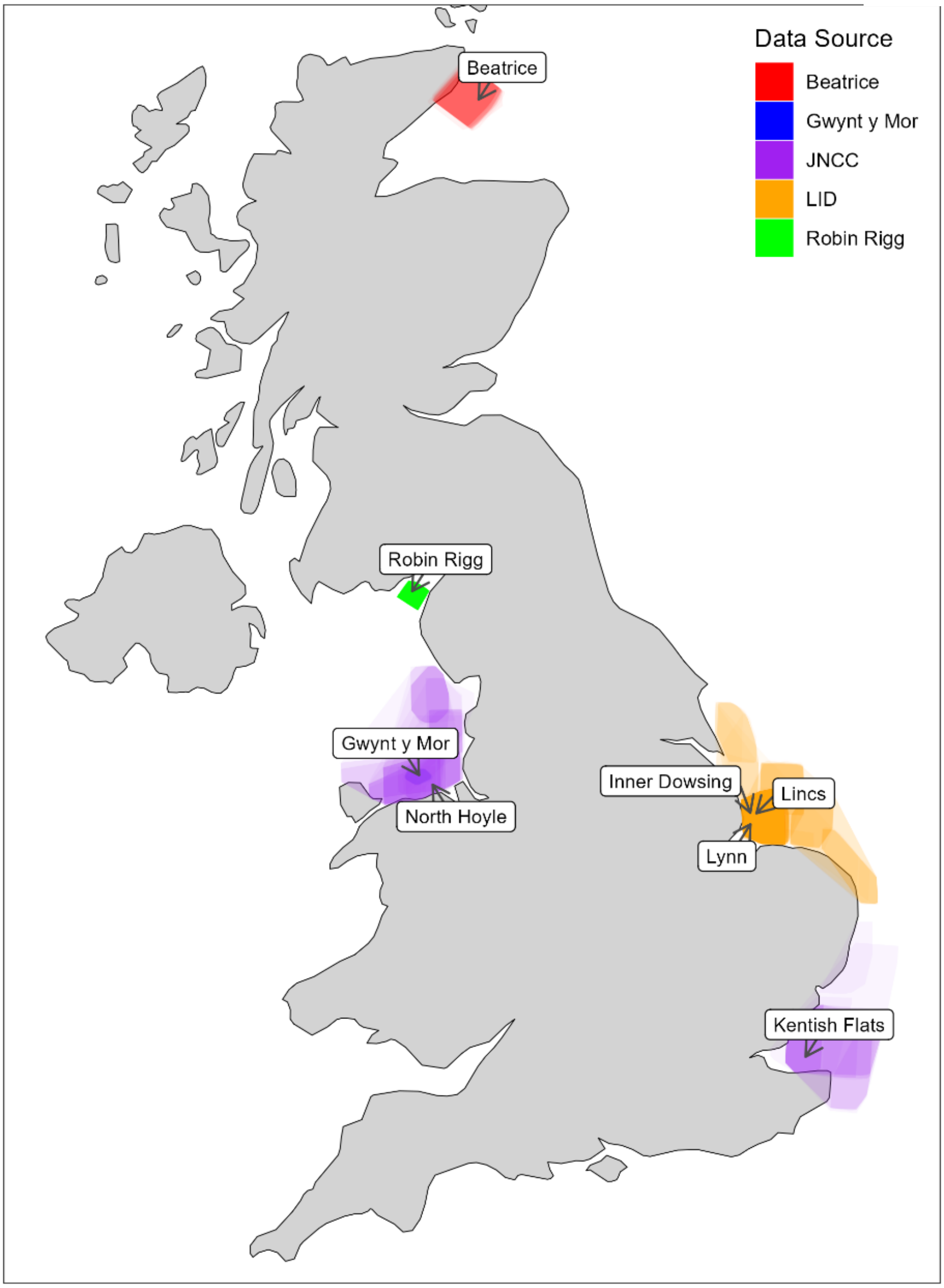

Figure 3: A map of each installation's site, against the relevant survey data. Each survey's polygon is provided as a transparent layer to demonstrate areas of greater survey effort.

Species and species groups modelled included kittiwake, guillemot, razorbill, puffin, gannet, auk groups and diver groups, though not all combinations could be analysed due to gaps in pre- or post-construction data, seasonal confounding or very low counts.

The resulting short list was given detailed analysis, by species:

- Kittiwake: Beatrice, Gwynt y Mor, North Hoyle, Robin Rigg
- Guillemot: Beatrice, Robin Rigg,
- Guillemot/Razorbill: Gwynt y Mor, North Hoyle

- Puffins: Beatrice
- Razorbill: Beatrice, Robin Rigg
- Auk group[2]: Gwynt y Mor, Lincs, Lincs, Lynn, North Hoyle, Robin Rigg
- Divers group[3]: Gwynt y Mor, Lincs, Lynn and Inner Dowsing, North Hoyle, Robin Rigg

All data were treated to place them in a common format and to do a quality check by the following process:

1. Ingestion of data
2. Formal spatial representation
3. Format time/date representation
4. Alignment of all factor coding (e.g., species codes)
5. Removal of surveyor tracks out-of-effort
6. Removal of inexplicable observations (e.g., those that fell well away from survey tracks)
7. Validation of alignment and availability of all observation and effort data
8. Amendment of obvious user-input errors

WP3 explored several modelling approaches designed to handle complex, non-linear relationships in count-based survey data with variable effort and non-independent errors. This included: Generalised Additive Mixed Models (GAMMs), Generalised Linear Mixed Models implemented with glmmTMB (Brooks et al., 2017; McGillycuddy, et al., 2025), Bayesian Regression Models, Integrated Nested Laplace Approximation (INLA), and the Marine Renewables Strategic Environmental Assessment (MRSea) framework. **Ultimately, the glmmTMB and mgcv R packages were chosen for this exercise due to their flexibility in family distributions, rapid fitting, and integration with tools for model diagnostics.**

Survey tracks were segmented into equal-length spatial units, typically corresponding to about 1 km², and counts of birds were aggregated per segment. Effort was calculated for each segment so that density could be modelled via offsets (Figure 4). Derived variables were then added, including construction phase, distance to realised OWF footprint, and bathymetry. For visual surveys, distance sampling was applied where possible to correct for detection bias, although this was not always feasible because some species showed strong avoidance of survey platforms. Many species datasets exhibited substantial zero inflation, meaning that Poisson, quasi-Poisson, negative binomial, or zero-inflated variants were necessary to adequately capture stochastic variation. All modelling steps were fully documented in reproducible, version-controlled workflows.

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[2] The definition/contents under this grouping can differ over surveys

[3] The definition/contents under this grouping can differ over surveys

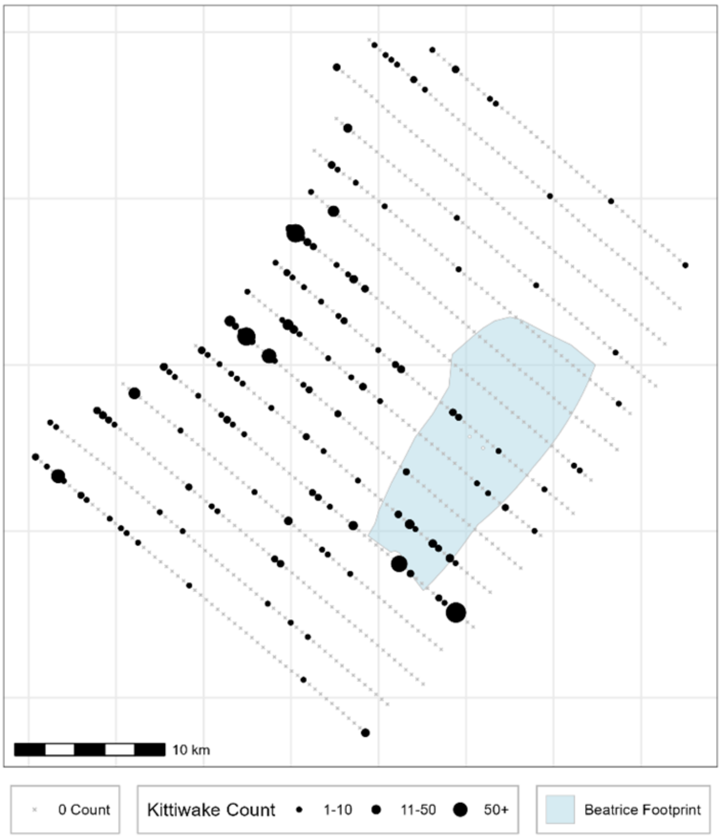

Figure 4. Figure 4 from WP3 . Example of segmented tracks and observations, binned into size groups.

Due to the extensive modelling required to cover all species and windfarms, the data treatment process and general interpretation of outputs was **illustrated using a focal case study of black-legged kittiwake surveys at the Beatrice OWF**, chosen for its relatively consistent survey methods and high data volume. WP3 presents the outputs from modelling approaches in three ways:

1. Simple redistribution: estimates of the general changes in animal abundance within the development footprint that can be associated with the operational vs pre-construction phases. **This is represented as proportional change in abundance within the OWF with associated confidence intervals.**

2. (simple) Functional redistribution: estimates of the general changes in animal abundance as a simple function of distance from the development, contrasting operational and pre-construction phases. **This is represented by the partial dependence plots of distance from the OWF against the functional relationship of density.**

3. (complex) Functional redistribution: estimates of the general changes in animal abundance as a spatial function around the development, contrasting operational and pre-construction phases. **This is represented by a gridded map of the differences between pre and post construction densities.**

Modelling in WP3, as per guidance laid out in WP2 accounted for the following:

- The fundamental response being animal counts at a location (at 1km^2 resolution)

- Fundamental changes in animal abundance beyond the development e.g. general temporal changes. All models contain annual terms for general broad-scale abundance changes, as well as monthly elements to capture seasonality over years.
- Random components in the mixed modelling context: year and surveys
- Variable effort, captured as an offset term. This is the effective area covered within the survey cell with its associated count. Given the cells are 1 km^2 this is equivalent to the proportion covered.
- Residual correlation in the errors/spatial autocorrelation. These are captured here as dependencies along transects.
- A model for the stochasticity of the response, given its expectation e.g. Poisson – the standard base model for count data. Data of this type (seabird counts) is often heavier in zeros than a Poisson and/or with greater variance. Candidates beyond this were negative binomial, zero-inflated Poisson or negative binomial. Quasi-Poisson is also considered as it generalises the mean-variance relationship of the Poisson.

For the focal study, WP3 highlighted in the **simple distribution approach** that there was a relative increase in the density of kittiwakes within the OWF footprint region, when moving from pre- to post-construction and other covariates have been accounted for (Table 3). This effect associated with the development was estimated to be approximately an **80% increase compared to what we be expected in its absence** – as indicated for the interaction term. While significant in the traditional statistical sense, there is still substantive uncertainty about the estimate, with the increase between 20% and 174%. This model was fit with a negative binomial which was found to be a good fit based on the diagnostics (Figure 5 in WP3).

Table 3: Table 2 from WP3 report showing fixed effects estimates for the Beatrice kittiwake simple displacement model. Highlighted term is the primary estimate for redistribution.

Species	Model term	Estimate	Lower 95% CI	Upper 95% CI
Kittiwake	Month 6 vs Month 5	360.7%	139.5%	932.8%
	Month 7 vs Month 5	368.8%	132.8%	1 023.7%
	Month 8 vs Month 5	186.3%	49.3%	703.6%
	Post installation	64.8%	30.0%	139.9%
	inside OWF footprint	120.7%	85.2%	170.9%
	pre/post OWF footprint interaction	181.7%	120.2%	274.6%

WP3 then examined the functional redistribution by investigating the partial dependence plot (Figure 6 from WP3), and the spatial contrast of the modelled distributions pre and post construction. The analysis provided evidence that kittiwakes redistributed following completion of the OWF, with higher abundance close to the development and lower abundance at greater distances. When modelled simply as a function of distance, densities increased near the OWF boundary and declined farther away, a pattern that corresponded spatially to increases in the north-west of the area and decreases to the south-east (Figure 5). Post-construction abundance at the OWF boundary was estimated to be around 50% higher than before construction, consistent with results from the simpler distance-based model.

Following the guidance set out in WP2 and as per the focal analysis, WP3 analysed the other species and site combinations as per the data triage exercise. For all the partial dependence plots and spatial redistribution maps, see Figures 8 – 17 in WP3. Results varied strongly by species and site. Gannets and puffins often showed avoidance of OWFs, kittiwakes often showed attraction at some sites, guillemots sometimes showed attraction, and divers and some auk groups tended to avoid or show no clear pattern (Table 4). Effects were sometimes detectable several kilometres from OWFs.

Results from other model runs (e.g., other species) are available in WP3 supplementary material but are summarize here in Table 4. Of note is that results of the review from WP1 suggests no studies that show attraction for Guillemot, yet both Robin Rigg and Beatrice were both to have statistically significant attraction in the WP3 analysis. Reports for the Beatrice OWF (Trinder et al. 2019, Trinder et al. 2024) and Robin Rigg OWF (Nelson et al. 2015) note that although there did not seem to be any significant response, attraction seemed to be occurring. A difference in how WP3 models are parameterized may explain this as the models generated in this work include all survey years and so it is possible that pooling may have increased the statistical signal. What does seem to be evident is that the displacement rates of 30 – 70% currently used in assessment are likely to be considerably over-estimated, particularly in this context during the breeding season.

WP3 found that simple inside–outside models were easiest to fit but may have associated low power. Functional distance and spatial models provided more insight where data allowed and often reduced residual autocorrelation by explicitly modelling spatial structure. The work also revealed many practical difficulties. Survey coverage often changed over time, confounding before–after contrasts. Species identification was inconsistent, especially in older visual surveys. Neighbouring OWFs and construction phases complicated attribution of effects. WP3 emphasised that results should be treated as indicative rather than definitive. More than 50 models were fitted in limited time, so individual model refinement was necessarily limited. The analyses are observational, not experimental, and confounding factors such as prey changes cannot be fully ruled out.

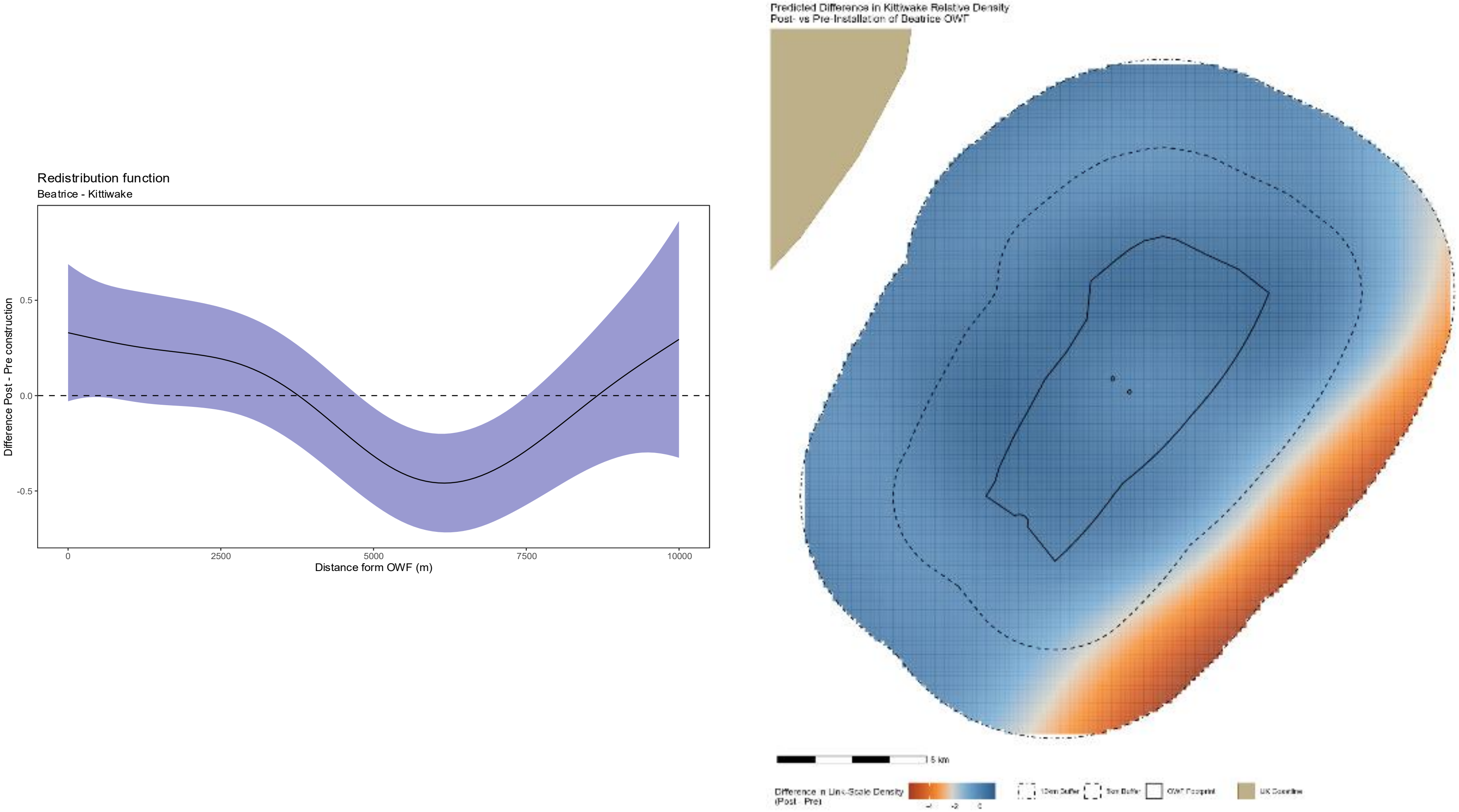

Figure 5. Figure 6 (left) and 7 (right) from WP3 showing the isolated redistribution function as a partial dependence plot and the functional redistribution depicted as the spatial contrast between kittiwake densities pre and post construction.

Table 4: Table 4 and 5 from WP3 showing simple and functional redistribution estimates for modelled species/site combinations. Grey shaded cells show statistically significant results while pink shaded cells show results that differ from the simple redistribution estimates.

Species or group	OWF	Simple redistribution estimate (Cis)	Distance redistribution	Spatial redistribution
Auks sp.	Lincs	77% (44 – 136%)	Not significant	Generally avoidant
	North Hoyle	71% (7 – 707%)	Attractant	Attractant
	Robin Rigg	69% (24 – 202%)	Not significant	Not significant
Diver sp.	Lincs	21% (1 – 637%)	Not significant	Failure to fit
	North Hoyle	169% (6 – 4990%)	Not significant	Not significant
	Robin Rigg	41% (18 – 93%)	Avoidant	Generally avoidant
Gannet	Beatrice	20% (7 – 57%)	Avoidant	Generally avoidant
	Lincs	4% (0 – 64%)	Avoidant	Complex spatial relationship
Guillemot	Beatrice	127% (92 – 175%)	Not significant	Generally attractant
	Robin Rigg	97% (75 – 125%)	Attractant	Generally attractant
Guillemot/ Razorbill	Gwynt y Mor	34% (13 – 90%)	Not significant	Not significant
Kittiwake	Beatrice	182% (120 – 275%)	Attractant	Generally attractant
	Robin Rigg	99% (59 – 167%)	Attractant	Generally attractant
Puffin	Beatrice	48% (30 – 75%)	Avoidant	Generally avoidant
Razorbill	Beatrice	137% (76 – 247%)	Not significant	Not significant
	Robin Rigg	90% (50 – 163%)	Not significant	Not significant

Responses to each of the research questions from section 3 (page 19 of this report) were addressed in WP3, which are reiterated here:

1. ***Is there evidence of redistribution of the species in response to OWFs?***

   Several species appear to show redistribution coincident with OWF developments, when other contributory factors are accounted for. This is consistent in many cases regardless of the complexity of model applied and is indicative of relatively clear changes in distribution associated with the OWF developments. Notably the redistribution can be attractive as well as repulsive. Gannet appeared generally avoidant, as did puffin - noting those were only represented substantially at one OWF (Beatrice) with only 3 years data. Kittiwakes however appeared attracted towards the development, when viewed in detail spatially.

2. ***What is the quantifiable extent of this redistribution?***

   This is heavily influenced by the spatial extent of the survey area around the OWF. In many cases there are dedicated surveys for an OWF and its surrounds, whereas other analyses rely on more opportunistic or historic surveying to give pre-construction coverage. This means there is a complex interplay of survey types (methods and intensity) and surveyed areas over time. Nonetheless, based on broad-scale visual surveys and digital aerial surveys focussed on the OWF, redistribution is estimable to at least 4km from OWF and up to 10km in some cases. Surveys with focus on a particular development are designed to include a few kilometres of buffer about the footprint and provide a good basis for estimation. Beyond this range there is more reliance on chance coverage from other surveys or broad-scale historical data. Therein the data supports broader modelling, but with greater chance of data artefacts, influences of topology and issues with model assumptions and limitations. Within our data specifically there was sufficient power to detect redistribution for gannets out to at least 7km, kittiwakes out to 7.5km, guillemot out to 6km, and puffin out to 5km.

3. ***Which candidate analysis methods are practically superior for modelling redistribution based on types of data from WP1?***

   There are broadly two aspects to this: the type of fundamental model being estimated, which differ in the complexity of their representation of redistribution (simple, functional distance or functional spatial), and the method used to fit these.

   In the former case, the simple displacement models are easiest to fit but appear to lack power in comparison to the functional redistribution models. The interpretation of the functional distance models is relatively easy, although can disguise complexities in how the animals redistribute in two-dimensions. The end use of the estimates may dictate to an extent, but the recommendation would be to fit the more complex models where the data permits, which can be simplified as required.

   In terms of model fitting methodology there are strong practical considerations. At a theoretical level, the flexibility offered by Bayesian methods allows the exact model desired to be fitted – this would be conducted through JAGS (Just Another Gibbs Sampler), Stan or INLA (Integrated Nested Laplace Approximation). However, the model construction/specification time can be extensive and fitting times prohibitive. By way of example, models were fitted using STAN with fitting times of 10s of hours to days which precludes model experimentation. For methods that are relatively fast to fit, such as INLA, fitting is still slow compared to frequentist methods and the time required for model construction and experimentation also prohibitive for modelling at volume. This is due in part to the lack of helper functions[4] e.g. the construction of model matrices generally and particularly for smoothers with interactions. The Template Model Builder based methods are however very fast with substantial functionality, but currently with little smoother support. Ultimately glmmTMB was favoured for simple models, with gamm via mgcv for more complex models. The principal limitation in the latter is a lack of zero-inflated error distributions when fitted mixed modes.

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[4] Programming “sugar”

4. ***What level of displacement granularity can be estimated/supported given types of data and methods?***

   From these data, 1km resolution is effectively the lower spatial resolution and temporally, monthly, and perhaps seasonal level for some species. This is imposed in many cases by the data being already aggregated to these resolutions. For the data analysed here, there was sufficient detail and power to estimate redistribution at 1km resolution for gannet, guillemot, kittiwake, and puffin. A finer resolution would be possible for within-OWF distributions of animals via the randomisation tests of Trinder et al., (2024)[5], or if exact location data of animals were used, then as a spatial point process model (e.g. via INLA) that avoids arbitrary gridding/coarsening of the data. Regardless, in the latter it seems unlikely that there would be sufficient power in such noisy data to detect fine scale changes.

5. ***What modelled covariates are important drivers of seabird distributions around OWF developments/within monitoring surveys, outside development effects?***

   Only a small set of covariates were considered in the modelling process, but bathymetry played a clear role, and temporally the month/season were extremely influential.

6. ***Can developments' data be pooled for estimation of redistribution, or does evidence support site-specific effects?***

   Generally results indicate site specific effects, and there is a general lack of data support in this study e.g. few species/OWF combinations that could be combined. This is also partly evidenced by different findings for different sites for the same species. This is complicated by the lack of consistency in survey methods across different developments – for example the species grouped under Diver/Auk are not certain to be comparable over sites. Other reasons would be the *a priori* lack of comparability of two-dimensional redistributions around developments influenced by site-specific topology and factors e.g. direction and distance to coast or nesting sites. However, there is some notable consistency in the redistribution of kittiwakes and gannets associate with differing OWF, albeit only supported here by 2-3 sites.

The WP3 report describes substantial practical difficulties in preparing and analysing data for WP3, **even after extensive triage to retain datasets most suitable for redistribution analysis.** Key problems stem from the heterogeneous nature of the data, which were collected across many offshore wind farms (OWFs), platforms, and time periods using different survey methods. Quality assurance issues are widespread, particularly in GPS and tracking data, where missing transect identifiers and incorrectly recorded survey segments require bespoke reconstruction and introduce risks of artefacts. Species identification is often inconsistent or only possible at higher taxonomic levels, with the degree of uncertainty varying by survey platform, making aggregation across sources problematic. Survey designs also change over time, such as shifts from visual to digital aerial surveys or alterations in survey extent, forcing analyses to focus only on the smallest spatial intersection of survey areas to avoid spurious results. In addition, critical metadata such as transect widths or survey polygons are frequently missing, undermining analytical robustness. Historical visual survey methods pose a fundamental limitation because detection rates vary across distance bands, violating

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[5] Noting this tests for attraction/repulsion given animals are already within the OWF footprint i.e. the null hypothesis does not explore general redistribution.

assumptions required for distance sampling and preventing effective correction for detectability; while less relevant for modern digital surveys, this significantly constrains the use of older data.

From a modelling perspective, WP3 emphasised the tension between methodological flexibility and practical feasibility, particularly given the need to fit a high volume of models within limited timeframes. While guidance from WP2 specifies model content and outputs rather than fitting approaches, extensive experimentation showed that well-established frequentist-leaning methods were most viable for large-scale application. Tools such as MRSea, glmmTMB, and mgcv offer fast fitting times and standardised functionality, enabling iterative model development and sensitivity testing, whereas Bayesian approaches using STAN or INLA require detailed, bespoke model construction and substantially longer fitting times, severely limiting exploration. Although INLA is attractive in principle—especially because it can model spatial processes without gridding animal locations—it was considered insufficiently mature for use *at scale* due to long run times, sensitivity to tuning parameters, limited supporting functionality, and opaque documentation. Even within the preferred frequentist frameworks, compromises were necessary: glmmTMB offers speed and flexibility but limited multi-dimensional smoothing, while mgcv provides highly developed GAMMs but restricted zero-inflation options in mixed models. Modelling is further complicated by uneven temporal coverage, changing survey extents, inconsistent species identification, and overlapping influences from nearby OWFs with staggered development phases, requiring data exclusions, temporal aggregation, or simplified phase definitions to isolate plausible redistribution effects without introducing artefacts.

5. WP4 – Stakeholder Workshop

Work Package 4 (WP4) focused on stakeholder engagement to discuss the methods and preliminary findings from WP1–WP3 and to move towards consensus on best practice for estimating seabird distributional change. A stakeholder workshop was held online on July 23rd, 2025 with participants from developers, consultancies, regulators, statutory nature conservation bodies, NGOs and academic institutions.

The workshop began with a presentation of project background and objectives, emphasising that uncertainty in displacement rates increases consenting risk by making it harder to rule out adverse effects on protected sites. The project aim was framed as improving parameter estimates of distributional change to reduce uncertainty and improve decision-making.

WP3 methods and results were then presented. This included a summary of data acquisition, the final dataset of around two million spatio-temporal observations from nine wind farms, the use of GLMMs and GAMs, and the distinction between simple and functional redistribution models (as presented in section 4 of this document). Preliminary results were shared, such as attraction of kittiwakes at Beatrice OWF and displacement of puffins, along with mixed and uncertain results for other species at other OWF sites. Functional models showing gradients of effect with distance were also discussed.

Discussion themes included concerns about grouping species when identification is poor, artefacts arising from uneven survey coverage, assumptions in distance-based models, and the difficulty of accounting for construction-phase and neighbouring wind farms.

An interactive Miro board session allowed participants to contribute ideas in breakout groups. Themes included modelling sensitivities, best practice guidance and future-proofing.

On modelling, stakeholders suggested **avoiding overly prescriptive model types**, instead defining essential features such as spatial autocorrelation, effort correction and uncertainty estimation. They encouraged **empirical comparison of species-level versus grouped data**.

On best practice guidance, they called for **data standardisation, numerical outputs suitable for displacement matrices, attention to seasonal and regional variation, and avoidance of over-generalisation across sites**.

On future-proofing, they recommended **mechanisms for reviewing new methods, a centralised data repository, consistent metadata standards and possibly a dedicated project focused on data infrastructure**.

The full meeting minutes of the workshop are found in Appendix 2.

6. Integration into the assessment process

Current guidance for the assessment of environmental impact of offshore windfarms in the UK is broadly aligned across the key Statutory Nature Conservation Bodies (SNCBs). At a high-level, displacement mortality is assessed primarily by displacement matrices, or more rarely by use of individual based models such as SeabORD (Searle et al. 2018). There are important caveats to this work due to the amount of variation in displacement estimates between sites and species (Table 4), indicating complex ecological relationships with space and time. This means that there is no one displacement rate for each species that could be applied within the framework of the current assessment process (e.g., within displacement matrices). The framework would also stipulate that in its application, users must locate currently constructed OWFs with the appropriate data that have similar ecological characteristics (e.g., within the same broad region). However, **the methodology as laid out here provides a framework that could potentially be integrated into the assessment process in several ways**.

The first is by applying the modelling exercise and calculating the simple redistribution value (and confidence limits) and then **applying that to the existing displacement matrix methodology**. This is a relatively simple, and somewhat crude, approach, but does give some justification for displacement rates used in the process. We note that the results laid out in this work are not time varying as the modelling accounts for temporal terms.

Another use for these outputs would be to **develop a gradient-based approach to mortality assessment**. This could represent a form of modified displacement matrix whereby mortality is calculated over the gradient with the assumption that birds being displaced further away from the wind-farm will suffer higher mortality rates. This report does not go into detail as to how this would be enacted exactly but provides the concept to be explored in further studies.

Similar to the previous concept, the more complex redistribution functions (either the functional relationship from the model or the spatial relationship) could be **adapted to be applied within an individual based model (IBM).** In this circumstance, the spatial relationship in particular could be applied as layers in an IBM, with seaBORD (Searle *et al.,* 2018) and DisNBS[6] being examples. This would require taking the density surface model as output during the pre-construction EIA and applying the redistribution function to the predicted outputs. This can form the basis of counter-factual runs within the IBMs to estimate differences in seabird condition due to redistribution. There would likely be many caveats to this kind of approach, but if an analogous OWF with appropriate data was to be used, it could provide a more evidence-based framework.

Broadly, the entire process as proposed through the ImpUDis project is made up of **three high level interdependent steps**. The first is the data collection process which involves querying existing pre and post construction survey data that could be analogous to the development being proposed, requesting it from appropriate data sources, verifying it, cleaning it, and then storing it (either locally for the study being performed or on some agreed upon database if it does not already exist there and with permission from the data owners; Figure 6). **This first data collection exercise could be greatly**

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[6] Recent ORJIP project that complements seaBORD by estimating the distribution of seabirds in the non-breeding season, in response to OWF.

improved by way of a focused program designed to collate all existing data into an accessible database with common metadata.

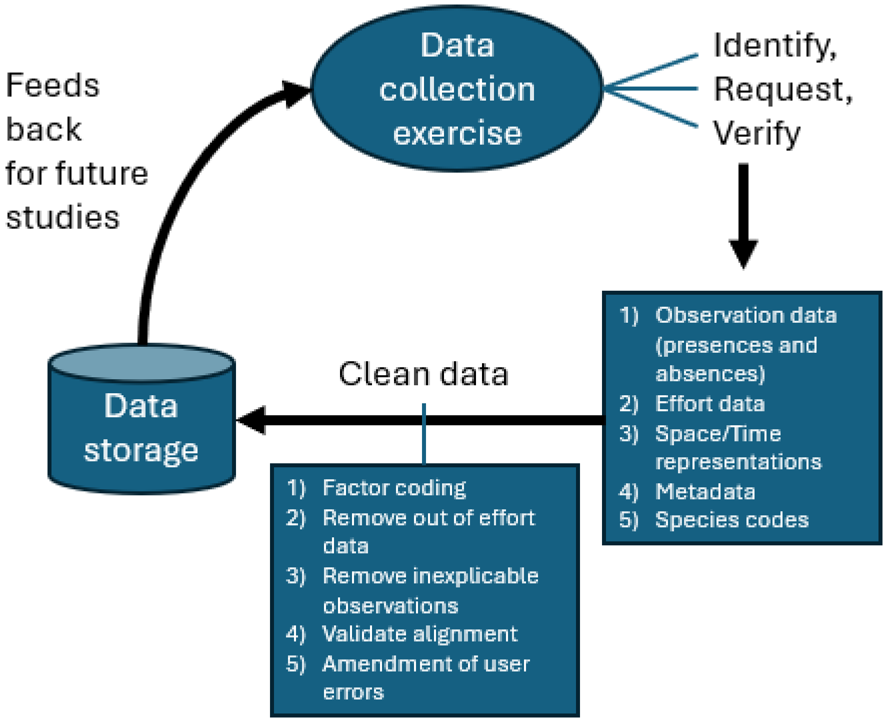

Figure 6. High level steps involved in data collection for a density surface modelling exercise for performing distributional response modelling at an OWF.

The second step is to **access and treat the data** by first determining the modelling framework to use. In WP3, GLMMs were identified as an appropriate option. However, other frameworks could be chosen here, and it was emphasized that this should not be prescriptive. Here, the data should be prepared by splitting it into segments along survey lines to aggregate observations. Once data are aggregated, the data should be associated with covariates such as spatial structure, distance to wind farm (or possibly turbines), distance to coast, and bathymetry. The model is then run using a distributional family that is appropriate for your data based on data exploration within this step. Querying the model diagnostics here is important as this is what will determine the most appropriate model to use. In WP3, WP3 recommended the DHARMa package for this in the R programming language, for models that are supported.

The final step is to output the simple redistribution calculation as well as the redistribution functions represented by the partial dependence plots and the spatial context. These outputs can then be brought forward to calculate mortality estimates that can then be fed forward in the assessment process. We note however that different legislative or environmental bodies will have different requirements in terms of environmental impact assessment. However, this framework as presented can be easily adapted for displacement analyses for other jurisdictions.

7. Conclusions

The ImpUDis project demonstrates that the methodology proposed in WP2 provides a coherent, transparent and technically defensible framework for estimating seabird redistribution around offshore wind farms when suitable data are available. Application of the guidance in WP3 shows that Before–After–Gradient designs, implemented through reproducible GAMM and GLMM-based density surface models, can quantify both the magnitude and spatial pattern of redistribution, rather than simply detecting presence or absence of effects. Functional distance and spatial models were generally more informative than simple inside–outside contrasts, particularly where survey coverage extended beyond the immediate OWF footprint. Importantly, the framework is flexible enough to support different levels of complexity depending on data volume and quality, and it produces outputs—numerical estimates with uncertainty, gradients with distance, and spatial contrasts—that are directly relevant to current assessment tools such as displacement matrices and individual-based models. As such, the project confirms that the proposed methodology is fit for purpose and represents a substantial advance on ad hoc or purely descriptive approaches historically used in assessments.

However, the project equally demonstrates that methodological advances alone cannot overcome fundamental constraints imposed by data availability, accessibility and quality. A very large proportion of potentially relevant monitoring data could not be used because of missing effort information, inconsistent formats, poor metadata, ambiguous species identification, or lack of clear documentation on survey design and OWF footprints. Even where data existed, substantial resources were required for bespoke cleaning, reconstruction and validation before analysis could begin, and many site–species combinations remained unusable due to confounding from changing survey extents, methods, or neighbouring developments. These issues are not peripheral: they directly limit statistical power, restrict the spatial and temporal scales over which redistribution can be estimated, and undermine confidence in results. Consequently, many WP3 outputs must be interpreted as indicative rather than definitive, despite the robustness of the analytical framework itself.

The findings therefore point to an urgent need for a coordinated, forward-looking data gathering and stewardship exercise if programmes such as ImpUDis are to continue unimpeded and deliver their full value. This should include systematic collation of existing pre- and post-construction survey data into an accessible repository; mandatory retention and sharing of effort data, survey tracks and key metadata; consistent species coding and survey descriptors; and clear, standardised definitions of OWF footprints based on realised turbine locations. Without such infrastructure, each new analysis will continue to expend disproportionate effort on data recovery rather than ecological inference, limiting cumulative learning across sites and time. In contrast, investment in data access and standardisation would allow the ImpUDis methodology to be applied routinely, enable cross-site synthesis, reduce uncertainty in displacement estimates, and support more proportionate and evidence-based decision-making in offshore wind consenting. In this sense, the project's most important conclusion is that improving displacement assessment is as much a data governance challenge as it is a statistical one, and sustained progress depends on addressing both together.

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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,	Black-headed Gull: no response	Rothery *et al.* 2009

			construction, post-construction	• 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	
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	Krijgsveld *et al.* 2011

				• Great Cormorant: no response • Herring Gull: no response • Lesser Black-backed Gull: no response • Little Gull: no response • Northern Gannet: macro-avoidance • 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)	Leopold *et al.* 2013

				• Northern Fulmar: no response • Northern Gannet: displacement • Razorbill: displacement (Princess Amalia) • Sandwich Tern: no response • All divers: displacement (Egmond aan Zee)	
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,	• All alcids: displacement	Petersen and Fox 2007

			construction, post-construction	• Common Eider: displacement • Common Scoter: attraction • Herring Gull: displacement • Little Gull: no response • All divers: displacement	
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	Blew *et al.* 2008

				- All large gulls: macro-avoidance - All marine birds: macro-avoidance	
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)	Petersen *et al.* 2006

				- Little Gull: attraction - Long-tailed Duck: displacement - Northern Gannet: displacement - Red-breasted Merganser: attraction	
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,	- Little Tern: no response	Perrow *et al.* 2006

			post-construction		
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	Skov *et al.* 2018

				Lesser Black-backed Gull: macro-avoidance Northern Gannet: macro-avoidance	
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,	• All divers: displacement	Vilela *et al.* 2021

			post-construction		

Appendix 2: Minutes from WP4 stakeholder workshop

ORJIP - ImpUDis

WP4 – Stakeholder Workshop

Date	08 August 2025	**Place of meeting**	Microsoft Teams
Minute taker	MCLA@NIRAS.com	**Date of meeting**	23/07/2025

Participants	Fraser Carter	NIRAS
	Matt Clamp	NIRAS
	Paul Watts	NIRAS
	Andie McQuillan	NIRAS
	Tim Kasoar	NIRAS
	Carl Donovan	DMP Stats
	Grant Humphries	Black Bawks Data Science
	Aonghais Cook	The Biodiversity Consultancy
	Michel Stelter	Bio Consult SH
	Zilvinas Valantiejus	Carbon Trust
	Sue O’Brien	MacArthur Green
	Rebecca Hall	JNCC
	Mark Trinder	MacArthur Green
	Aly McCluskie	RSPB
	Sophy Allen	Natural England
	Gillian Moore	RWE
	Gillian Vallejo	Natural Power
	Richard Berridge	Natural England
	Anna Lowden	Scot Gov
	Jimmy Wright	Ocean Winds
	Katherine Booth Jones	Scot Gov

Alexander Gilliland	Scot Gov
Emily Nelson	SSE

Welcome and Agenda (Fraser Carter - NIRAS)

- Fraser Carter opened the meeting, explained recording and copilot note-taking, and outlined the agenda proposed for the workshop.
- The workshop will aim to provide an interactive session, with a presentation of the project findings, and breakout groups for discussions on the findings.

Project Background (Fraser Carter - NIRAS)

The ImpUDis project aims to reduce uncertainty in seabird displacement rates related to offshore wind farms, improving impact assessments and decision-making. Uncertainty in displacement rates leads to increased risk and a higher likelihood of incorrectly concluding adverse effects at the application stage.

*‘**Project Objective:** Provide improved parameter estimates of seabird distributional change for use in impact assessments and to reduce uncertainty in predictions and consenting risk through improved decision-making.’*

To achieve this objective the project was broken down into the following work packages (WP):
- *Collation of existing data (WP1/2)*
- *Standardisable analyses (WP2/3)*
- *Stakeholder engagement (WP4/5)*
- *Independent validation (WP6)*

WP’s 1 to 3 have been completed, this discussion is part of WP4.

Workshop Objectives (Fraser Carter - NIRAS)

Fraser Carter presented the aims of the workshop, explaining what the project wants to achieve from this consultation:
- Present a summary of work to date, including methods, results, and outstanding uncertainties.
- Facilitate stakeholder engagement and discussion on interpreting results for impact assessment.
- Work towards consensus on best practice guidance for quantifying seabird distribution change.

Data Analysis and Modelling (Carl Donovan – DMPstats)

The data analysis and modelling (WP3) was undertaken by DMP Stats. Carl Donovan presented the key findings of the study.

Scope

Carl ran through the proposed scope of WP3:

- WP3 is the implementation of the extant data analysis plan from WP2. The data analysis plan was informed by the WP2 guidance document.
- The data from WP2 was restructured to a usable consistent form usable for displacement modelling.
- DMP then fitted various models to estimate/characterise redistribution ostensibly from OWF developments (pre to post construction).

Summary of WP2 Data Acquisition and Preparation

Carl explained how data was identified and obtained in WP2.

- Over 60 publications were identified with redistribution analyses that were investigated further.
- Data acquisition challenges included missing metadata (e.g., survey effort) and inconsistencies in format.
- It was essential that all data included had a clearly defined pre- and post-construction data.
- The final dataset included around 2 million spatial-temporal observations across 9 wind farms in 5 regions across the UK.
- Surveys included vessel-based, visual aerial, and high-definition digital aerial methods.
- Standardisation was made for detection probability, survey effort, and survey geometry.

Species and Regions

- Eight focal species/groups were selected: auks, black guillemots, divers, gannets, common guillemots, kittiwakes, puffins, razorbills. These were represented well in one or more of the selected datasets.
- Coverage varied by region and species, with some sites offering rich data and others limited by survey scope or species presence.

Modelling Approach

- Generalised Linear Mixed Models (GLMMs) and Generalised Additive Mixed Models (GAMMs) were used in the modelling approach.
- Two model types:
  - Simple redistribution: compares bird abundance inside vs. outside wind farm footprint pre- and post-construction.
  - Functional redistribution: models abundance as a function of distance from wind farm.
- Models accounted for:
  - Temporal autocorrelation (e.g., AR(1) structure).
  - Survey effort via offsets.
  - Environmental covariates like bathymetry.
  - Random effects for year and survey.

Key Results

Carl explained some of the preliminary results coming out of the modelling:

> ***Significant attraction:***
- Kittiwakes at Beatrice: ~68% increase within footprint post-construction.

> ***Significant displacement:***
- Puffins at Beatrice: ~46% decrease within footprint.

> Mixed or inconclusive results for other species, with wide confidence intervals.

> ***Functional models showed nuanced patterns:***
- Some species showed increased abundance near wind farms and reduced abundance further away (e.g., guillemots, kittiwakes).
- Others showed clear repulsion (e.g., puffins).
- Confidence envelopes often encompassed the null line, indicating uncertainty.

Limitations and Caveats

> Survey coverage asymmetry may introduce artefacts.
> Species identification limitations, especially in older or boat-based surveys.
> Groupings of data (e.g., "auk species") may obscure species-specific responses.
> Construction phase effects not modelled due to data limitations.
> Site-specific factors (e.g., proximity to colonies) likely influence results.

Q&A and Discussion Themes

Following Carls presentation, Fraser gave the opportunity to discuss any of the approaches/findings presented.

Species Grouping and Identification

> Gillian Vallejo raised concerns about lumping species and potential biases in unidentified individuals.
> Carl acknowledged variability in species-level discrimination and the challenges of allocating group-level observations.

Survey Coverage and Artefacts

> Anna Lowden noted consistent troughs in abundance ~5km from wind farms, questioning whether this was ecological or artefactual.
> Carl suggested it may reflect survey geometry or asymmetry in coverage.

Model Interpretation

- Mark Trinder questioned the symmetry assumption in distance-based models, noting colony proximity and breeding season effects.
- Carl agreed and discussed the trade-offs between site-specific 2D models and generalisable 1D functions.

Data Quality and Standardisation

- Aly McCluskie emphasized the need for prescriptive data standards for future surveys.
- Carl noted the difficulty of obtaining consistent turbine footprint data and suggested convex hulls around turbine locations as a refinement.

Construction Phase Effects

- Gillian Moore asked about neighbouring wind farms and construction disturbance.
- Carl acknowledged these complexities but noted they were excluded for simplicity and data availability.

Interactive Miro Board Session (Fraser Carter - NIRAS)

Fraser gave a quick demonstration of how all the meeting participants could use the discussion board set up on ‘MiroBoard’. Participants had the option to add anonymous comments, or sign their name, in an attempt to get as many comments and opinions as possible. The output of this discussion is attached to this document as **Error! Reference source not found.**.

Participants were split into two groups to contribute ideas across three themes. Discussions on these three themes is detailed in brief below, but for further details see **Error! Reference source not found.**.

Modelling Sensitivities and Data Use

- Avoid prescriptive model types; instead, define essential features (e.g., spatial autocorrelation, effort correction).
- Explore empirical comparisons of species groups vs. species-level data.
- Use convex hulls around turbines for accurate footprint modelling.
- Recognize limitations of older data lacking species-level detail.

Best Practice Guidance

- Prioritize data standardisation and access.
- Recommend numerical displacement outputs for use in impact matrices.
- Emphasize seasonal and regional variation in survey design.
- Avoid overgeneralisation; support site-specific modelling where possible..

Future Proofing

- Establish mechanisms for introducing and reviewing new methods (e.g., peer review, stakeholder forums).
- Advocate for a centralized, accessible data repository.

- Encourage consistent metadata and survey protocols.
- Recognize the need for a dedicated project focused solely on data infrastructure.

Next Steps

Immediate Actions:

- NIRAS to Compile workshop transcript, notes, and Miro board inputs.
- Draft workshop summary and circulate to attendees.
- Keep Miro board open for additional contributions post meeting.

Future Deliverables for ImpUDis:

- Final project report integrating stakeholder feedback.
- Third-party validation of analysis methods and results.
- Potential peer-reviewed publication based on findings.

Fraser Carter thanked all participants for their time and contributions. Grant Humphries emphasized the value of the discussion and the importance of refining the analysis and outputs. Zilvinas Valantiejus confirmed that updates on project outputs and finalisation would follow in the coming weeks.

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