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

3

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17 Highlights

- 18 • Variable amounts of information affect certainty of renewables impacts on seabirds.
- 19 • There is uncertainty around displacement of seabirds by vessels and helicopters.
- 20 • There is uncertainty around the use of tidal races by seabirds.
- 21 • Displacement by structures and flight around turbines are better understood.
- 22 • Uncertainty indices can be used to inform decision making processes.

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32 Abstract

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

48

49 Keywords: wave energy, offshore wind, tidal energy, shipping, collision, displacement.

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63 1. Introduction

64 Marine renewable energy developments (MREDs) are increasing worldwide to provide an
65 alternative to fossil fuels, increase energy security and mitigate against climatic change (Gill,
66 2005; Grecian et al., 2010; Scottish Government, 2011). Scotland has valuable marine
67 renewable energy resources (ABP Marine Environmental Research, 2008; Shields et al.,
68 2009) and has developed a marine plan, including offshore wind, wave and tidal-stream
69 technologies, to contribute to generating 100% of Scotland's electricity through renewable
70 sources by 2020 (Scottish Government, 2011). Scotland is internationally important for
71 seabirds (Forrester and Andrews, 2007; Mitchell et al., 2004), with special protection areas
72 (SPAs) designated to safeguard breeding colonies (JNCC, 2014; Scottish Government, 2013;
73 Scottish Natural Heritage et al., 2014). With several leased and proposed Scottish MRED
74 sites located close to SPAs for breeding seabirds, consideration of the potential
75 consequences for seabirds is necessary.

76

77 The effects of MREDs on seabirds are uncertain because of the relative infancy of the
78 industry, the early stage of some environmental monitoring programmes (Witt et al., 2012)
79 and a limited ability to effectively monitor post-construction effects (Maclean et al., 2014,
80 2013; MMO, 2014). Uncertainty over effects can delay the consenting process as regulators
81 adopt a precautionary approach (Masden et al., 2015); for example, by using avoidance
82 rates that may overestimate collision risk. In the absence of information regarding specific
83 effects of MREDs on seabirds, a common approach is to use existing knowledge of seabird
84 behaviour and ecology to derive estimates of seabird vulnerability (e.g. Furness et al., 2012,
85 2013; Garthe and Hüppop, 2004). Uncertainty in the contributing data is, however, rarely
86 presented, but is vital information, as the reliability of results and confidence in
87 interpretations can be affected by the quality, quantity and relevance of contributing data
88 (Masden et al., 2015). These measures of data uncertainty identify where evidence
89 supporting vulnerability rankings is more robust; where caution in interpreting results may
90 be required; and where additional monitoring and research could prove beneficial (Thaxter
91 et al., 2012).

92

93 Using Furness et al. (2012, 2013) as examples, this study developed novel methods to
94 incorporate uncertainty into indices ranking the vulnerability of Scottish seabird populations

95 to MREDs. Furness et al. (2012, 2013) developed four indices ranking vulnerability to i)
96 collision with offshore wind turbines, ii) displacement caused by offshore wind farms, iii)
97 wave energy, and iv) tidal-stream energy developments. These indices have been used by
98 MRED regulators and developers during initial scoping and impact assessment (e.g. JNCC,
99 2015) but measures of uncertainty in data contributing to rankings were not explicitly
100 included. This study develops uncertainty indices to aid transparent and consistent
101 application of vulnerability index predictions. Recently available data were consolidated
102 with information in Furness et al. (2012, 2013), to account for new developments in our
103 understanding of how seabirds respond to i) structures and ii) vessels and helicopters, and
104 to incorporate a reduced risk of collision with offshore wind turbines for species displaced
105 by structures. The development of uncertainty indices and modified vulnerability indices
106 more accurately represent the risks posed by MREDs to seabirds.

107

108 2. Methods

109 2.1 Calculating uncertainty

110 Four vulnerability factors were identified as important in driving seabird vulnerability to
111 MREDs (Furness et al., 2012, 2013): i) percentage of flight overlapping with wind turbine
112 blades, ii) displacement caused by structures, iii) displacement caused by vessels and/or
113 helicopters, and iv) use of tidal races. The quality, quantity and relevance of data
114 contributing to these factors were assessed for each of 38 Scottish seabird species to
115 estimate data uncertainty (see Supplementary Table 1 for scientific names). Data
116 uncertainty was assessed using five criteria, with greater scores reflecting a greater quantity
117 and quality of data, and therefore indicating lower levels of uncertainty:

118

119 1) **Species Score:** Did data refer to the target species or a related species? Species
120 were scored 3 if $\geq 50\%$ of data sources referred to the target species, 2 if data
121 referred to a related species or to higher taxa, and 1 if no published data were
122 available.

123 2) **Number of Sites:** How many sites contributed data?

124 3) **Number of Studies:** How many studies are included?

125 4) **Mean Years:** What was the mean period of years over which data were collected?

126 5) **Method Score:** What level of uncertainty was associated with the methods used to
 127 collect data? For a full explanation of the Methods Score, Method Categories and
 128 associated Uncertainty Levels see Section 2.1.1 and Table 1.

129
 130 The five criteria scores derived for each species, in each vulnerability factor, are shown in
 131 Supplementary Tables 2-5.

132

Vulnerability factor	Vulnerability factor attributes	Uncertainty Level (Uncertainty Scores)				
		Very high (1)	High (2)	Moderate (3)	Low (4)	Very low (5)
<i>% time flying at turbine height</i>	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
<i>Disturbance by structures</i>	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
<i>Disturbance by vessel and/or helicopter activity</i>	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
<i>Use of tidal races</i>	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

133

134 **Table 1.** Uncertainty Levels and Scores indicating the level of uncertainty associated with
 135 data contributing to species vulnerability rankings. Five categories with associated ranking
 136 scores indicate the level of uncertainty: very high (score 1), high (score 2), moderate (score

137 3), low (score 4) and very low uncertainty (score 5). Capital letters in brackets refer to the
138 Method Categories included in Equations 1 and 2. The table indicates the Uncertainty Level
139 and Score assigned to each Method Category and outlines the range of values included in
140 the Combined Score at each Uncertainty Level, which differs among vulnerability factors.
141 Greater scores reflect a greater quantity and quality of data, and therefore correspond to
142 lower levels of uncertainty.

143

144 2.1.1 Method Score

145 To generate a Method Score for each species, in each vulnerability factor, the number of
146 studies in each Method Category (with different Method Categories considered relevant for
147 the four vulnerability factors; Table 1) were multiplied by the Uncertainty Score under which
148 the Method Category was located (Table 1). Greater weight was given to studies using more
149 reliable and robust methods; for example, before-after-control-impact studies and studies
150 collecting data on flight altitudes using bird-borne GPS devices. These more reliable
151 methods were associated with greater scores to reflect a greater quality of data, and
152 therefore a corresponding lower Uncertainty Level (Table 1; Equations 1 and 2). The
153 Method Score reflects the reliability of the methods used in all studies considered for each
154 species in each vulnerability factor, and the uncertainty inherent in those data. Equation 1
155 was used to calculate uncertainty associated with each species in the vulnerability factors
156 ‘percentage of flight overlapping with wind turbine blades’, and ‘use of tidal races’.
157 Equation 2 was used to calculate uncertainty associated with each species in the
158 vulnerability factors ‘displacement caused by structures’ and ‘displacement caused by
159 vessels and/or helicopter activity’. The letters in Equations 1 and 2 represent the number of
160 studies considered within each corresponding Method Category, and the numbers
161 represent the Uncertainty Score associated with those Method Categories (Table 1). The
162 different equations account for the different methods used to collect data pertaining to the
163 four vulnerability factors (Table 1).

164

$$165 \text{ Method Score} = (A) + (B \times 2) + (C \times 3) + (D \times 4) + (E \times 5) \quad \text{Equation 1.}$$

166

$$167 \text{ Method Score} = (A) + (B \times 2) + (C \times 3) \quad \text{Equation 2.}$$

168

169 2.1.2 Combined Score

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

173

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

175

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

186

187 In this paper, the term 'uncertainty' refers to the level of confidence in the data used to
188 derive vulnerability rankings; based on the quality, quantity and relevance of that data. The
189 Uncertainty Categories and Scores presented are generated based only on the data
190 considered in this study (see Supplementary Material for data sources) and provide a
191 relative estimation of uncertainty inherent in the data considered in each of the four
192 vulnerability factors. Uncertainty Categories and Scores are measured on an ordinal scale;
193 which means that the categories are ordered according to numerical values but that the
194 numerical quantities represented by those values have no significance beyond allowing a
195 ranking to be established. The Uncertainty Scores are labels that represent a categorical
196 order and do not represent any concept of equal interval between categories. Uncertainty
197 Categories and Scores do not represent an absolute scale and should not be taken to
198 suggest that additional data collection may not be beneficial, even for those species
199 associated with very low uncertainty. For example, if results indicated a very low
200 uncertainty surrounding a particular species' flight altitude because of a large quantity of

201 data available for that species, there may still be a poor understanding of the influence of
202 different behaviour or weather conditions on flight height. As such, additional data
203 collection could prove beneficial, as a better understanding of flight altitude would improve
204 collision risk estimations.

205

206 2.2 Modification of vulnerability indices

207 2.2.1 Differing responses to structures and vessels and/or helicopters

208 Developments in understanding how seabirds respond to MREDs indicate that some species
209 (e.g. gannets) react differently to structures (e.g. offshore wind turbines) than to vessels and
210 helicopters. This study modifies methods presented in Furness et al. (2012, 2013) to
211 separately rank species according to vulnerability to i) structures, and ii) vessels and/or
212 helicopters; rather than present a combined vulnerability factor. Greater weighting was
213 applied to displacement/disturbance caused by structures (a) than to
214 displacement/disturbance caused by vessels and/or helicopters (b) when calculating
215 vulnerability to displacement/disturbance caused by offshore wind farms (Equation 4). This
216 incorporates a likely greater influence of permanent structures over transient vessel and
217 helicopter traffic. A measure of habitat specialisation (c) and a species conservation score
218 (see Furness et al., 2012, 2013) were included (Equation 4).

219

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

220

Equation 4.

221

222 2.2.2 Reduced risk of collision if displaced by structures

223 Birds avoiding and/or displaced by structures reduce their risk of collision. This study
224 modifies the Furness et al. (2013) calculation ranking seabird vulnerability to collision with
225 offshore wind turbines by dividing the time spent at altitudes overlapping with turbine
226 blades (d) by the level of displacement caused by structures (a) to incorporate this. Flight
227 agility, percentage of time spent in flight, nocturnal flight activity (Y) and a species
228 conservation score (see Furness et al., 2012, 2013) were included (Equation 5).

229

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

231

232 All four vulnerability indices presented in Furness et al. (2012, 2013) were recalculated
233 following modification of index calculations and inclusion of new data (see Supplementary
234 Tables 6-9 and Supplementary Reference List).

235

236 3. Results

237 3.1 Calculating uncertainty

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

248

249 3.2 Modification of vulnerability indices

250 Overall seabird vulnerability rankings remained broadly the same, with only minor changes,
251 following modification and recalculation of the four vulnerability indices presented in
252 Furness et al. (2012, 2013) (Supplementary Tables 6-9). Northern gannets *Morus bassanus*
253 increased in vulnerability to displacement by wind farms but decreased in vulnerability to
254 collision with offshore wind turbines; cormorant species decreased in vulnerability to
255 displacement but increased in vulnerability to collision; and auks species, including common
256 guillemot *Uria aalge*, razorbill *Alca torda* and puffin *Fratercula arctica*, were ranked as more
257 vulnerable to displacement.

258

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

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

266

267 4. Discussion

268 Uncertainty associated with data used to calculate vulnerability indices is not always
269 presented but is vital to make useful predictions. This study used Furness et al. (2012, 2013)
270 to develop novel methods to demonstrate uncertainty associated with vulnerability indices.
271 This was achieved by assigning uncertainty to four measures of vulnerability for 38 Scottish
272 seabird species to highlight where evidence supporting vulnerability rankings is more
273 robust, where caution in interpreting results may be required, and where additional
274 monitoring and research would be beneficial. The study also consolidates data from
275 Furness et al. (2012, 2013) with recent findings to consider developments in understanding
276 how seabirds respond to MREDs and to present up-to-date vulnerability predictions.

277

278 4.1 Uncertainty indices

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

283

284 Results indicate greater uncertainty in data regarding displacement caused by vessels
285 and/or helicopters, and use of tidal races by seabirds, than in data regarding the percentage
286 of flight overlapping with wind turbine blades and the level of displacement caused by
287 structures. This is because the offshore wind industry has developed more rapidly than
288 other technologies (Witt et al., 2012) and establishing a level of collision and displacement
289 caused by structures is a key component to gaining consent. As such, more data exist
290 relating to these factors; particularly regarding seabird flight altitudes (Supplementary

291 Tables 2-5). Results also indicate varying uncertainty associated with vulnerability rankings
292 among species. For example, white-tailed eagles *Haliaeetus albicilla* were ranked as the
293 species most vulnerable to collision with wind turbines, whilst lesser black-backed gulls
294 *Larus fuscus* were ranked as the second most vulnerable species (Supplementary Table 6).
295 The uncertainty indices indicate that white-tailed eagles have a 'very high' level of
296 uncertainty (score 1) associated with data informing the percentage of time spent
297 overlapping with wind turbine blades, whilst lesser black-backed gull data are associated
298 with a 'very low' level of uncertainty (score 5). These differing uncertainty levels are a result
299 of varying data quality, quantity and relevance: with data on flight altitudes for white-tailed
300 eagle originating from two studies undertaken at two terrestrial wind farms, compared with
301 35 studies undertaken at 28 different sites for lesser black-backed gull (Supplementary
302 Table 2). This example indicates the importance of being explicit about uncertainty inherent
303 in vulnerability indices to highlight where caution in interpreting rankings might be required
304 and where estimates are more robust. Those areas highlighted as lacking in data would
305 particularly benefit from additional monitoring and research to improve predictions of how
306 seabirds may be affected by MREDs.

307

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

318

319 4.2 Vulnerability indices

320 Species rankings remained broadly the same following revision and recalculation of the
321 Furness et al. (2013, 2012) vulnerability indices (Supplementary Tables 6-9). Recently
322 available data (see Supplementary Reference List for sources) tended to support previous

323 scores rather than alter them, which gives confidence in the approach and the broad
324 rankings of species' vulnerabilities used.

325

326 In some cases, vulnerability rankings did alter. For example, vulnerability of northern
327 gannets to collision with wind turbines decreased (Supplementary Table 1). This is
328 attributed to the modified calculation that separately scores vulnerability to i) structures
329 and ii) vessel and helicopter traffic (Equation 4) rather than combining the two potential
330 threats. The modification incorporates new evidence that some species respond differently
331 to structures than to vessels and/or helicopters; for example, gannets are displaced by
332 structures (therefore reducing their risk of collision) but show little response to vessels and
333 helicopters (Leopold et al., 2013; Vanermen et al., 2013; Walls et al., 2013).

334

335 For some species, predicted vulnerability to wind farms increased. European shags
336 *Phalacrocorax aristotelis*, great cormorants *Phalacrocorax carbo* and some tern species
337 increased in vulnerability to collision with wind turbines because of evidence indicating
338 attraction to wind farms; potentially for foraging or roosting opportunities (Krijgsveld et al.,
339 2011; Leopold et al., 2011; Vanermen et al., 2013; Walls et al., 2013) (Supplementary Table
340 1). Common guillemots, razorbills and Atlantic puffins increased in vulnerability to
341 displacement caused by wind farms, as recent evidence indicates auks are displaced by
342 structures and vessels (Leopold et al., 2013; Vanermen et al., 2013; Walls et al., 2013)
343 (Supplementary Table 2). Gannets also increased in their vulnerability to displacement
344 caused by wind farm structures but were not ranked as highly vulnerable to overall
345 displacement caused by wind farms because of their large foraging ranges (Supplementary
346 Table 7) and the comparably small area of habitat loss represented by a single wind farm.
347 However, displacement caused by wind farms could prove a greater issue for gannets, and
348 other species, if the cumulative effects of several installations throughout foraging ranges
349 are considered. In this study, vulnerability indices could not take into consideration
350 cumulative effects, or assess differences in seabird vulnerability to MREDs based on
351 seasonality and life stage, but these issues should be borne in mind when applying the
352 results of vulnerability indices, and should be considered at a site-specific level.

353

354 5 Conclusion

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

364

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371

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