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Short Communication

Incorporating data uncertainty when estimating potential vulnerability of Scottish seabirds to marine renewable energy developments

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ABSTRACT

The effects of marine renewable energy developments (MREDs) on seabirds are uncertain because of the relative infancy of the industry. This uncertainty can delay the consenting process as regulators adopt a precautionary approach. This study uses novel methods to demonstrate uncertainty in two indices that ranked the vulnerability of seabird populations to MREDs. The study also consolidates recently available data with information from the two indices to consider developments in our understanding of how seabirds respond to MREDs and to present up-to-date vulnerability predictions. Results indicate greater uncertainty in data regarding displacement caused by vessels and/or helicopters, and use of tidal races by seabirds, than in data regarding the percentage of flight overlapping with wind turbine blades and the level of displacement caused by structures. Results also indicate varying uncertainty among species. Overall vulnerability rankings remained broadly the same, with some minor changes. The uncertainty indices highlight areas lacking data, identify robust predictions, and indicate where particular caution in interpreting vulnerability indices should be adopted. They are a useful tool to inform impact assessment and identify strategic research and monitoring priorities.

1. Introduction

Marine renewable energy developments (MREDs) are increasing worldwide to provide an alternative to fossil fuels, increase energy security and mitigate against climatic change [6,7,19]. Scotland has valuable marine renewable energy resources [1,21] and has developed a marine plan, including offshore wind, wave and tidal-stream technologies, to contribute to generating 100% of Scotland's electricity through renewable sources by 2020 [19]. Scotland is internationally important for seabirds [2,16], with special protection areas (SPAs) designated to safeguard breeding colonies [9,18,20]. With several leased and proposed Scottish MRED sites located close to SPAs for breeding seabirds, consideration of the potential consequences for seabirds is necessary.

The effects of MREDs on seabirds are uncertain because of the relative infancy of the industry, the early stage of some environmental monitoring programmes [25] and a limited ability to effectively monitor post-construction effects [13,14,17]. Uncertainty over effects can delay the consenting process as regulators adopt a precautionary approach [15]; for example, by using avoidance rates that may overestimate collision risk. In the absence of information regarding specific effects of MREDs on seabirds, a common approach is to use existing knowledge of seabird behaviour and ecology to derive estimates of seabird vulnerability (e.g. [3–5]). Uncertainty in the contributing data is, however, rarely presented, but is vital information, as the reliability of results and confidence in interpretations can be affected by the quality, quantity and relevance of contributing data [15]. These measures of data uncertainty identify where evidence supporting vulnerability rankings is more robust; where caution in interpreting results may be required; and where additional monitoring and research could prove beneficial [22].

Using Furness et al. [3,4] as examples, this study developed novel methods to incorporate uncertainty into indices ranking the vulnerability of Scottish seabird populations to MREDs. Furness et al. [3,4] developed four indices ranking vulnerability to i) collision with offshore wind turbines, ii) displacement caused by offshore wind farms, iii) wave energy, and iv) tidal-stream energy developments. These indices have been used by MRED regulators and developers during initial scoping and impact assessment (e.g.

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[8]) but measures of uncertainty in data contributing to rankings were not explicitly included. This study develops uncertainty indices to aid transparent and consistent application of vulnerability index predictions. Recently available data were consolidated with information in Furness et al. [3,4], to account for new developments in our understanding of how seabirds respond to i) structures and ii) vessels and helicopters, and to incorporate a reduced risk of collision with offshore wind turbines for species displaced by structures. The development of uncertainty indices and modified vulnerability indices more accurately represent the risks posed by MREDs to seabirds.

2. Methods

2.1. Calculating uncertainty

Four vulnerability factors were identified as important in driving seabird vulnerability to MREDs [3,4]: i) percentage of flight overlapping with wind turbine blades, ii) displacement caused by structures, iii) displacement caused by vessels and/or helicopters, and iv) use of tidal races. The quality, quantity and relevance of data contributing to these factors were assessed for each of 38 Scottish seabird species to estimate data uncertainty (see Supplementary Table 1 for scientific names). Data uncertainty was assessed using five criteria, with greater scores reflecting a greater quantity and quality of data, and therefore indicating lower levels of uncertainty:

1) **Species Score**: Did data refer to the target species or a related species? Species were scored 3 if $\geq 50\%$ of data sources referred to the target species, 2 if data referred to a related species or to higher taxa, and 1 if no published data were available.
2) **Number of Sites**: How many sites contributed data?
3) **Number of Studies**: How many studies are included?
4) **Mean Years**: What was the mean period of years over which data were collected?
5) **Method Score**: What level of uncertainty was associated with the methods used to collect data? For a full explanation of the Methods Score, Method Categories and associated Uncertainty Levels see Section 2.1.1 and Table 1.

The five criteria scores derived for each species, in each vulnerability factor, are shown in Supplementary Tables 2–5.

2.1.1. Method Score

To generate a Method Score for each species, in each vulnerability factor, the number of studies in each Method Category (with different Method Categories considered relevant for the four vulnerability factors; Table 1) were multiplied by the Uncertainty Score under which the Method Category was located (Table 1). Greater weight was given to studies using more reliable and robust methods; for example, before-after-control-impact studies and studies collecting data on flight altitudes using bird-borne GPS devices. These more reliable methods were associated with greater scores to reflect a greater quality of data, and therefore a corresponding lower Uncertainty Level (Table 1; Eqs. (1) and (2)). The Method Score reflects the reliability of the methods used in all studies considered for each species in each vulnerability factor, and the uncertainty inherent in those data. Eq. (1) was used to

Table 1
Uncertainty Levels and Scores indicating the level of uncertainty associated with data contributing to species vulnerability rankings. Five categories with associated ranking scores indicate the level of uncertainty: very high (score 1), high (score 2), moderate (score 3), low (score 4) and very low uncertainty (score 5). Capital letters in brackets refer to the Method Categories included in Eqs. (1) and (2). The table indicates the Uncertainty Level and Score assigned to each Method Category and outlines the range of values included in the Combined Score at each Uncertainty Level, which differs among vulnerability factors. Greater scores reflect a greater quantity and quality of data, and therefore correspond to lower levels of uncertainty.

Vulnerability factor	Vulnerability factor attributes	Uncertainty Level (Uncertainty Scores)				
		Very high (1)	**High (2)**	**Moderate (3)**	**Low (4)**	**Very low (5)**
% Time flying at turbine height	**Method Category**	Anecdotal observation (or unknown method) **(A)**	Observations not recorded in the presence of turbines (indirect study 2) **(B)**	Observations recorded in the presence of turbines (indirect study 1) **(C)**	Study combining results from 5 or more studies/ sites to produce modelled flight information **(D)**	GPS or radar (direct study) **(E)**
	Combined Score	0.0 – 28.5	29.0 – 56.5	57.0 – 84.5	85.0 – 112.5	113.0–140.5
Disturbance by structures	**Method Category**	Anecdotal observation (or unknown method) **(A)**	Observation **(B)**	Before-After- Control-Impact study (BACI) **(C)**		
	Combined Score	0.0–12.5	13.0–24.5	25.0–36.5	37.0–48.5	49.0–60.5
Disturbance by vessel and/or helicopter activity	**Method Category**	Anecdotal observation (or unknown method) **(A)**	Observation **(B)**	BACI or experimental method **(C)**		
	Combined Score	0.0–8.5	9.0–16.5	17.0–24.5	25.0–32.5	33.0–40.5
Use of tidal races	**Method Category**	Anecdotal observation (or unknown method) **(A)**	Observation without current data **(B)**	Observation with modelled or inferred current data **(C)**	Study combining results from 5 or more studies/ sites with modelled or inferred current data **(D)**	Observation with concurrent current data **(E)**
	Combined Score	0.0–8.5	9.0–16.5	17.0–24.5	25.0–32.5	33.0–41.5

calculate uncertainty associated with each species in the vulnerability factors ‘percentage of flight overlapping with wind turbine blades’, and ‘use of tidal races’. Eq. (2) was used to calculate uncertainty associated with each species in the vulnerability factors ‘displacement caused by structures’ and ‘displacement caused by vessels and/or helicopter activity’. The letters in Eqs. (1) and (2) represent the number of studies considered within each corresponding Method Category, and the numbers represent the Uncertainty Score associated with those Method Categories (Table 1). The different equations account for the different methods used to collect data pertaining to the four vulnerability factors (Table 1).

$$\text{Method Score} = (A)+(B \times 2)+(C \times 3)+(D \times 4)+(E \times 5) \tag{1}$$

$$\text{Method Score} = (A)+(B \times 2)+(C \times 3) \tag{2}$$

2.1.2. Combined Score

Combining the scores from each of the five criteria (Z: Species Score, Number of Sites, Number of Studies, Mean Years, Method Score) provided an estimation of uncertainty inherent in the data considered for each species in each vulnerability factor (Eq. (3)).

$$\text{Combined Score} = \sum_{i=Z}^{5} \text{score}_i \tag{3}$$

Combined Scores were assigned to one of five Uncertainty Levels and an associated Uncertainty Score (very low: 5, low: 4, moderate: 3, high: 2, and very high uncertainty: 1). To allocate Combined Scores to Uncertainty Levels, the greatest Combined Score for each vulnerability factor was rounded to the nearest ten and divided into five equal ranges to correspond to five Uncertainty Levels (Table 1). This provided a measure of uncertainty inherent in the data underlying species' vulnerability rankings in the four vulnerability factors (Supplementary Tables 2–5). For each species, the four Uncertainty Scores (generated from the Combined Score in each vulnerability factor) were summed to provide an overall estimation of uncertainty (Overall Uncertainty Score) associated with each species (Table 2).

In this paper, the term ‘uncertainty’ refers to the level of confidence in the data used to derive vulnerability rankings; based on the quality, quantity and relevance of that data. The Uncertainty Categories and Scores presented are generated based only on the data considered in this study (see Supplementary Material for data sources) and provide a relative estimation of uncertainty inherent in the data considered in each of the four vulnerability factors. Uncertainty Categories and Scores are measured on an ordinal scale; which means that the categories are ordered according to numerical values but that the numerical quantities represented by those values have no significance beyond allowing a ranking to be established. The Uncertainty Scores are labels that represent a categorical order and do not represent any concept of equal interval between categories. Uncertainty Categories and Scores do not represent an absolute scale and should not be taken to suggest that additional data collection may not be beneficial, even for those species associated with very low uncertainty. For example, if results indicate a very low uncertainty surrounding a particular species' flight altitude because of a large quantity of data available for that species, there may still be a poor understanding of the influence of different behaviour or weather conditions on flight height. As such, additional data collection could prove beneficial, as a better understanding of flight altitude would improve collision risk estimations.

2.2. Modification of vulnerability indices

2.2.1. Differing responses to structures and vessels and/or helicopters

Developments in understanding how seabirds respond to MREDs indicate that some species (e.g. Northern gannets *Morus bassanus*) react differently to structures (e.g. offshore wind turbines) than to vessels and helicopters. This study modifies methods presented in Furness et al. [3,4] to separately rank species according to vulnerability to i) structures, and ii) vessels and/or helicopters; rather than present a combined vulnerability factor. Greater weighting was applied to displacement/disturbance caused by structures (a) than to displacement/disturbance caused by vessels and/or helicopters (b) when calculating vulnerability to displacement/disturbance caused by offshore wind farms (Eq. (4)). This incorporates a likely greater influence of permanent structures over transient vessel and helicopter traffic. A measure of habitat specialisation (c) and a species conservation score (see [3,4]) were included (Eq. (4)).

$$\text{Displacement/disturbance score} = \frac{(((a \times c)+b) \times \text{conservation score})}{10} \tag{4}$$

2.2.2. Reduced risk of collision if displaced by structures

Birds avoiding and/or displaced by structures reduce their risk of collision. This study modifies the Furness et al. [3] calculation ranking seabird vulnerability to collision with offshore wind turbines by dividing the time spent at altitudes overlapping with turbine blades (d) by the level of displacement caused by structures (a) to incorporate this. Flight agility, percentage of time spent in flight, nocturnal flight activity (Y) and a species conservation score (see [3,4]) were included (Eq. (5)).

$$\text{Collision risk score} = \frac{d}{a} \times \frac{1}{3} \sum_{i=Y}^{3} \text{score}_i \times \text{conservation score} \tag{5}$$

All four vulnerability indices presented in Furness et al. [3,4] were recalculated following modification of index calculations and inclusion of new data (see Supplementary Tables 6–9 and Supplementary Reference List).

3. Results

3.1. Calculating uncertainty

There is greater uncertainty in our understanding of species' vulnerability to displacement caused by vessel and/or helicopter traffic, and seabird use of tidal races, than in data regarding the percentage of flight overlapping with wind turbine blades and the level of displacement caused by structures. Results indicate varying uncertainty among species in the four vulnerability factors, with storm petrels, sooty shearwater *Puffinus griseus* and Arctic skua *Stercorarius parasiticus* associated with very high uncertainty in three of the four vulnerability factors. Common goldeneye *Bucephala clangula*, greater scaup *Aythya marila*, long-tailed duck *Clangula hyemalis*, Manx shearwater *Puffinus puffinus*, roseate tern *Sterna dougallii*, white-tailed eagle *Haliaeetus albicilla* and grebes were associated with very high and high uncertainty (Table 2).

3.2. Modification of vulnerability indices

Overall seabird vulnerability rankings remained broadly the same, with only minor changes, following modification and recalculation of the four vulnerability indices presented in Furness et al. [3,4] (Supplementary Tables 6–9). Northern gannets

Table 2
Uncertainty inherent in data underlying the generation of four vulnerability factors for 38 seabird species. Uncertainty Scores equate to five Uncertainty Categories with greater scores indicating lower uncertainty: very high (score 1), high (score 2), moderate (score 3), low (score 4) and very low uncertainty (score 5). These categories and scores are on an ordinal scale where the numerical values have no significance beyond allowing a ranking to be established. Species rankings and scores were generated relative to data considered in each of the four vulnerability factors.

Species	Uncertainty Level: % of time at altitudes overlapping with turbine blades	Uncertainty Score	Uncertainty Level: Displacement caused by structures	Uncertainty Score	Uncertainty Level: Displacement caused by vessels and/or helicopters	Uncertainty Score	Uncertainty Level: Use of tidal races	Uncertainty Score	Overall Uncertainty Score (max 20)
European storm-petrel	Very high	1	Very high	1	High	2	Very high	1	5
Leach's storm-petrel	Very high	1	Very high	1	High	2	Very high	1	5
Sooty shearwater	Very high	1	Very high	1	High	2	Very high	1	5
Arctic skua	Moderate	3	Very high	1	Very high	1	Very high	1	6
Common goldeneye	Very high	1	Very high	1	High	2	High	2	6
Greater scaup	Very high	1	Very high	1	High	2	High	2	6
Manx shearwater	High	2	Very high	1	High	2	Very high	1	6
Slavonian grebe	Very high	1	High	2	High	2	Very high	1	6
White-tailed eagle	Very high	1	High	2	High	2	Very high	1	6
Great-crested grebe	High	2	High	2	High	2	Very high	1	7
Long-tailed duck	Very high	1	High	2	High	2	High	2	7
Roseate tern	Very high	1	High	2	High	2	High	2	7
Great skua	Moderate	3	High	2	High	2	Very high	1	8
Little tern	Very high	1	Moderate	3	Very high	1	Moderate	3	8
Velvet scoter	High	2	Very high	1	Moderate	3	High	2	8
Black-headed gull	Moderate	3	Moderate	3	High	2	Very high	1	9
Northern fulmar	Low	4	High	2	High	2	Very high	1	9
Arctic tern	Moderate	3	Moderate	3	High	2	High	2	10
Great northern diver	High	2	High	2	Very high	1	Very low	5	10
Little auk	Very high	1	Low	4	Low	4	Very high	1	10
Black-throated diver	High	2	Moderate	3	High	2	Low	4	11
Common gull	Low	4	Low	4	High	2	Very high	1	11
Common eider	Moderate	3	Moderate	3	Moderate	3	Moderate	3	12
Sandwich tern	Low	4	Low	4	High	2	High	2	12
Black guillemot	Very high	1	High	2	Very low	5	Very low	5	13
European shag	High	2	Low	4	High	2	Very low	5	13
Great black-backed gull	Low	4	Very low	5	Moderate	3	Very high	1	13
Great cormorant	Moderate	3	Very low	5	High	2	Moderate	3	13
Black-legged kittiwake	Very low	5	Very low	5	High	2	High	2	14
Common tern	Very low	5	Low	4	High	2	Moderate	3	14
Herring gull	Very low	5	Very low	5	Moderate	3	Very high	1	14
Lesser black-backed gull	Very low	5	Very low	5	Moderate	3	Very high	1	14
Northern gannet	Very low	5	Very low	5	High	2	High	2	14
Red-throated diver	Low	4	Low	4	High	2	Low	4	14
Common scoter	Low	4	Very low	5	Low	4	High	2	15
Atlantic puffin	Moderate	3	Moderate	3	Very low	5	Very low	5	16
Razorbill	Low	4	Very low	5	Very low	5	Low	4	18
Common guillemot	Low	4	Very low	5	Very low	5	Very low	5	19

increased in vulnerability to displacement by wind farms but decreased in vulnerability to collision with offshore wind turbines; cormorant species decreased in vulnerability to displacement but increased in vulnerability to collision; and auks species, including common guillemot *Uria aalge*, razorbill *Alca torda* and Atlantic puffin *Fratercula arctica*, were ranked as more vulnerable to displacement.

4. Discussion

Uncertainty associated with data used to calculate vulnerability indices is not always presented but is vital to make useful predictions. This study used Furness et al. [3,4] to develop novel methods to demonstrate uncertainty associated with vulnerability indices. This was achieved by assigning uncertainty to four measures of vulnerability for 38 Scottish seabird species to highlight where evidence supporting vulnerability rankings is more robust, where caution in interpreting results may be required, and where additional monitoring and research would be beneficial. The study also consolidates data from Furness et al. [3,4] with recent findings to consider developments in understanding how seabirds respond to MREDs and to present up-to-date vulnerability predictions.

4.1. Uncertainty indices

Being transparent and explicit about uncertainty is important to ensure consistent consideration of uncertainty inherent in vulnerability rankings. In assigning uncertainty to measures of vulnerability, this study identifies areas lacking data and highlights where caution in interpreting vulnerability index results should be adopted.

Results indicate greater uncertainty in data regarding displacement caused by vessels and/or helicopters, and use of tidal races by seabirds, than in data regarding the percentage of flight overlapping with wind turbine blades and the level of displacement caused by structures. This is because the offshore wind industry has developed more rapidly than other technologies [25] and establishing a level of collision and displacement caused by structures is a key component to gaining consent. As such, more data exist relating to these factors; particularly regarding seabird flight altitudes (Supplementary Tables 2–5). Results also indicate varying uncertainty associated with vulnerability rankings among species. For example, white-tailed eagles were ranked as the species most vulnerable to collision with wind turbines, whilst lesser black-backed gulls *Larus fuscus* were ranked as the second most vulnerable species (Supplementary Table 6). The uncertainty indices indicate that white-tailed eagles have a 'very high' level of uncertainty (score 1) associated with data informing the percentage of time spent overlapping with wind turbine blades, whilst lesser black-backed gull data are associated with a 'very low' level of uncertainty (score 5). These differing uncertainty levels are a result of varying data quality, quantity and relevance: with data on flight altitudes for white-tailed eagle originating from two studies undertaken at two terrestrial wind farms, compared with 35 studies undertaken at 28 different sites for lesser black-backed gull (Supplementary Table 2). This example indicates the importance of being explicit about uncertainty inherent in vulnerability indices to highlight where caution in interpreting rankings might be required and where estimates are more robust. Those areas highlighted as lacking in data would particularly benefit from additional monitoring and research to improve predictions of how seabirds may be affected by MREDs.

Species may lack data for several reasons: 1) they may be uncommon and rarely recorded; 2) they may be difficult to detect (e.g. small species like storm petrels); 3) they may be active during sea states incompatible with surveying (e.g. shearwaters in conditions above Beaufort sea state 4); or 4) they may be absent from MRED sites because they do not occur there (e.g. coastal species at offshore wind farms). For example, rare species associated with high uncertainty caused by a lack of observations may be highly vulnerable to potential impacts of MREDs because they come from small populations. Conversely, species absent from MRED sites could be associated with high uncertainty but may not be vulnerable to MREDs. It is important to distinguish why species might be associated with high uncertainty to ensure appropriate monitoring efforts.

4.2. Vulnerability indices

Species rankings remained broadly the same following revision and recalculation of the Furness et al. [3,4] vulnerability indices (Supplementary Tables 6–9). Recently available data (see Supplementary Reference List for sources) tended to support previous scores rather than alter them, which gives confidence in the approach and the broad rankings of species' vulnerabilities used.

In some cases, vulnerability rankings did alter. For example, vulnerability of Northern gannets to collision with wind turbines decreased (Supplementary Table 1). This is attributed to the modified calculation that separately scores vulnerability to i) structures and ii) vessel and helicopter traffic (Eq. (4)) rather than combining the two potential threats. The modification incorporates new evidence that some species respond differently to structures than to vessels and/or helicopters; for example, gannets are displaced by structures (therefore reducing their risk of collision) but show little response to vessels and helicopters [12,23,24].

For some species, predicted vulnerability to wind farms increased. European shags *Phalacrocorax aristotelis*, great cormorants *Phalacrocorax carbo* and some tern species increased in vulnerability to collision with wind turbines because of evidence indicating attraction to wind farms; potentially for foraging or roosting opportunities [10,11,23,24] (Supplementary Table 1). Common guillemots, razorbills and Atlantic puffins increased in vulnerability to displacement caused by wind farms, as recent evidence indicates auks are displaced by structures and vessels [12,23,24] (Supplementary Table 2). Gannets also increased in their vulnerability to displacement caused by wind farm structures but were not ranked as highly vulnerable to overall displacement caused by wind farms because of their large foraging ranges (Supplementary Table 7) and the comparably small area of habitat loss represented by a single wind farm. However, displacement caused by wind farms could prove a greater issue for gannets, and other species, if the cumulative effects of several installations throughout foraging ranges are considered. In this study, vulnerability indices could not take into consideration cumulative effects, or assess differences in seabird vulnerability to MREDs based on seasonality and life stage, but these issues should be borne in mind when applying the results of vulnerability indices, and should be considered at a site-specific level.

5. Conclusion

These uncertainty indices present vital information for the application of vulnerability indices ranking seabird vulnerability to MREDs. Uncertainty measures can inform MRED impact assessment processes by identifying species of potential concern that lack data, and contribute to identifying post-consent monitoring and strategic research priorities. The combined uncertainty and vulnerability indices could be employed to complement MRED site characterisation and inform sectoral plans by identifying areas supporting species that may be sensitive to MREDs. Given the evolving understanding of species' responses to MREDs, these indices should be viewed as a work in progress and would benefit from regular consolidation with new information.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.marpol.2016.04.045.

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