Received: 9 February 2024 | Accepted: 21 May 2025

DOI: 10.1111/1365-2664.70087

BRITISH ECOLOGICAL SOCIETY Journal of Applied Ecology

RESEARCH ARTICLE

The Global Energy Transition: Ecological Impact, Mitigation and Restoration

Life-cycle impact assessment of offshore wind energy development on migrating bird diversity in the North Sea

Emma Jane Critchley[1] | Anna Nilsson[2] | Morten Helberg[3] | Roel May[1]

[1]Norwegian Institute for Nature Research, Trondheim, Norway

[2]Norwegian Institute for Nature Research, Bergen, Norway

[3]BirdLife Norway, Trondheim, Norway

Correspondence
Emma Jane Critchley
Email: emma.critchley@nina.no

Funding information
Norges Forskningsråd, Grant/Award Number: RCN 326985

Handling Editor: Virginia Morera-Pujol

Abstract

1. As offshore wind energy development increases, it is vital to rapidly assess the cumulative impacts to biodiversity, particularly for migratory species that could be impacted across multiple sites. Life-cycle assessments (LCAs) are a useful tool for assessing and comparing cumulative effects over a large scale and are frequently used for decision-making in industry. We have adapted the LCA methodology to assess collision, disturbance and barrier impacts of offshore wind energy developments in the North Sea on migrating birds from Norway by 2030.
2. The potentially disappeared fraction of species (PDF)—a measure of the potential loss of species richness in an area—for collision, disturbance and barrier impacts was calculated for birds on migration within migration groups, relative to wind farm energy production in GWh. Distributions were modelled based on ring recoveries from countries surrounding the North Sea Basin, using a Brownian bridge approach.
3. Wind farm developments in the North Sea were found to have the greatest impact on migrating waterbirds and soaring birds. For most groups, potential impacts from disturbance and barrier effects were higher than impacts caused by collision. Maps highlight where cumulative PDF values for combined collision, disturbance and barrier effects are expected to be highest, both by group and for all migratory species combined.
4. *Synthesis and applications*. Our findings stress the potential cumulative impacts to migrating birds from large-scale offshore wind energy development in the North Sea by 2030 relative to wind farm energy production. The combination of long-term bird ringing data and LCAs, which are already widely used by industry in other contexts, could be a useful tool for comparing potential impacts across proposed wind farm sites for environmental impact assessments and national strategic environmental assessments. The LCA methodology presented here could be adapted further to rapidly assess impacts of other types of energy developments on a wide range of migratory species.

KEYWORDS

bird migration, cumulative impacts, life-cycle impact assessment, offshore wind farm, ringing recoveries

1 | INTRODUCTION

Over the coming decade, a rapid expansion of offshore wind energy developments is expected in the North Sea, as European governments set ambitious targets for renewable energy growth to address climate change (Ostend declaration of energy ministers on the North Seas as a green power plant of Europe, 2023). Offshore wind power is regarded as one of the key technologies for reducing greenhouse gas emissions globally (Offshore Wind Outlook 2019: World Energy Outlook Special Report, 2019). However, it can negatively impact biodiversity through multiple impact pathways and at multiple scales (Bailey et al., 2014; Furness et al., 2013; Gill, 2005). Birds and bats on migration, both of which could cross offshore wind farms (OWFs) in large numbers, are particularly at risk of collision mortality, disturbance and barriers to migration. Disturbance and barriers are indirect sources of mortality, where effects can be long-term, that is affecting future survival and reproduction, and are particularly impactful to migratory species (Shuter et al., 2011). Disturbance of migratory birds might lead to avoidance of the area, entirely or partly, whereas barrier effects induce migrants to fly around or over the wind farm with subsequent extra energetic flight costs (Masden et al., 2009). Assessing these impacts can be challenging given the difficulties of monitoring offshore and the large distances often covered by species in the marine environment, including migrating birds. As offshore wind energy expands, it is crucial that the balance of mitigating climate change whilst also conserving biodiversity is considered.

In the North Sea, the large-scale development of OWFs will place several large wind farms directly in the key migration pathway for many migratory bird species. As of July 2023, there was 27 GW of installed offshore wind farm capacity in the North Sea and if all currently planned developments are completed by 2030, capacity within the North Sea alone will increase rapidly to 147 GW (Critchley & Buckingham, 2024). It will be important to assess the potential cumulative impacts to biodiversity within the North Sea from this rapid development to ensure that impacts can be mitigated and accounted for in future strategic environmental assessments and wind energy development plans.

It is estimated that hundreds of millions of birds cross the North Sea every year on Spring and Autumn migration, partially in large mass migration events (Shamoun-Baranes & van Gasteren, 2011). Large numbers of migrating birds crossing the North Sea come from Norwegian, Scandinavian and Arctic breeding populations migrating east–west to and from the UK, and north–south along the Danish, German and Dutch coasts (Alerstam, 1993). Several of these belong to species listed as threatened on the IUCN red list both in Norway (Artsdatabanken, 2021) and globally (IUCN, 2022), and their populations are already under pressure from many other stressors, including climate change and land use changes (Croxall et al., 2012; Kirby et al., 2008). However, due to the challenges of monitoring offshore, very little is known about the exact migration paths of these birds when crossing the North Sea (Brust & Hüppop, 2022; Nilsson et al., 2019), or the potential overlap with offshore infrastructure, including wind energy developments. From radar observations at coastal and offshore wind farms in the southern North Sea, peak migration traffic rates of around 500 to 1000 birds per km/hour, likely at lower elevations, crossing a wind farm at night have been measured during the migration period (Degraer et al., 2017; Fijn et al., 2015).

Ringing data is a valuable source of information on bird movements on a large scale (Fiedler, 2009) and has been used extensively to reveal migration flyways in Europe for over 100 years (Hüppop & Hüppop, 2011). Whilst it provides a much lower resolution than data collected from telemetry devices, it covers many more species and individuals over a longer period. However, ringing recovery data for most species only provides two points in time—when the bird was first ringed and when it was recovered—leaving us to infer the path taken by the bird between the two points. Brownian bridge movement models (BBMMs) can be used to create more realistic pathways of animal movement based on the time between locations and have previously been used to estimate migration routes (Horne et al., 2007; Palm et al., 2015). In this study, we utilise BBMMs of ringing recovery data to map migration movements of Norwegian breeding birds across the North Sea basin. By combining ringing data for multiple species within a migration group, we infer likely migration routes utilised by different bird groups across the North Sea.

Measuring the cumulative impacts of energy developments on multiple species over a large area, such as birds on migration across the North Sea, can be challenging, particularly when trying to assess future impacts. Methods such as Environmental Impact Assessments, which are usually applied on a by wind farm basis, are not as well-suited to cover such a large scope. Other frameworks that have been developed to assess the consequences of disturbance on populations, such as the Population Consequences of Disturbance framework (Keen et al., 2021), require significant amounts of data for a complete assessment, which may not be available when assessing impacts to many species over a large area offshore. Life-cycle impact assessments (LCIAs) provide a useful alternative tool for assessing the potential relative environmental impacts from energy technology in a standardised way across multiple sites, for instance the impact of bird collisions per kWh energy production in an onshore wind farm (May et al., 2020). LCIAs have previously been used to assess greenhouse gas emissions and energy accounting for wind farms (Wang et al., 2019) and were further developed by May et al. (2020, 2021) to assess impacts of onshore wind energy developments on bird diversity both globally and in Norway, through habitat loss, disturbance, collisions and barrier effects. These LCIA models use the spatial distributions of species (e.g. migrating bird distributions) to quantify relative impacts and have the advantage of allowing the assessment of multiple impact pathways for multiple species or groups simultaneously. LCIA models would be most useful for the early stages of offshore wind farm planning, particularly for site selection as the method allows direct comparison of impacts across multiple sites.

Here, we adapt the methodology of May et al. (2020, 2021) to assess the life-cycle impact of offshore wind energy developments in the North Sea on Norwegian migrating bird diversity through three impact pathways: collision, disturbance and barrier effects. We demonstrate how LCIAs can be used to assess relative impacts to bird diversity in an area from both current and future offshore wind energy developments, and how the method can be used for comparing potential impacts across a region to inform strategic wind farm siting.

2 | MATERIALS AND METHODS

A LCA was applied to maps of Norwegian birds on migration to assess the potential effects of offshore wind energy developments in the North Sea up to 2030 through three impact pathways: (1) collision, (2) disturbance and (3) barrier effects. The methods were adapted from May et al. (2020, 2021), who developed LCAs to evaluate impacts of onshore wind energy on bird species richness, and first tested for a pilot wind farm study in Norwegian waters (Layton-Matthews et al., 2023) before being expanded to the entire North Sea. The potentially disappeared fraction of species (PDF)—a measure of the potential loss of species richness in an area—for each impact, pathway was calculated for each migration group based on (a) the number, size and location of all current and future wind turbines in the North Sea up to 2030, and (b) values within each individual grid cell for a standard 15-MW turbine (Evan et al., 2020). PDF is a relative impact metric recommended for use in LCA models, which assess biodiversity impacts (Verones et al., 2017). PDF values are not an absolute metric, that is they do not quantify expected mortalities or population loss but instead represent the estimated fractional loss of species richness in an area due to unfavourable conditions. An overview of the LCA methodology is shown in Figure 1.

2.1 | Estimating bird migration trajectories

Ringing and recovery data were provided by the Norwegian Bird Ringing Centre at Stavanger Museum, Norway and their collaborators within the EURING network to produce maps of migration trajectories. The available data ranged from 1906 to 2021, with most records (93%) recorded in the last 50 years (1974 or later). We used ringing and recovery events for Norwegian migratory birds crossing the North Sea basin, where at least one event occurred either in the UK, France, Belgium, the Netherlands, Germany or Denmark. Events occurring at longitudes outside −17–40, and latitudes less than 45 were excluded. Time intervals longer than 60 days between ringing and recovery events were also excluded to reduce the likelihood of including recoveries from two migration events. Data were pooled for all years and both Spring and Autumn migration periods; therefore, distributions reflect average bird migration patterns and diversity during migration across an entire year. This resulted in data for 123 species, which were then grouped into five migration groups according to their taxonomy and migration ecology: marine birds, soaring birds, songbirds, waders and waterbirds. See the Supporting Information for a full list of species (Table S1) and reasoning for the group composition.

A Brownian bridge movement model (BBMM) was used to estimate migration trajectories from the filtered ringing and recovery data and plot kernel densities for each migration group. The BBMM estimates an animal's likely occurrence in an area based on individual observations, using a conditional random walk and taking into account the distance and time between observations (Horne et al., 2007). Thus, it can also be used to estimate migration trajectories based on spatial and temporal observations (Horne et al., 2007; Palm et al., 2015). We used the BBMM to estimate migratory trajectories between the ringing and recovery events as a kernel density on a 2 × 2 km grid across the North Sea basin. The resulting maps estimate the likelihood of a grid cell being utilised by a species from the given migration group whilst on migration. Core migration areas for each group were delineated as the top 5% of kernel density values. The R package 'adehabitatHR' was used to model the BBMMs and produce kernel density maps (Calange, 2006).

2.2 | North Sea offshore wind energy developments

Data on current and future offshore wind energy developments in the North Sea up to 2030 were compiled from several publicly available sources. Turbine locations for most existing wind farms were sourced from Martins et al. (2023), which compiled data from multiple sources to generate a dataset of wind turbines in the North Sea. Proxy turbine locations for future wind farms were created based on the projected number of turbines or projected wind farm and turbine capacity as per Critchley and Buckingham (2024). To estimate the potential impacts relative to annual energy production, the PDF per GWh was calculated for each wind farm and for each group. We used the average annual capacity factor of 35.59% for all offshore wind farms in the North Sea in 2021 (IRENA, 2023) to calculate energy production in GWh for a full year (8760 h) from total wind farm capacity in MW.

$$\text{Annual energy production} = \frac{\text{Wind farm capacity} * 8760 * 0.3559}{1000}$$

All wind farms that overlap with the core migration area for each group were identified and the total GWh located within each groups' core area was calculated per country.

2.3 | Life-cycle assessment for collision, disturbance, and barrier impacts

PDF values for the collision, disturbance and barrier impact pathways were calculated for each migration group based on the methods in May et al. (2020, 2021) on a per turbine basis and then combined for each wind farm. See Table 1 for details of the equations and inputs.

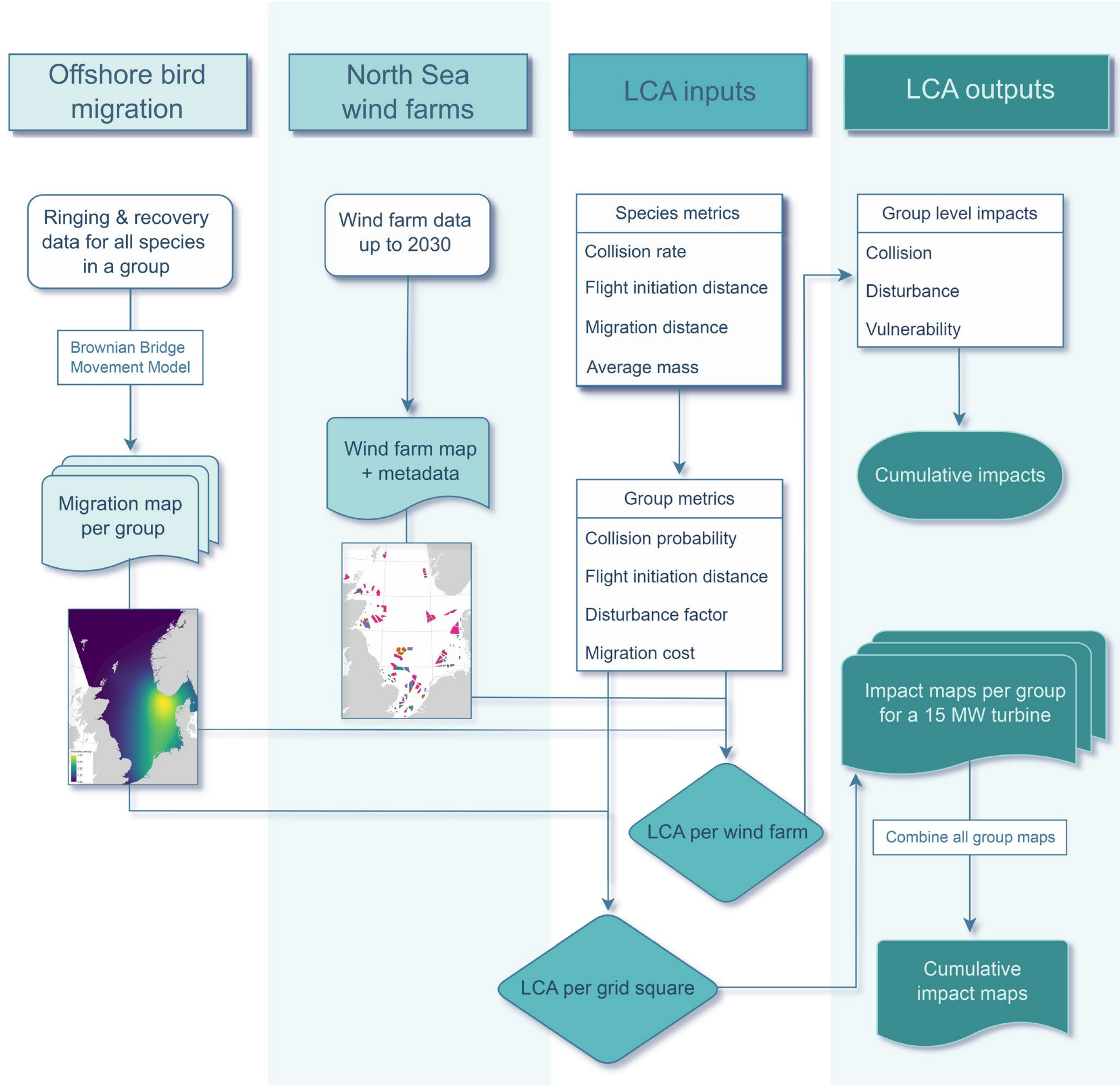


FIGURE 1 Flow chart of the LCA methodology.

As in May et al. (2020), the slope of the species–area relationship in logarithmic scale (z) was taken to be 0.21. For all impact pathways, the area within which impacts were calculated (A_{org}) was 4 km^2. As this study included several species not assessed in the previous onshore wind energy LCAs, mainly seabirds, new data were collated for these species as detailed below.

PDF values for collision impacts were quantified as the reduction of the species at risk due to collision (Table 1, Equation 1). The number of species at risk is those that utilise the influence area surrounding each turbine delineated by the rotor sweep zone (πr_w^2) and have some probability of collision (R_k) based on species-specific collision rates for wind turbines (taken from Thaxter et al. (2017)) within group k. There is currently little available data on turbine collision rates for seabird species given the challenges of monitoring offshore wind farms. We therefore estimated collision rates for some seabirds based on the species' ranking within a collision vulnerability index, which were calculated using the methodology from Furness et al. (2013) (updated to account for avoidance behaviour; Wade et al., 2016) and modelled estimates of time spent flying at turbine height (Johnston et al., 2014). For species with missing collision rates, the average value between the two species ranked above and below them in the collision vulnerability rankings was calculated. New values for R_k per migration group were then calculated using this updated data.

Disturbance PDF values are measured as the proportion of species displaced from the influence area (Table 1, Equation 2), based

BRITISH ECOLOGICAL SOCIETY Journal of Applied Ecology

TABLE 1 Equations for calculating the potential disappeared fraction (PDF) of species from May et al. (2020, 2021) and parameter definitions. In all equations, *k* represents a migration group and *w* represents an individual wind turbine.

Equation	Parameters
Equation 1: Collision	
$$\text{PDF(C)}_{k,w} = \frac{S_k P_{k,i}\left(1-\left(\frac{A_{org}-R_k * t_w * \left(\pi * \left(\frac{r_w}{1000}\right)^2\right)}{A_{org}}\right)^z\right)}{\sum_i^I S_k P_{k,i}}$$	$S_k\ P_{k,i}$ = number of species locally present at cell *i* within group *k* $A_{org} = 4\,\text{km}^2$ t_w = one turbine r_w = rotor blade length of turbine *w* (m) R_k = probability of annual per turbine collision within group *k* $z = 0.21$ (species-area relationship)
Equation 2: Disturbance	
$$\text{PDF(D)}_{k,w} = \frac{S_k P_{k,i}\left(1-\left(\frac{A_{org}-t_w * \left(\pi * \left(D_k * \frac{d_{k,\max}}{1000}\right)^2\right)}{A_{org}}\right)^z\right)}{\sum_i^I S_k P_{k,i}}$$	D_k = disturbance factor within group *k* $d_{k,\max}$ = maximum flight initiation distance within group *k* (m)
Equation 3: Barrier	
$$\text{PDF(B)}_{k,w} = \frac{S_k P_{k,i}\left(1-\left(\frac{A_{org}-\left(\pi * t_w * M_k * \left(D_k * \frac{d_{k,\max}}{1000}\right)^2\right)}{A_{org}}\right)^z\right)}{\sum_i^I S_k P_{k,i}}$$	M_k = migration cost within group *k*

on migration group disturbance factors (D_k) and species-specific flight initiation distances (d_k). Flight initiation distances were taken from May et al. (2021) and updated with new values for 14 species (Critchley et al., 2025). New values for D_k per migration group were then calculated using this updated data. See Supporting Information for details of how D_k was calculated.

PDF values for impacts due to barrier effects (Table 1, Equation 3) were calculated as the proportion of species displaced from the influence area with an additional relative migration cost (M_k). Migration distance and average mass values (the inputs for M_k) were collated for all new species. To calculate the barrier effect, it was assumed that the most utilised migratory paths would lie within the 50% kernel of the migration maps. Any presence values outside of the 50% kernel were set to zero. Values within the kernel were then rescaled to between zero and one. See Supporting Information for details of how M_k was calculated.

PDF values were calculated for each group per turbine and then summed to produce cumulative impacts per wind farm, per country and across the entire North Sea for existing and future wind farms up to 2030. Cumulative PDF values per year were calculated for all wind farms in the North Sea combined and compared with annual energy production (GWh). The sensitivity of the PDF equations to key parameters ($S_k\ P_{k,i}$, r_w, R_k, D_k, $d_{k,\max}$ and M_k) was investigated by a Sobol variance-based sensitivity analysis using the *sensobol* R package (Puy et al., 2022). Finally, we assessed which wind farm parameters were most important for predicting the PDF value using a linear regression model for the following parameters: country; distance to coast (m); sea depth (m); turbine power (MW); and number of turbines. All analyses were performed using R version 4.2.2 (R Core Team, 2022).

3 | RESULTS

The map of combined kernel densities for all migration groups in Figure 2 highlights hotspots of migration for Norwegian birds between the Shetland Islands and the western Norwegian coast, between the southern Norwegian coast and Denmark, and along the Swedish and Dutch coasts. Kernel densities per migration group highlight the importance of different regions for each migration group (see Figure S1 in the Supporting Information).

A large variation was observed in the amount of wind energy production (GWh) estimated to be located within the 5% kernel delineating the core migration area for each migration group by 2030 (Figure 3). The highest amount of wind energy production (148,930 GWh per year) was found in the core migration area for waterbirds, whilst the lowest (17,578 GWh per year) amount was found in the core migration area for marine birds.

Cumulative PDF values (annual PDF for all groups and wind farms combined) for all impact pathways are predicted to be higher in 2030 than they currently are in 2023. Cumulative PDF values steadily increase by year in line with annual energy production, with collision impacts estimated to increase more rapidly than disturbance or barrier impacts between 2023 and 2030 (Figure 4a). The large increase in impacts seen in a single year in 2030 is due to the 34 wind farms that are planned for completion in that year. Cumulative impacts relative to annual energy production (PDF/GWh) have slowly been decreasing since 2002 for both disturbance and barrier effects (Figure 4b). Whereas impacts relative to annual energy production for collisions show an initial decrease followed by a slight increase and then a levelling off from around 2020 onwards.

Results of the Sobol sensitivity analysis found that disturbance distance ($d_{k,\max}$) has the biggest influence on both the barrier PDF values ($S_i = 0.346$, $T_i = 0.585$) and the disturbance PDF values ($S_i = 0.384$, $T_i = 0.611$). Rotor length (r_w) has the largest influence on the collision PDF values ($S_i = 0.264$, $T_i = 0.460$), although this is very similar to the influence of both species' presence ($S_i = 0.247$, $T_i = 0.445$) and collision probability ($S_i = 0.223$, $T_i = 0.402$). Here, S_i refers to the Sobol index value, which measures the first-order effects of parameters in the model and their influence on the model output (PDF value). T_i refers to the total-order index value, which

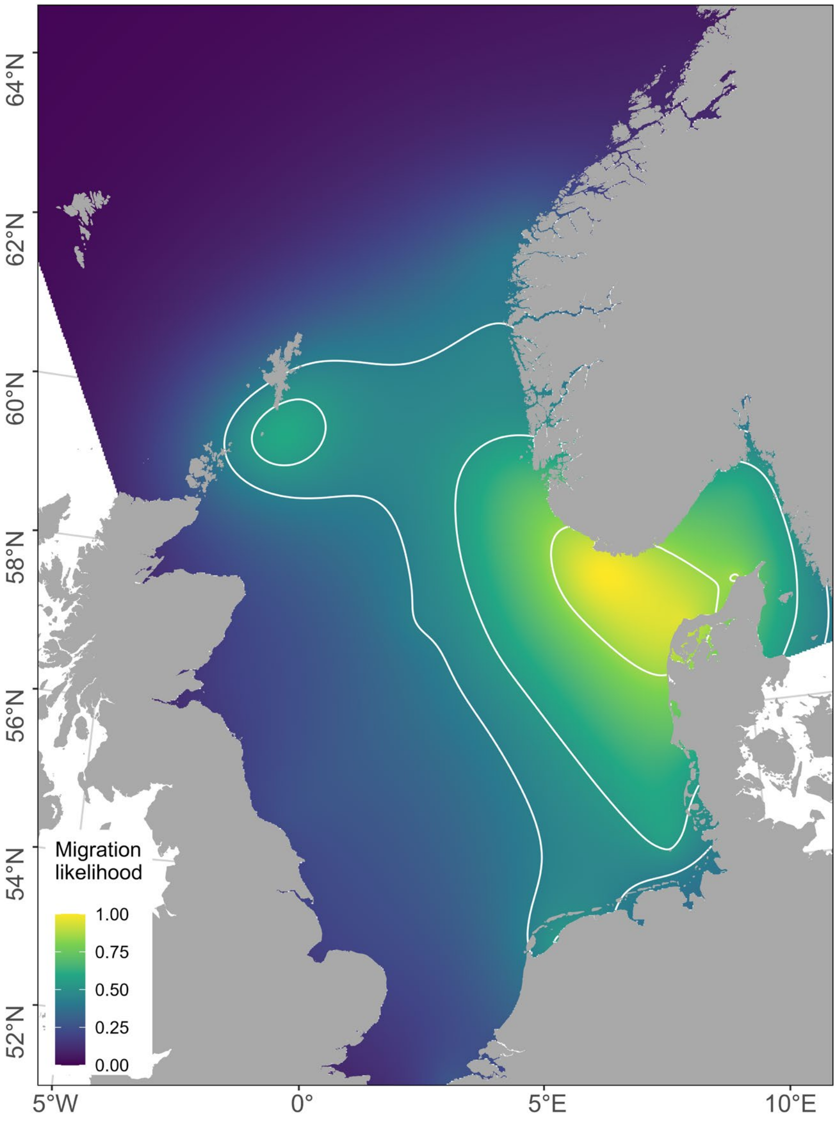


FIGURE 2 Kernel density of Norwegian bird migration trajectories in the North Sea for all migration groups combined. The white lines delineate the top 1%, 5% and 10% of grid square values, that is the regions most utilised by Norwegian birds on migration. See Supporting Information for kernel density maps and migration corridors per group.

measures the first-order effect of each parameter jointly with its interactions with all other parameters (Puy et al., 2022). See the Supporting Information for reporting of second-order effects and Sobol' indices plots (see Figure S2, Tables S2–S4). The results of the linear regression model to assess which wind farm parameters best predict PDF value are shown in Table 2. Number of turbines has a large significant effect on PDF value for all three impact pathways. Turbine capacity (in MW) also has a larger influence on collision impacts, but not on disturbance or barrier impacts.

Efficiency of wind energy production in relation to impacts on Norwegian migrating birds (PDF/GWh) varies by country, with current and future wind farms in Denmark estimated to have the highest impacts across all three impact pathways (Figure 5). PDF values per GWh are predicted to decrease for all countries between 2023 and 2030, apart from in France and Sweden—both of which did not have any existing wind farms in the North Sea prior to 2023. Wind farms in Germany and the UK will have the largest GWh capacity by 2030 and are therefore predicted to have the highest cumulative impact (PDF) on migrating birds by 2030 (Figure S2).

For all migration groups combined, offshore wind farms in the North Sea in 2030 were estimated to lead to an annual PDF of 0.749×10^{-9} (0.031×10^{-9}–3.064×10^{-9}) due to disturbance, 0.065×10^{-9} (0.028×10^{-9}–0.101×10^{-9}) due to collision, and 0.322×10^{-9} (0.019×10^{-9}–1.296×10^{-9}) due to barrier effects (see Table S5 for values per migration group).

The migration group with the highest disturbance and barrier PDF values from offshore wind farms in the North Sea is migrating waterbirds (including waterfowl) (Figure 6, Table S5). The group with the highest collision PDF values is migrating soaring birds (raptors and owls). Migrating marine birds and waders have the lowest PDFs for collision but still have high susceptibility to the impacts of disturbance and barrier effects. The species most impacted across all three impact pathways (see order in Figure 6) are waterbirds and soaring birds. Migrating songbirds ranked the lowest for combined impacts, although they do rank slightly higher for collision risks on their own. PDF values for all other migration groups combined are highest for disturbance impacts, followed by barrier impacts and lowest for collision impacts (Table S2).

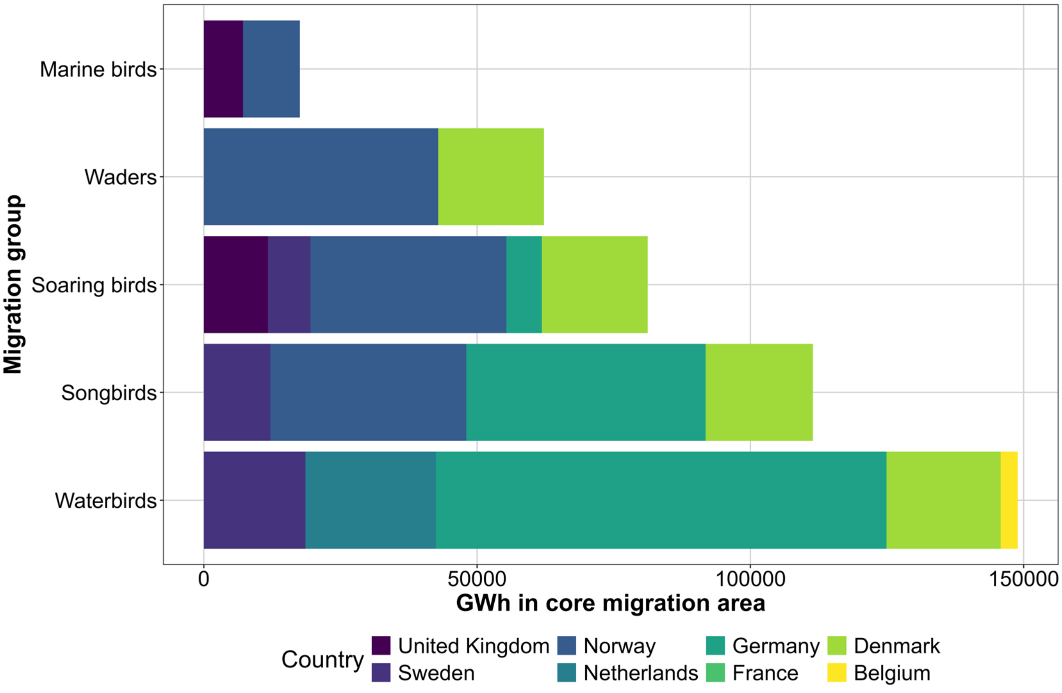


FIGURE 3 Amount of annual GWh per country located in the core migration areas for each group by 2030.

The results for the second part of the analysis, estimating impacts if a 15-MW turbine was placed in each grid square of the migration group kernel density maps, are shown in Figure 7. Mapping cumulative PDF values for all migration groups combined highlights variation in estimated impacts across the North Sea. Collision impacts (Figure 7b) are highest between southern Norway and northern Denmark, whereas barrier and disturbance impacts (Figure 7a,c) have additional hotspots along the coasts of Belgium and the Netherlands. Waterbirds are the group most likely to be impacted due to barrier, collision and disturbance effects, particularly along their migration corridor between southern Norway and northern Denmark and along the coast of the Netherlands (Figure S1).

4 | DISCUSSION

Migrating birds from Norway and other northern European populations will be at increasing risk of impacts from multiple offshore wind farms in the North Sea as development in the region rapidly expands. Many species from these groups are already listed as threatened on the Norwegian Red List of threatened species, and additional pressures both on their migration routes as well as at their breeding and wintering grounds will likely have negative population-level impacts. Our results highlight how several hazards due to OWF (collision, barriers and disturbance) add up to potentially large impacts on migrating species beyond their country of origin, and the need to consider transboundary effects when siting offshore wind farms.

The migration groups exposed to the highest amount of GWh in their core migration area are waterbirds and songbirds, with much of this capacity located in Germany for both groups. However, when looking at how this exposure translates to cumulative impacts, we found that Denmark has the highest cumulative PDF values per GWh, both currently and for future planned developments. This indicates that offshore wind farms in Denmark are not well-sited for mitigating impacts to migrating birds from Norway, reflecting the fact that the core migration area for all migration groups combined covers the majority of the Danish EEZ and the older existing wind farms are built close to the coast (Figures 2 and 7). Cumulative impacts relative to total installed capacity (GWh) in the North Sea have slowly declined since 2002 for both disturbance and barrier effects, indicating that offshore wind farms overall are increasingly being better sited in a way that mitigates these impacts (either intentionally or unintentionally). It is estimated that cumulative impacts per GWh for disturbance and barrier effects will continue to decrease up to 2030. This pattern is less clear for cumulative impacts per GWh for collisions, and there appears to be a stabilising of collision impacts relative to annual energy production up to 2030. This could partly be explained by the sensitivity of the collision PDF equation to turbine rotor length (Table S4) and the large significant influence of turbine MW capacity and number of turbines on the PDF values for collision impacts (Table 2). Most planned wind farms in the North Sea will have very large turbines of 15–20-MW capacity, resulting in a smaller number of turbines per wind farm compared to early offshore wind farms built in the 2000s. The larger turbine size increases the collision risk zone per turbine; however, the reduced number of turbines may partly mitigate this risk (Johnston et al., 2014; Thaxter et al., 2017).

For all migration groups combined, disturbance and barrier effects resulted in the highest expected impacts on species richness,

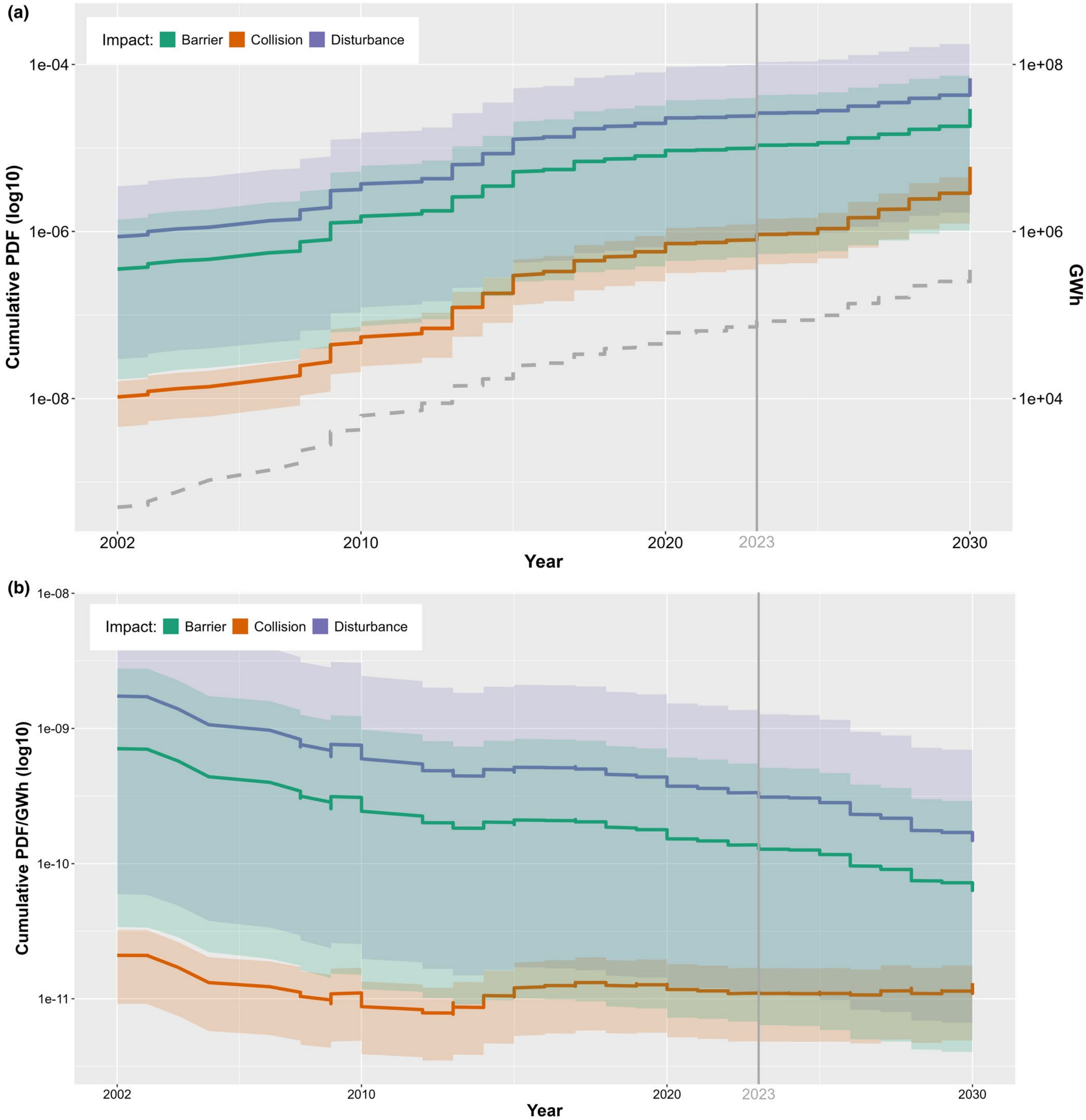


FIGURE 4 Annual cumulative potentially disappeared fraction (PDF) of species across all migration groups and wind farms in the North Sea per year combined for each impact pathway, both (a) absolutely and (b) relative to the annual energy production. Green lines show barrier impacts (± SD), orange lines show collision impacts (± SD), and blue lines show disturbance impacts (± SD). The grey-dashed line in the upper panel shows annual energy production (GWh) of North Sea offshore wind farms. The grey vertical line delineates the current (up to 2023) and future (2023–2030) time periods for developments.

whereas collision impacts were substantially lower—in line with the findings of May et al. (2021) for onshore wind energy developments in Norway. The most obvious consequence of wind energy developments is bird collisions, representing a source of direct mortality (Drewitt & Langston, 2006). There is currently very limited monitoring of collisions at offshore wind farms, and in general, onshore wind farm monitoring studies report relatively low levels of collision mortality, with studies primarily focussed on large birds (eagles, partridges, etc.) found during post-construction carcass surveys (Drewitt & Langston, 2006; Stokke et al., 2020). A recent study also found that true mortality for small birds may be considerably underreported due to lower detection rates—17% of small dummy carcasses were recovered compared to 74% of large dummy (thrush- and wader-sized) carcasses (Nilsson et al., 2023). Based on

BRITISH ECOLOGICAL SOCIETY Journal of Applied Ecology

the migration distributions and LCA used here, the groups expected to be most affected by collisions were, unsurprisingly, waterbirds and soaring birds. Many waterbird species follow a mostly coastal migration path across the North Sea (Kruckenberg et al., 2023), which would place them in or near multiple offshore wind farms in Norway, Sweden, Denmark, Germany, the Netherlands and Belgium. There has been much concern about soaring birds in relation to onshore wind energy development, in Norway at Smøla wind farm (Stokke et al., 2020), but also worldwide (Drewitt & Langston, 2006; Kuvlesky Jr. et al., 2007). Soaring birds such as raptors are particularly vulnerable to anthropogenically induced mortality due to their high longevity, low reproductive rates and preference for thermal soaring during foraging trips. Despite limited possibilities for thermal soaring across open sea, raptors are still prone to collisions offshore during migratory crossings due to their attraction to wind farms, in part for roosting (Skov et al., 2016). Collision mortality due to attraction to offshore structures for roosting is also a risk for some marine birds such as gulls (Johnston et al., 2022). Similar to raptors, marine bird populations are vulnerable to additional mortality due to their reproductive strategies. Songbirds were the only group estimated to have higher impacts from collisions rather than disturbance and barrier effects, and whilst they are the most numerous group of migrating birds, collision mortality is still likely to have a lower effect on songbird populations due to their higher reproductive rates (Erickson et al., 2014). Whilst collision risks are lower than barrier and disturbance impacts for most migration groups, there is still a lack of empirical data on collision rates for birds at offshore wind farms. Improved monitoring through the deployment of radars and camera systems at offshore wind farms, along with transparent reporting, will allow us to better assess the potential collision risks.

As for collisions, waterbirds and soaring birds were the groups expected to be most impacted by disturbance and barrier effects. Both groups have large disturbance distances, and the barrier and disturbance PDF equations are most sensitive to the disturbance distance parameter. Whereas migrating marine birds and waders had the lowest values for collisions, they were considerably more sensitive to disturbance and barrier effects. In contrast to breeding marine birds, which might regularly encounter a wind farm near their colony, habituation to offshore wind farms during migratory crossings seems less likely. Some species of marine birds and waterbirds are known to avoid and adjust their flight trajectories to

TABLE 2 Results of a linear regression model assessing the influence of wind farm parameters on log-transformed PDF values for each impact pathway.

	Impact pathway		
Covariate	Barrier	Collision	Disturbance
Country	15.416***	17.033***	18.722***
Distance to coast	13.162***	17.621***	12.631***
Sea depth	36.457***	38.726***	30.494***
Turbine MW	27.759***	333.051***	21.187***
Nr. of turbines	193.124***	221.203***	176.102***
Turbine MW: Nr. of turbines	39.981***	46.4***	41.204***
Adjusted R-squared	0.7002	0.8145	0.6972

Note: *F* values are reported with a significance of ***$p < 0.001$.

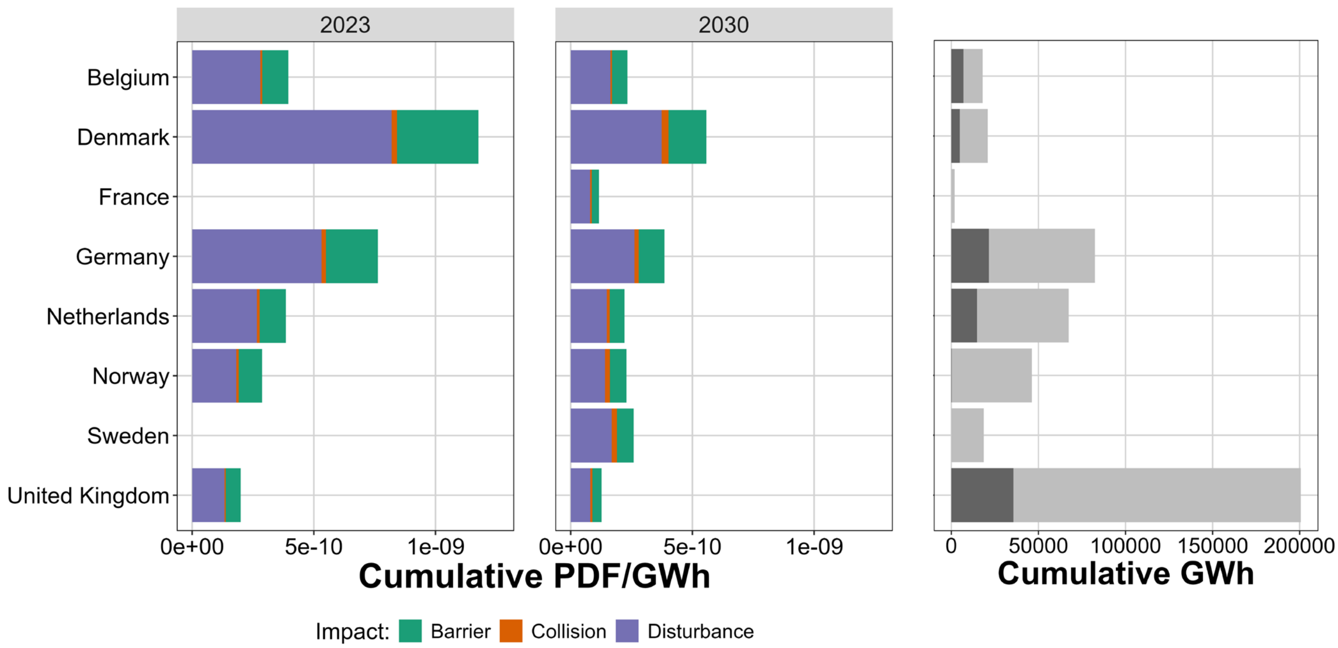


FIGURE 5 Cumulative PDF values per GWh by country for all current (up to 2023) and future (up to 2030) offshore wind farms in the North Sea. The panel on the right shows cumulative GWh per year for all wind farms currently operational in the North Sea up to 2023 (dark grey) and expected cumulative GWh per country by 2030 (light grey). Note that some countries, for example France, Sweden and the UK, have offshore wind farms that are located outside of the North Sea.

some degree in response to offshore wind farms, with subsequent increased energetic flight costs (Masden et al., 2009; Petersen et al., 2006). Whilst disturbance and barrier effects do not cause direct mortality, these additional energetic costs can have long-term impacts, particularly when birds encounter multiple wind farms along their migration pathway (Cabrera-Cruz & Villegas-Patraca, 2016; Masden et al., 2010). Here, we calculate relative impacts per wind farm; however, there is a risk that if wind farms are placed too close together within a core migration area, the cumulative impact due to barrier effects could be greater due to the large additional distances travelled by the migrating birds. Siting of future wind farms in the North Sea beyond 2030 should be carefully considered in this context to ensure that we are not creating excessively large barriers across core migration routes.

Identifying bird migration pathways to assess the potential impacts from wind farms remains a challenge given the extensive areas covered and the difficulties of monitoring migration offshore. In this study, we show how readily available ringing data and the use of BBMMs can recreate more realistic migration pathways, an approach that could easily be applied to other ringing data sets. However, it is important to note the uncertainties that accompany the use of ringing data. Bird ringing locations are not evenly spread across the investigated countries and are strongly biased towards bird observatories and other active bird ringing sites. Bird observatories have the advantage of being located at sites where many migrants aggregate before and after sea crossings. However, this is dependent on migratory season; some sites are used more during autumn than spring and vice versa, as well as weather conditions. Recovery locations are less biased, as recoveries can also stem from public observations of dead ringed birds, typically killed by cats or in collisions with windows and cars. However, ringing and recovery locations might also bias the observed migratory pathway across the North Sea, as the ringing or recovery might occur some distance from the actual crossing over. Although there are hundreds of thousands of recoveries between the selected countries, the data become restricted when enforcing the 60-day limit on the time interval between ringing and recovery events (to exclude recoveries encompassing two migratory seasons). Furthermore, the kernel densities provide an estimate of the utilisation of areas by migration groups rather than a measure of abundance in each grid square. The results presented here should be used as a relative indicator of the variation in impact between migration groups and not an exact measure of the number of birds that

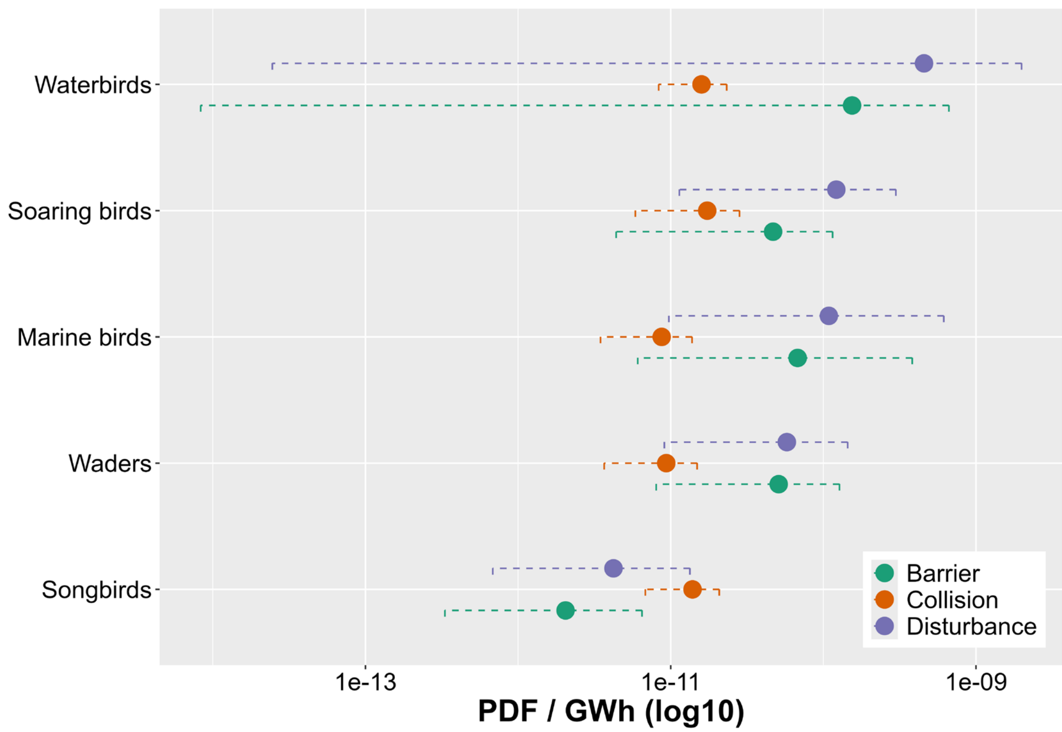
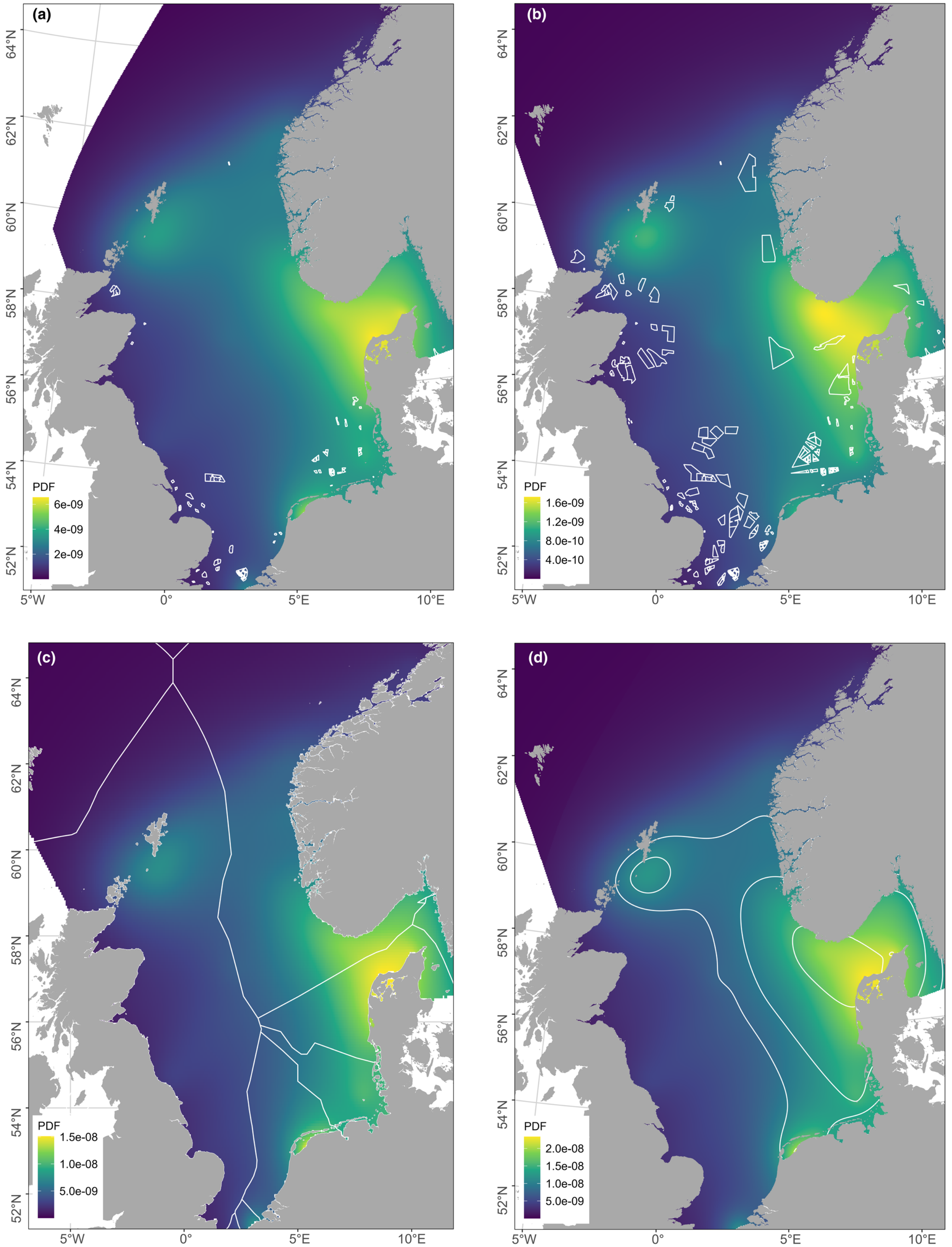


FIGURE 6 Potentially disappeared fractions (PDF) of migrating bird species richness in the North Sea relative to annual energy production (GWh) for each impact pathway. Dashed lines show the upper and lower limits of variability in impacts across species within each migration group.

FIGURE 7 Cumulative PDF value for all bird groups if a 15-MW turbine was placed in each grid cell for (a) barrier, (b) collision, (c) disturbance and (d) all impacts combined. White outlines show in (a) the footprint of all existing wind farms in the North Sea up to July 2023, (b) the footprint of all existing and future wind farms in the North Sea up to 2030, (c) the Exclusive Economic Zones of all countries in the North Sea basin and (d) the 1%, 5%, and 10% kernel density contours from the migration map in Figure 1. Note that maps are not plotted on the same colour scale.

BRITISH ECOLOGICAL SOCIETY Journal of Applied Ecology



will be impacted, or subsequent changes to population sizes (e.g. through increased morality from collisions). These impacts are also only relevant for migrating birds from Norwegian, Scandinavian and Arctic breeding populations and do not provide insight on impacts to migrating birds from populations breeding in countries west of the North Sea (e.g. Ireland and the UK).

Our findings highlight the potential impacts to migrating birds from offshore wind farms in the North Sea, particularly due to disturbance and barrier effects. By calculating impacts per GWh, we can assess how energy production relates to impacts and directly compare relative impacts across bird groups, impact pathways, wind farm sites and countries. The LCA methods presented here could provide a useful tool for quickly assessing cumulative impacts to migrating birds from offshore wind energy in the North Sea, or in other regions, as the industry rapidly expands or comparing relative impacts across proposed wind farm sites in an environmental impact assessment. The LCA methodology could be adapted further to rapidly assess impacts of other types of energy developments on a wide range of migratory species, for example the barrier impacts of hydropower on migrating salmon. The method uses existing data collected from the literature and can be applied to any distribution data. Rapid assessment tools such as this will be vital for assessing and mitigating unintended negative impacts from the accelerated expansion of renewable energy developments globally.

AUTHOR CONTRIBUTIONS

Emma Jane Critchley, Anna Nilsson and Roel May conceived the ideas and designed methodology; Emma Jane Critchley, Anna Nilsson collated the data, Morten Helberg collected and collated the colour ring data for gulls; Emma Jane Critchley, Anna Nilsson and Roel May analysed the data; Emma Jane Critchley drafted the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

ACKNOWLEDGEMENTS

This work was funded by the Norwegian Research Council under the MARCIS project (RCN 326985). We would like to thank the Norwegian Bird Ringing Centre at Stavanger Museum and Håvard Husebø for providing ring recovery data, and James Wilson for colour ring data on oystercatchers. We also thank Lila Buckingham for assistance in collating the data and information on offshore wind farms in the North Sea. We thank the reviewers for helpful comments on an earlier draft of this manuscript.

CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest to declare.

DATA AVAILABILITY STATEMENT

Data on offshore wind farms in the North Sea are available from Zenodo https://doi.org/10.5281/zenodo.10478448 (Critchley & Buckingham, 2024). The species and group-specific data used for the life-cycle impact assessment are available from Zenodo https://doi.org/10.5281/zenodo.15527472 (Critchley et al., 2025).

STATEMENT ON INCLUSION

The lead author and authorship team were based in Norway, the country where this study was carried out. The study utilised secondary data; therefore, there was no local data collection. Whenever possible, our research was discussed with local interested parties to seek feedback on the questions to be tackled and the approach to be considered. Whenever relevant, literature published by scientists from the region was also cited, including relevant work published in the local language.

ORCID

Emma Jane Critchley https://orcid.org/0000-0002-5845-2830
Roel May https://orcid.org/0000-0002-6580-4064

REFERENCES

Alerstam, T. (1993). *Bird migration*. Cambridge University Press.

Artsdatabanken. (2021). *Norsk rødliste for arter 2021*. Artsdatabanken.

Bailey, H., Brookes, K. L., & Thompson, P. M. (2014). Assessing environmental impacts of offshore wind farms: Lessons learned and recommendations for the future. *Aquatic Biosystems*, *10*(1), 8. https://doi.org/10.1186/2046-9063-10-8

Brust, V., & Hüppop, O. (2022). Underestimated scale of songbird offshore migration across the south-eastern North Sea during autumn. *Journal of Ornithology*, *163*(1), 51–60. https://doi.org/10.1007/s10336-021-01934-5

Cabrera-Cruz, S. A., & Villegas-Patraca, R. (2016). Response of migrating raptors to an increasing number of wind farms. *Journal of Applied Ecology*, *53*(6), 1667–1675. https://doi.org/10.1111/1365-2664.12673

Calange, C. (2006). The package adehabitat for the R software: A tool for the analysis of space and habitat use by animals. *Ecological Modelling*, *197*, 516–519.

Critchley, E. J., & Buckingham, L. (2024). Offshore wind farms in the North Sea—A dataset of developments estimated to be operational by 2030 [Dataset]. *Zenodo*. https://doi.org/10.5281/zenodo.10478448

Critchley, E. J., Nilsson, A., Helberg, M., & May, R. (2025). Data from: Lifecycle impact assessment of offshore wind energy development on migrating bird diversity in the North Sea [Dataset]. *Zenodo*. https://doi.org/10.5281/zenodo.15527473

Croxall, J. P., Butchart, S. H. M., Lascelles, B., Stattersfield, A. J., Sullivan, B., Symes, A., & Taylor, P. (2012). Seabird conservation status, threats and priority actions: A global assessment. *Bird Conservation International*, *22*(1), 1–34. https://doi.org/10.1017/S0959270912000020

Degraer, S., Brabant, R., Rumes, B., & Vigin, L. (2017). *Environmental impacts of offshore wind farms in the Belgian part of the North Sea: A continued move towards integration and quantification*. Royal Belgian Institute of Natural Sciences, OD Natural Environment, Marine Ecology and Management Section.

Drewitt, A. L., & Langston, R. H. W. (2006). Assessing the impacts of wind farms on birds. *Ibis*, *148*(s1), 29–42. https://doi.org/10.1111/j.1474-919X.2006.00516.x

Erickson, W. P., Wolfe, M. M., Bay, K. J., Johnson, D. H., & Gehring, J. L. (2014). A comprehensive analysis of small-passerine fatalities from collision with turbines at wind energy facilities. *PLoS One*, *9*(9), e107491. https://doi.org/10.1371/journal.pone.0107491

Evan, G., Rinker, J., Sethuraman, L., Zahle, F., Anderson, B., Barter, G., Abbas, N., Meng, F., Bortolotti, P., Skrzypinski, W., Scott, G., Feil, R., Bredmose, H., Dykes, K., Shields, M., Allen, C., & Viselli, A. (2020). *Definition of the IEA 15-megawatt offshore reference wind* (No. NREL/TP-5000-75698). National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy20osti/75698.pdf

Fiedler, W. (2009). New technologies for monitoring bird migration and behaviour. *Ringing & Migration*, *24*(3), 175–179. https://doi.org/10.1080/03078698.2009.9674389

Fijn, R. C., Krijgsveld, K. L., Poot, M. J. M., & Dirksen, S. (2015). Bird movements at rotor heights measured continuously with vertical radar at a Dutch offshore wind farm. *Ibis*, *157*(3), 558–566. https://doi.org/10.1111/ibi.12259

Furness, R. W., Wade, H. M., & Masden, E. A. (2013). Assessing vulnerability of marine bird populations to offshore wind farms. *Journal of Environmental Management*, *119*, 56–66. https://doi.org/10.1016/j.jenvman.2013.01.025

Gill, A. B. (2005). Offshore renewable energy: Ecological implications of generating electricity in the coastal zone. *Journal of Applied Ecology*, *42*(4), 605–615. https://doi.org/10.1111/j.1365-2664.2005.01060.x

Horne, J. S., Garton, E. O., Krone, S. M., & Lewis, J. S. (2007). Analyzing animal movements using Brownian bridges. *Ecology*, *88*(9), 2354–2363. https://doi.org/10.1890/06-0957.1

Hüppop, O., & Hüppop, K. (2011). Bird migration on Helgoland: The yield from 100 years of research. *Journal of Ornithology*, *152*(1), 25–40. https://doi.org/10.1007/s10336-011-0705-2

IRENA. (2023). *Renewable energy statistics 2023*. International Renewable Energy Agency.

IUCN. (2022). *The IUCN Red List of Threatened Species* (No. Version 2022-2). https://www.iucnredlist.org

Johnston, A., Cook, A. S. C. P., Wright, L. J., Humphreys, E. M., & Burton, N. H. K. (2014). Modelling flight heights of marine birds to more accurately assess collision risk with offshore wind turbines. *Journal of Applied Ecology*, *51*, 31–41. https://doi.org/10.1111/1365-2664.12191

Johnston, D. T., Thaxter, C. B., Boersch-Supan, P. H., Humphreys, E. M., Bouten, W., Clewley, G. D., Scragg, E. S., Masden, E. A., Barber, L., Conway, G. J., Clark, N. A., Burton, N. H. K., & Cook, A. S. C. P. (2022). Investigating avoidance and attraction responses in lesser black-backed gulls *Larus fuscus* to offshore wind farms. *Marine Ecology Progress Series*, *686*, 187–200. https://doi.org/10.3354/meps13964

Keen, K. A., Beltran, R. S., Pirotta, E., & Costa, D. P. (2021). Emerging themes in population consequences of disturbance models. *Proceedings of the Royal Society B: Biological Sciences*, *288*(1957), 20210325. https://doi.org/10.1098/rspb.2021.0325

Kirby, J. S., Stattersfield, A. J., Butchart, S. H. M., Evans, M. I., Grimmett, R. F. A., Jones, V. R., O'Sullivan, J., Tucker, G. M., & Newton, I. (2008). Key conservation issues for migratory land- and waterbird species on the world's major flyways. *Bird Conservation International*, *18*(S1), S49–S73. https://doi.org/10.1017/S0959270908000439

Kruckenberg, H., Moonen, S., Kölzsch, A., Liljebäck, N., & Müskens, G. J. D. M. (2023). Migration routes and stepping stones along the western flyway of lesser white-fronted geese (*Anser erythropus*). *Bird Conservation International*, *33*, e42. https://doi.org/10.1017/S0959270922000478

Kuvlesky, W. P., Jr., Brennan, L. A., Morrison, M. L., Boydston, K. K., Ballard, B. M., & Bryant, F. C. (2007). Wind energy development and wildlife conservation: Challenges and opportunities. *The Journal of Wildlife Management*, *71*(8), 2487–2498. https://doi.org/10.2193/2007-248

Layton-Matthews, K., Buckingham, L., Critchley, E. J., Nilsson, A. L. K., Ollus, V. M. S., Ballesteros, M., Christensen-Dalsgaard, S., Denhard, N., Fauchald, P., Hanssen, F., Helberg, M., Masden, E., May, R. F., Sandvik, H., Tarroux, A., & Reiertsen, T. K. (2023). *Development of a cumulative impact assessment tool for birds in Norwegian off-shore waters: Trollvind OWF as a case study* (NINA Report No. 2295). Norwegian Institute for Nature Research.

Martins, M. C. I., Carter, M. I., Rouse, S., & Russell, D. J. (2023). Offshore energy structures in the North Sea: Past, present and future. *Marine Policy*, *152*, 105629. https://doi.org/10.1016/j.marpol.2023.105629

Masden, E. A., Fox, A. D., Furness, R. W., Bullman, R., & Haydon, D. T. (2010). Cumulative impact assessments and bird/wind farm interactions: Developing a conceptual framework. *Environmental Impact Assessment Review*, *30*(1), 1–7. https://doi.org/10.1016/j.eiar.2009.05.002

Masden, E. A., Haydon, D. T., Fox, A. D., Furness, R. W., Bullman, R., & Desholm, M. (2009). Barriers to movement: Impacts of wind farms on migrating birds. *ICES Journal of Marine Science*, *66*(4), 746–753. https://doi.org/10.1093/icesjms/fsp031

May, R., Jackson, C. R., Middel, H., Stokke, B. G., & Verones, F. (2021). Life-cycle impacts of wind energy development on bird diversity in Norway. *Environmental Impact Assessment Review*, *90*, 106635. https://doi.org/10.1016/j.eiar.2021.106635

May, R., Middel, H., Stokke, B. G., Jackson, C., & Verones, F. (2020). Global life-cycle impacts of onshore wind-power plants on bird richness. *Environmental and Sustainability Indicators*, *8*, 100080. https://doi.org/10.1016/j.indic.2020.100080

Nilsson, A. L. K., Molværsmyr, S., Breistøl, A., & Systad, G. H. R. (2023). Estimating mortality of small passerine birds colliding with wind turbines. *Scientific Reports*, *13*(1), 21365. https://doi.org/10.1038/s41598-023-46909-z

Nilsson, C., Dokter, A. M., Verlinden, L., Shamoun-Baranes, J., Schmid, B., Desmet, P., Bauer, S., Chapman, J., Alves, J. A., Stepanian, P. M., Sapir, N., Wainwright, C., Boos, M., Górska, A., Menz, M. H. M., Rodrigues, P., Leijnse, H., Zehtindjiev, P., Brabant, R., … Liechti, F. (2019). Revealing patterns of nocturnal migration using the European weather radar network. *Ecography*, *42*(5), 876–886. https://doi.org/10.1111/ecog.04003

Offshore Wind Outlook 2019: World Energy Outlook Special Report. (2019). *International Energy Agency*. https://www.iea.org/reports/offshore-wind-outlook-2019

Ostend declaration of energy ministers on the North Seas as a green power plant of Europe. (2023). https://www.regjeringen.no/contentassets/78bfc87bb04044c0933002ad7dd6e0f1/erklaring-energiministere.pdf

Palm, E. C., Newman, S. H., Prosser, D. J., Xiao, X., Ze, L., Batbayar, N., Balachandran, S., & Takekawa, J. Y. (2015). Mapping migratory flyways in Asia using dynamic Brownian bridge movement models. *Movement Ecology*, *3*(1), 3. https://doi.org/10.1186/s40462-015-0029-6

Petersen, I. K., Christensen, T. K., Kahlert, J., Desholm, M., & Fox, A. D. (2006). Final results of bird studies at the offshore wind farms at Nysted and Horns Rev. *Denmark. Commissioned by DONG Energy and Vattenfall A/S NERI/Ministry of Environment NERI Report*, 161. http://tethys.pnnl.gov/sites/default/files/publications/NERI_Bird_Studies.pdf

Puy, A., Piano, S. L., Saltelli, A., & Levin, S. A. (2022). Sensobol: An R package to compute variance-based sensitivity indices. *Journal of Statistical Software*, *102*(5), 1–37. https://doi.org/10.18637/jss.v102.i05

R Core Team. (2022). *R: A language and environment for statistical computing* [Computer software]. R Foundation for Statistical Computing. https://www.R-project.org/

Shamoun-Baranes, J., & van Gasteren, H. (2011). Atmospheric conditions facilitate mass migration events across the North Sea. *Animal Behaviour*, *81*(4), 691–704. https://doi.org/10.1016/j.anbehav.2011.01.003

Shuter, J. L., Broderick, A. C., Agnew, D. J., Jonzén, N., Godley, B. J., Milner-Gulland, E. J., & Thirgood, S. (2011). Conservation and management of migratory species. In *Animal migration* (pp. 172–206). Wiley Blackwell. https://doi.org/10.1093/acprof:oso/9780199568994.003.0011

Skov, H., Desholm, M., Heinänen, S., Kahlert, J. A., Laubek, B., Jensen, N. E., Žydelis, R., & Jensen, B. P. (2016). Patterns of migrating soaring migrants indicate attraction to marine wind farms. *Biology Letters*, *12*(12), 20160804. https://doi.org/10.1098/rsbl.2016.0804

Stokke, B. G., Dahl, E. L., Hamre, Ø., Kleven, O., May, R., Nygård, T., Pavòn-Jordàn, D., Roksvåg, L. M., Sandercock, B. K., & Åström, J. (2020). *Langtidseffekter av Smøla vindpark på den lokale bestanden av havørn (Haliaeetus albicilla)*. Norsk institutt for naturforskning (NINA). https://brage.nina.no/nina-xmlui/handle/11250/2688685

Thaxter, C. B., Buchanan, G. M., Carr, J., Butchart, S. H. M., Newbold, T., Green, R. E., Tobias, J. A., Foden, W. B., O'Brien, S., & Pearce-Higgins, J. W. (2017). Bird and bat species' global vulnerability to collision mortality at wind farms revealed through a trait-based assessment. *Proceedings of the Royal Society B: Biological Sciences*, *284*(1862), 20170829. https://doi.org/10.1098/rspb.2017.0829

Verones, F., Bare, J., Bulle, C., Frischknecht, R., Hauschild, M., Hellweg, S., Henderson, A., Jolliet, O., Laurent, A., Liao, X., Lindner, J. P., Maia De Souza, D., Michelsen, O., Patouillard, L., Pfister, S., Posthuma, L., Prado, V., Ridoutt, B., Rosenbaum, R. K., … Fantke, P. (2017). LCIA framework and cross-cutting issues guidance within the UNEP-SETAC life cycle initiative. *Journal of Cleaner Production*, *161*, 957–967. https://doi.org/10.1016/j.jclepro.2017.05.206

Wade, H. M., Masden, E. A., Jackson, A. C., & Furness, R. W. (2016). Incorporating data uncertainty when estimating potential vulnerability of Scottish seabirds to marine renewable energy developments. *Marine Policy*, *70*, 108–113. https://doi.org/10.1016/j.marpol.2016.04.045

Wang, S., Wang, S., & Liu, J. (2019). Life-cycle green-house gas emissions of onshore and offshore wind turbines. *Journal of Cleaner Production*, *210*, 804–810. https://doi.org/10.1016/j.jclepro.2018.11.031

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Table S1. The species composition of the migration groups used in the Brownian Bridge Movement Models (BBMM) and subsequent Life-cycle Impact Assessments (LCIA) to elucidate the migratory trajectories of birds based on Norwegian, British, Belgian, Dutch, German and Danish ringing events and recoveries.

Table S2. Results of the Sobol sensitivity analysis for the barrier PDF equation.

Table S3. Results of the Sobol sensitivity analysis for the collision PDF equation.

Table S4. Results of the Sobol sensitivity analysis for the disturbance PDF equation.

Table S5. Mean PDF values of estimated barrier, collision and disturbance impacts for wind farms in the North Sea up to 2030.

Figure S1. Kernel densities of the migration trajectories in the North Sea of each migration group based on ringing recovery data and Brownian bridge models.

Figure S2. First- (Si) and total- (Ti) order Sobol' indices for (a) the barrier PDF equation, (b) the collision PDF equation, and (c) the disturbance PDF equation.

Figure S3. Cumulative PDF values for all current (up to 2023) and future (up to 2030) offshore wind farms in the North Sea.

How to cite this article: Critchley, E. J., Nilsson, A., Helberg, M., & May, R. (2025). Life-cycle impact assessment of offshore wind energy development on migrating bird diversity in the North Sea. *Journal of Applied Ecology*, *62*, 1597–1610. https://doi.org/10.1111/1365-2664.70087