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1 **Assessing the vulnerability of the marine bird community in the western North Sea to climate**
2 **change and other anthropogenic impacts**

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10

1 **ABSTRACT**

2 Ocean warming and anthropogenic activities such as fishing, shipping and marine renewable developments,
3 are affecting marine top predators. Research has focussed on the impacts of single stressors on single
4 species, yet understanding cumulative effects of multiple stressors on communities is vital for effective
5 conservation management. We studied a marine bird community (45 species; 11 families) utilising the Forth
6 and Tay region of the North Sea for breeding, overwintering or migration between 1980 and 2011. Local sea
7 surface temperatures (SST) increased significantly over this period, with concomitant changes in marine
8 communities. Simultaneously, the region has been subject to fishing pressure and shipping disturbance and is
9 a priority area for renewable energy developments. We used colony-based and at-sea data to quantitatively
10 assess relationships between SST and counts, productivity and survival of 25 species for which sufficient
11 data were available for analysis. For the remaining species, we applied a qualitative approach using
12 published population trends, published climate relationships and foraging sensitivity. In total, 53% of species
13 showed negative relationships with SST. Trends in counts and demography were combined with climate
14 vulnerability to give an index of population concern to future climate warming, and 44% of species were
15 classified as high or very high concern, notably cormorants, grebes, skuas, shearwaters, terns and auks, as
16 well as species breeding in the region. Qualitative assessments of vulnerability to fisheries, pollutants,
17 disturbance (including introduced predators), marine renewables and climate found that 93% of species were
18 vulnerable to ≥ 2 threats, and 58% to ≥ 4 . Our results indicate that the majority of birds in this region of the
19 North Sea face an uncertain future, potentially threatening the resilience of this important marine bird
20 community.

21

22 **Keywords:**

23 Global warming, marine renewables, European Birds Directive, seabird, fisheries, SST, resilience,
24 demography

25

26

1 INTRODUCTION

2 Global climate change is altering the physiology, phenology, abundance and distribution of
3 species, resulting in dramatic changes in ecosystem structure (McCarty 2001, Walther et al. 2002,
4 Thackeray et al. 2010). Warming of the oceans is evident throughout the globe (Levitus et al. 2000,
5 Gille 2002) with a higher pace of climate change in the ocean than on land (Burrows et al. 2011,
6 Poloczanska et al. 2013). Increased sea temperatures have already had significant impacts on
7 marine ecosystems (Harley et al. 2006, Parry 2007, Alheit 2009), modifying water stratification and
8 nutrient availability (Sathyendranath et al. 2001, Hays et al. 2005), with associated effects on the
9 distribution, abundance and population dynamics of phytoplankton, zooplankton and mid-trophic
10 level fish (Beaugrand et al. 2002, Edwards et al. 2002, Hays et al. 2005, Perry et al. 2005,
11 Behrenfeld et al. 2006, Brander 2007, van Deurs et al. 2009, Ottersen et al. 2013). Marine top
12 predators are vulnerable to bottom up effects of climate change operating through lower trophic
13 levels (Frederiksen et al. 2006, Stige et al. 2010, Schwarz et al. 2013, Springer & van Vliet 2014).
14 Globally, there is extensive evidence that marine bird species are experiencing predominantly
15 negative impacts of climate change operating indirectly on prey species (Votier et al. 2005, Lee et
16 al. 2007, Monticelli et al. 2007, Grémillet & Boulinier 2009, Sydeman & Bograd 2009, Lehikoinen
17 et al. 2013, Paiva et al. 2013). Furthermore, climate projections indicate that sea temperatures will
18 continue to increase globally throughout the 21st century (Parry 2007).

19 Marine systems are also subject to a wide variety of other anthropogenic pressures acting
20 simultaneously with climate warming, most notably fisheries, introduced predators and pollution
21 (Halpern et al. 2007). Such anthropogenic pressures may intensify in the future, due to increased
22 exploitation associated with human population growth (Sanderson et al. 2002). Furthermore, a large
23 expansion of marine renewable developments is underway, potentially placing additional pressure
24 on marine ecosystems, particularly in coastal areas. The cumulative effects of multiple stressors,
25 and in particular how they interact, are generally poorly understood (Sala et al. 2000, Moller 2013).
26 A recent review of experimental manipulations of multiple stressors in marine environments
27 concluded that overall interactions tended to be synergistic, suggesting this may be common in the
28 wild (Crain et al. 2008). For marine top predators, there is some evidence that interactions between
29 climate and other threats may be additive (Frederiksen et al. 2004, Votier et al. 2005, Ainley &
30 Blight 2009). However, most studies have tended to consider the impacts of single stressors on
31 single species at certain times of the year, and hence may be unrepresentative of the suite of
32 pressures that top predator communities are experiencing over the annual cycle. Since many marine
33 bird populations are of conservation concern (Croxall et al. 2012), community wide approaches that
34 consider responses to multiple threats, including climate change, are critical in order to provide a
35 comprehensive evaluation of vulnerability and to provide a baseline from which to assess future
36 changes and inform management practices such as marine spatial planning (Grandgeorge et al.
37 2008).

38 Here, we evaluate vulnerability of a marine bird community in the Forth and Tay coastal
39 region of the western North Sea, UK to climate and other anthropogenic threats, using data on
40 counts and demographic rates (productivity and adult survival) from 1980 and 2011. This
41 internationally important bird community comprises breeding, wintering and migrating birds from
42 12 different families (Anatidae, Gaviidae, Procellariidae, Hydrobatidae, Sulidae, Phalacrocoracidae,
43 Podicepedidae, Scolopacidae, Stercorariidae, Laridae, Sternidae and Alcidae). Sea temperatures in

1 the North Sea have increased significantly since the 1970s (Edwards et al. 2006), particularly
2 following a major regime shift in the late 1980s (Beaugrand 2004). Associated with this warming
3 there have been profound and sustained changes in distribution and abundance of plankton and fish
4 (Edwards et al. 2002, Perry et al. 2005, Lindley et al. 2010, Frederiksen et al. 2013). Several long-
5 term datasets on marine bird abundance and demography have been collected over this period, and
6 previous studies have shown that some species are sensitive to indirect effects of climate change
7 (Frederiksen et al. 2007, Frederiksen et al. 2008, Burthe et al. 2012, Luczak et al. 2012). The North
8 Sea is currently under intense pressure from multiple anthropogenic threats. It is one of the most
9 heavily fished areas of the world, traditionally supporting a range of fish and shellfish fisheries
10 (Worm et al. 2009). Furthermore, a large expansion of marine renewable developments is proposed
11 for the region (Marine Scotland 2011). Therefore, there is an urgent need to quantify the
12 vulnerability of this marine bird community to these multiple anthropogenic threats. Two studies
13 have undertaken qualitative assessments of vulnerability of a subset of this bird community to
14 specific threats. Furness and Tasker (2000) used species foraging strategies to classify those that
15 were potentially vulnerable to climate induced changes in sandeel prey availability. More recently,
16 Furness et al. (2013) evaluated the vulnerability of species to collision and displacement associated
17 with the development of marine renewables in the region. Here, we consider a wider community of
18 species and larger suite of anthropogenic threats, and undertake quantitative assessments of climate
19 impacts. This study is the first, to our knowledge, to assess the vulnerability of a marine bird
20 community to indirect effects of climate change and other anthropogenic pressures including
21 fisheries, disturbance, development of offshore wind farms and pollution. We aimed to determine
22 which species and families are most vulnerable to climate change and multiple threats in this region,
23 and provide an overall assessment of the vulnerability of the marine bird community to future
24 climate warming.

25

26 **METHODS**

27 **STUDY SPECIES AND DATA COVERAGE**

28 We focused on the Forth and Tay region, East Scotland (Figure 1). This region is important for a
29 wide range of marine bird species throughout the year, supporting nationally and internationally
30 important populations of summer visitors, migrants, breeding and overwintering species (Söhle et
31 al. 2007, JNCC 2013). We extracted data for the 45 marine bird species from 11 families protected
32 by the European Birds Directive 79/409/EEC because they are listed in Annex 1 or because they are
33 regularly occurring migratory species, and for which data were available for the western North Sea
34 (Lack 1986, Mitchell et al. 2004, Forrester et al. 2007, Worm et al. 2009) (see Table S1 in
35 supplementary information for details). Data were obtained from 4 sources: the European Seabirds
36 at Sea database (ESAS); the Seabird Monitoring Programme (SMP); the Wetlands Bird Survey
37 (WeBS); and the Isle of May Long-term Study (IMLOTS). We focused analyses on the period
38 between 1980 and 2011 as prior to this many data sets were too sparse.

39 ***ESAS data***

40 The ESAS database is a collaborative scheme managed by the Joint Nature Conservation
41 Committee (JNCC; <http://jncc.defra.gov.uk/page-4469>) and contains data on the distribution and

1 abundance of seabirds in European waters recorded during ship and aerial surveys. Data were
2 extracted for an area of the western North Sea between 55° - 58°N and 4°W - 0°E (Figure 1), in
3 order to provide a balance between areas that lie within the foraging range of birds at major
4 breeding sites in the Forth and Tay region and sampling resolution, since data were very sparse for
5 many species. The total area surveyed was 24159 km² (range per season per year: 0-1791km²). Data
6 were collected throughout the year so we considered two seasons in our analysis: summer (April to
7 September) and winter (October to March). The winter season for a particular year consisted of the
8 last three months of the preceding year and first three months of the year in question (e.g. winter
9 1997 included October-December 1996). We analysed counts of birds from aerial and boat based
10 transects, and we included snapshot counts for flying birds, but excluded incidental sightings,
11 presence/absence data and records not identified to species (see Tasker et al. 1984 for detailed
12 methods). For each species, analysis was undertaken on the summed counts in each season in each
13 year, offset by the total area surveyed. ESAS data have limited power for detecting trends in
14 abundance (Maclean et al. 2013). Therefore, we took the following steps to ensure robust analyses.
15 Data per season per species were only analysed if ten or more years of non-zero counts were
16 available. Counts for some species were low and/or contained large single peaks which could have
17 strong leverage in analyses. We therefore excluded data if average counts for a species in a season
18 were <20 birds/100km² or if the time series showed single peaks 5 times greater in size than the
19 average count of the remaining data points. Time series for further analysis were available for 7
20 species: razorbill (*Alca torda*) in summer; herring gull (*Larus argentatus*) and great black-backed
21 gull (*Larus marinus*) in winter; and northern fulmar (*Fulmarus glacialis*), northern gannet (*Morus
22 bassanus*), black-legged kittiwake (*Rissa tridactyla*) and guillemot (*Uria aalge*) in both seasons.

23

24 ***SMP Data***

25 The SMP is a joint scheme managed by JNCC (<http://jncc.defra.gov.uk/page-4460>). The online
26 database contains complete breeding colony censuses or counts of subsets of colonies (plots).
27 Annual estimates of productivity were also available for some colonies (average number of young
28 fledged per Apparently Occupied Nest; see Walsh (1995) for full method details). We included data
29 for all major breeding colonies in the Forth and Tay where data were available for ten or more
30 years, to ensure that sufficient data were available for analyses (Figure 1). In addition, data for the
31 St Fergus gas terminal (120 km north of the northern boundary of our core study area) were
32 included because this was one of the best time series of Arctic tern (*Sterna paradisaea*) and
33 common tern (*Sterna hirundo*) productivity. We also included two major breeding colonies with
34 good quality data (Farne Islands and Fowlsheugh; Figure 1) that were in close proximity to the
35 study area (c40 and c50km to the south and north respectively) and whose birds were likely to be
36 subject to the same local climatic conditions. In the analysis, productivity data were treated as
37 binomial counts, relative to the number of possible chicks per nest based on maximum brood size
38 (Cramp 1977, 1983).

39

40 ***WeBS Data***

1 The Wetland Bird Survey is a joint scheme coordinated by the British Trust for Ornithology,
2 the Wildfowl and Wetlands Trust, the Royal Society for the Protection of Birds and JNCC
3 (<http://www.bto.org/volunteer-surveys/webs/data>). Volunteers undertake monthly land-based counts
4 of birds. Counts are classed as being “good” or “poor” quality, depending on whether the count is
5 regarded as a reliable estimate of the numbers of birds present at a site. We analysed data from four
6 sites (the Forth Estuary, Eden Estuary, Tay Estuary and St Andrews Bay; Figure 1). Data for each
7 species for all sites were examined to establish when the peak count occurred. If there was a clear
8 tendency for peaks to occur in a particular month then years were excluded if data for that month
9 were missing from the dataset or confidence in the count was poor. We analysed the maximum
10 monthly count per site occurring in winter and/or summer. We included sites where data were
11 available for ten or more years, to ensure that sufficient data were available for analyses. We
12 excluded sites where counts were of poor quality, where more than one month out of six was
13 missing, or time series where average counts were <10 birds. Data were available for further
14 analysis from 13 species: 5 in summer, 7 in winter and 1 in both seasons.

15

16 *IMLOTS data*

17 IMLOTS is the long-term study of seabird populations breeding on the Isle of May, south-
18 east Scotland carried out by the Centre for Ecology & Hydrology (CEH)
19 (http://www.ceh.ac.uk/sci_programmes/isleofmaylong-termstudy.html). Annual adult survival
20 estimates were calculated for five species between 1986 and 2009 (see Frederiksen et al. 2004,
21 Harris et al. 2005 and Frederiksen et al. 2008 for details): black-legged kittiwake; razorbill;
22 guillemot; Atlantic puffin (*Fratercula artica*) and European shag (*Phalacrocorax aristotelis*). M-
23 arrays of recaptures for each cohort of ringed birds were used to calculate Jolly-Seber survival
24 estimates per year and species between 1986 and 2009 (see Lebreton et al. 1992 for details).

25

26 *Environmental Data*

27 Monthly average SST data were obtained from NOAA Pathfinder version 5.0 (Kilpatrick et
28 al. 2001) for the same area as the ESAS data (55° - 58°N, 4°W - 0°E). We analysed annual mean
29 values across this area for the following seasons: winter (December, January, February); spring
30 (March, April, May); summer (June, July, August) and autumn (September, October, November).
31 SST values were generally not highly correlated between seasons except for winter vs spring and
32 summer vs autumn (correlation coefficients: winter vs spring= 0.80; spring vs summer= 0.51;
33 spring vs autumn= 0.50; summer vs autumn= 0.80; summer vs winter=0.39; autumn vs
34 winter=0.60). Previous research has found correlations between SST lagged by one year and seabird
35 productivity indicative of indirect effects of climate (Frederiksen et al. 2007, Burthe et al. 2012).
36 We therefore considered SST lagged by up to two years in our analysis.

37

38 **STATISTICAL ANALYSIS**

39 *Relationships with climate*

1 We examined whether each data series was correlated with climate by regressing each time
2 series against current and lagged SST. Fifteen measures of SST were considered: spring, summer,
3 autumn, winter and annual (January to December) mean SST values for the current year and for
4 each of the previous two years. The same model structures were used as for the temporal trends
5 (GLMMs fitted in glmmPQL incorporating an AR(1) correlation structure). As time series were
6 generally limited in length, we only fitted one climate term at a time to avoid overparameterisation
7 of models. Tables of model results for relationships with climate and trends are provided in the
8 supplementary information (Tables S2-S7).

9 *Temporal trends*

10 We analysed trends in SST and in count and demography (productivity and survival) data
11 separately for each data source and, where appropriate, season for each species. For each
12 combination the relationship with year was analyzed using a generalized linear mixed model
13 (GLMM). Count data were modeled with a Poisson distribution and productivity and survival data
14 with a binomial distribution. GLMMs were run using the glmmPQL function in the MASS package
15 in program R (Venables et al. 2002) because this automatically adjusts for overdispersion, if
16 present, and because it enabled us to include an AR(1) correlation structure in all models in order to
17 account for temporal autocorrelation. Site was included as a random effect when analyzing WeBS
18 count data for species with data from multiple estuaries/bays, and colony was included as a random
19 effect when analyzing SMP count and productivity data for species with data from multiple
20 colonies. Hence, models provide an estimate of overall trends rather than site-specific estimates. For
21 other data, a redundant random effect with a single category was included. This redundant random
22 effect had a variance of zero but including it in the model allowed us to fit the models as GLMMs
23 rather than GLMs, and so allowed us to include AR(1) correlation structure. For the ESAS data, the
24 logarithm of total area surveyed was included as an offset in all models. Visual examination of bird
25 time series suggested that some may have exhibited non-linear trends. For these, we confirmed that
26 a model fitted with year as a quadratic term was not better than a model fitted with year as a linear
27 term. Detrending of the data was not undertaken in this analysis because we were primarily
28 interested in constructing an index that represents the risk to a species within a changed climate and
29 the index of risk includes both the relationship with climate and trend in time as separate
30 components. Constructing a meaningful index using a detrending approach would be difficult
31 because robust projections for how de-trended climate variables will change in future are not readily
32 available.

33

34 **ASSESSING VULNERABILITY TO CLIMATE AND OTHER IMPACTS**

35 *Quantitative assessment of vulnerability*

36 An index of vulnerability to climate was constructed based on the statistical analysis of
37 relationships with climate and trends in counts and/or demographic rates. In total, 25 species had
38 sufficient data for quantitative analysis.

39 For each species, we synthesised the relationships with climate to assign climate vulnerability in
40 two steps. First, for each particular combination of data source and season, we assessed whether
41 relationships with climate were consistently in one direction (positive, no relationships or negative).

1 Our criteria for consistency where models were significant (positive or negatively related to
2 climate) were that at least two models were significant and that 75% of significant models had
3 relationships in the same direction. Relationships that could not be classed as either consistently
4 positive or consistently negative (<2 models were significant) were considered to show no
5 relationship with climate. This approach used all fifteen climate variables in determining whether
6 there was evidence for a relationship with climate, rather than attempting to interpret each of the
7 fifteen relationships individually, so no explicit adjustment for multiple testing was required.
8

9 In a second step, we synthesised these data source/season level results into an overall index of
10 climate vulnerability for the species, as follows:

- 11 1. **Positive response to climate change:** counts or demographic rates showing positive
12 relationships with climate (counts or demographic rates increase with warmer SST)
- 13 2. **No response to climate change:** counts or demographic rates showing no
14 relationships with climate
- 15 3. **Negative response to climate change:** counts or demographic rates showing
16 negative relationships with climate (counts or demographic rates decrease with
17 warmer SST)

18

19 For 9 species, there was only 1 data source/season combination available and hence for these
20 species climate vulnerability was based on this single assessment. Multiple data source/season
21 combinations were available for the other 16 species. For two of these, there was no evidence of
22 relationships with climate. In the remaining 14, some data sources showed significant relationships
23 with climate so we assigned vulnerability to climate based on the direction of these relationships,
24 because we cannot exclude the possibility that climate may be accounting for variation in the data
25 for non-relationships. Crucially, however, this approach was balanced with both positive and
26 negative relationship favoured over no response. There were 9 species where one data source
27 showed negative relationships with climate and 3 species where one data source showed positive
28 relationships with climate that overrode data sources for the species showing no relationships with
29 climate. There were 2 species where different data sources showed opposing relationships with
30 climate (common guillemot and razorbill) and these species were therefore qualitatively assessed
31 for climate vulnerability (see next section). Thus, quantitative assessment was undertaken on a total
32 of 23 species.

33 We calculated an index of population concern to future climate warming incorporating two sources
34 of information: the vulnerability to climate index described above (positive, no or negative
35 response) and count/demographic trends (increasing, stable or decreasing). In synthesizing trends,
36 we took a similar approach to climate vulnerability; thus, if multiple data were available and
37 showed evidence of significant trends in some data sources and no trends in others, trends were
38 assigned based on the direction of significant trends. The index of population concern ranged from a
39 score of 0 (very low concern: counts or demographic rates increasing and positive response to
40 climate) to 4 (very high concern: counts or demographic rates decreasing and negative response to
41 climate; Table 1).

42

1 *Qualitative assessment of vulnerability*

2 A qualitative assessment of vulnerability to climate was undertaken for the remaining 22 species.
3 This assessment was carried out by first reviewing published relationships with climate in the
4 literature. These were only available for Manx shearwater (*Puffinus puffinus*), great skua
5 (*Stercorarius skua*), common guillemot and razorbill. Vulnerability for the 19 remaining species
6 was based on the foraging ecology sensitivity index in Furness and Tasker (2000). This index is
7 based on sum of scores (0-4 per category for 6 categories with 4 being the highest in terms of
8 vulnerability to climate induced changes in sandeel prey availability; hence minimum score 0 and
9 maximum of 24) for body size, costs of foraging, foraging range, ability to dive, amount of spare
10 time and ability to switch diet (see Furness and Tasker 2000 and supplementary information for full
11 details).

12 Vulnerability to climate was assigned as follows:

- 13 1. **Positive response or low foraging sensitivity to climate change:** counts or
14 demographic rates showing positive relationships with climate variables or
15 low foraging sensitivity score (<10)
- 16 2. **No response or moderate foraging sensitivity to climate change:** counts or
17 demographic rates showing no relationships with climate variables or
18 medium foraging sensitivity score (10-14)
- 19 3. **Negative response or high foraging sensitivity to climate change:** counts
20 or demographic rates showing negative relationships to climate variables or
21 high foraging sensitivity score (>14)

22 Published population trends (increasing; stable; decreasing; unknown) were combined with the
23 climate vulnerability index to assign an index of population concern to future climate based on the
24 same criteria as for the quantitative assessment (Table 1). In order to be as relevant as possible to
25 the study area, published trend information for Scotland (Perkins et al. 2005, Newson et al. 2008,
26 Dillon et al. 2009, Daunt & Mitchell 2013, JNCC 2013) was used where available (9 species: red-
27 throated diver *Gavia stellata*, Slavonian grebe *Podiceps auritus*, Leach's storm-petrel
28 *Oceanodroma leucorhoa*, Arctic skua *Stercorarius parasiticus*; great skua, common gull *Larus*
29 *canus*, Roseate tern *Sterna dougallii*; common guillemot and razorbill). Data at this scale were not
30 available for Mediterranean gull (*Ichthyaetus melanocephalus*) and population trend data for the
31 UK were used for this species (JNCC 2013). Published population trends were not available for the
32 remaining 12 species. For 11 of these species, we used conservation status (Eaton et al. 2009) with
33 "green" conservation status assumed to be equivalent to increasing populations, "amber" to
34 populations showing no trend, and "red" to declining populations. No information was available for
35 surf scoter (*Melanitta perspicillata*) and this species' index of population concern was scored
36 according to vulnerability to climate.

37

38 *Non-climate threats*

39 We also assessed the vulnerability of species to anthropogenic threats other than climate during the
40 time of year they are present in the Forth and Tay region. Threats from wind farm developments
41 were based on scores presented in Furness et al. (2013). Collision risk was assessed from flight

1 height and agility, the % of time flying and tendency for night flight. Disturbance and displacement
2 was scored based on reaction distances, and flexibility of habitat use. We modified the Furness et al.
3 (2013) scores to make them comparable to our scoring system for climate vulnerability. Species
4 with collision scores <150 were assigned a collision risk score of 1 (low vulnerability), 150-299 as
5 2 (moderate vulnerability) and >299 as 3 (high vulnerability). Displacement or disturbance scores
6 of 0-6 were coded as 1, 7-12 as 2 and >12 as 3. For 7 species not included in Furness et al. (2013),
7 we assigned scores based on those for related species (see Table S9 in supplementary information).

8 We also assessed vulnerability to reduction in fisheries discards, fisheries bycatch,
9 competition with fisheries, oil pollution, contaminants other than oil, plastics, introduced predators
10 (considered to be brown rats (*Rattus norvegicus*), American mink (*Neovison vison*), domestic cats
11 (*Felis catus*) and white-tailed eagles (*Haliaeetus albicilla*) for this study area) and disturbance
12 associated with boats and/or human presence in breeding colonies. Assessment of vulnerability was
13 based on the scoring system in Frederiksen (2010) where vulnerability was scored from 0 (no
14 threat) to 3 (severe threat). Scores were adjusted to have the same scale as our other vulnerability
15 assessments: a score of 0 was coded 1 (low vulnerability); 1 as 2 (moderate vulnerability) and ≥ 2 as
16 3 (high vulnerability). In addition scores for 17 species were modified to take account of local
17 conditions in the Forth and Tay region. Forrester et al. (2007) and our own experience of the species
18 and study area were used to assign vulnerability scores for 20 species not included in Frederiksen
19 (2010). See supplementary information (Table S10) for full details of these scores.

20

21 ***Overall vulnerability to multiple threats***

22 To obtain an overall vulnerability index to multiple threats, we first consolidated the single non-
23 climate threats into four main threats: fisheries (bycatch, discards or competition), pollutants (oil
24 pollution, contaminants and plastics), disturbance (introduced predators, human disturbance in
25 breeding colonies) and wind farms (collision risk, displacement and boat disturbance). For each
26 species, we adopted the highest vulnerability score per individual threat as the score for the
27 representative main threat. We calculated two indices of vulnerability to multiple threats. The first
28 indicated the severity of combined threats by summing the scores of vulnerability indices from each
29 main threat (climate and four non-climate threats). The second index summed the number of main
30 threats a species was vulnerable to: species were considered vulnerable to climate if scored as 3 and
31 vulnerable to other threats if scored as moderate or above (≥ 2). This was justified because the
32 middle category of vulnerability to climate represents no relationships between bird data and
33 climate in the quantitative analysis, whereas for other threats the middle category infers some
34 negative impact or risk.

35 We calculated an overall index of population concern to multiple threats based on vulnerability to
36 multiple threats (not vulnerable: vulnerable to <2 threats; vulnerable: ≥ 2 main threats) and the status
37 of population trends using the following index:

- 38 0. **Very low concern:** population or demographic rates increasing and not vulnerable to
39 multiple threats
- 40 1. **Low concern:** population or demographic rates showing no trend and not
41 vulnerable to multiple threats

- 1 2. **Moderate concern:** population or demographic rates decreasing but not vulnerable
2 to multiple threats; population or demographic rates increasing but vulnerable to
3 multiple threats
- 4 3. **High concern:** population or demographic rates showing no trend and vulnerable to
5 multiple threats
- 6 4. **Very high concern:** population or demographic rates decreasing and vulnerable to
7 multiple threats

8 For 11 species where population trends were not available we based our assessments on the current
9 conservation status (Eaton et al. 2009). Thus we assumed that species with “green” status were the
10 equivalent of increasing populations and “amber” the equivalent of no trends in the designations
11 above. One species (surf scoter) with no population trend or conservation status was assumed to
12 show no trend.

13

14 **RESULTS**

15 **CLIMATE TRENDS**

16 Between 1980 and 2011, SST in the Forth and Tay region increased significantly (mean annual rate
17 0.05°C per year) with the effect apparent in each season of the year (Table 2). This equates to a
18 predicted increase in annual SST in absolute terms of 1.57°C between 1980 and 2010 (1980: 9.04°C
19 $\pm 0.13^{\circ}\text{C}$ S.E.; 2010: $10.61^{\circ}\text{C} \pm 0.12^{\circ}\text{C}$).

20

21 **VULNERABILITY TO CLIMATE AND OTHER IMPACTS**

22 *Quantitative assessment of vulnerability*

23 In total, 25 species had sufficient data to assess relationships with climate and trends in counts
24 and/or demography (productivity or survival). Of these, common guillemot and razorbill showed
25 inconsistent relationships with climate and were therefore assessed qualitatively.

26 Overall, of the 23 remaining species, 13 (57%) showed negative relationships between SST and
27 count or demography data, five species (22%) showed positive relationships and 5 species (22%)
28 showed no relationships.

29 Of the species with count data, 10 showed negative relationships with climate, 7 no relationships, 5
30 positive relationships and 1 inconsistent relationships with climate (European shag; Tables 3 and
31 S2). None of the demographic data showed positive relationships with climate. Of the 10 species
32 with productivity data, 5 showed negative and 5 no relationships with climate (Tables 3 and S3). Of
33 the 5 species with survival data, 3 showed negative relationships with climate and two showed no
34 relationship with climate (Tables 3 and S4).

35 Seven of the 23 species showed significant declines in counts, 12 no trend and 4 significant
36 increases in counts (Table 3 and S5). Two out of 10 species showed significant decreases in
37 productivity and 8 showed no trend (Table 3 and Table S6). Two out of 5 species showed

1 significant declines in survival and 3 showed no trend (Table 3 and Table S7). Five species were of
2 very high population concern to future climate change because they had a negative response to
3 climate and declining population counts or demography: great crested grebe; northern fulmar;
4 European shag; greater scaup and black-legged kittiwake. A further 7 species were considered to
5 have high population concern because they showed a negative response to climate but no trends in
6 population counts or demography: black scoter (*Melanitta americana*); red-breasted merganser
7 (*Mergus serrator*); herring gull; common tern; Arctic tern; little tern (*Sternula albifrons*) and
8 Atlantic puffin. Six species were considered of moderate population concern, 3 of low concern and
9 2 of very low concern (Table 3).

10 ***Qualitative assessment of vulnerability***

11 In the qualitative assessment, 11 species had a climate vulnerability index of 3 (4 species with
12 negative responses to climate and 7 with high foraging sensitivity to climate), 10 species an index
13 of 2 (all with moderate foraging sensitivity to climate) and 1 an index of 1 (low foraging sensitivity
14 to climate; Table 4).

15 Population trend data were available for 10 species, of which 7 declined and 3 increased (Table 4).
16 Based on trends or conservation status combined with climate vulnerability, 5 species were of very
17 high population concern to future climate change (Slavonian grebe; Arctic skua; Roseate tern;
18 common guillemot and razorbill), 3 of high concern (Manx shearwater; black-necked grebe
19 (*Podiceps nigricollis*) and little gull (*Hydrocoloeus minutus*)), 13 of moderate concern, 1 of low
20 concern and none of very low concern (Table 4).

21 ***Non-climate threats***

22 Species were considered to have moderate to high vulnerability to the following non-climate
23 threats: changes to discard policy (15 species), bycatch (18), fisheries competition (17), oil pollution
24 (33), contaminants (8), plastics (5), introduced predators (17), disturbance (18), collision risk from
25 wind farms (27) and displacement from wind farms (21; Table 5).

26 Of the four main threats that were defined by integrating the above single threats (see methods), 35
27 species (78%) were considered to have moderate to high vulnerability to fisheries, 34 (76%) to
28 pollutants, 25 (56%) to disturbance and 39 (87%) to wind farms (Table 6).

29

30 ***Overall vulnerability to climate and multiple threats***

31 A total of 24 species (53%) were considered to have a negative relationship with or high foraging
32 sensitivity to climate (Table 6). Furthermore, 42 (93%) species were considered vulnerable to >1
33 main anthropogenic threat with 8 species considered vulnerable to 5 threats; 18 species to 4 threats;
34 11 to 3 threats, 5 to 2 threats, 2 to 1 threat and 1 to 0 threats (Table 6). Thirteen (29%) species were
35 considered of very high population concern to multiple threats, exhibiting declines in counts or
36 demographic rates in conjunction with vulnerability to multiple threats. A further 21 species (47%)
37 were of high population concern.

38 All of the 24 species in the highest climate vulnerability category were considered to have moderate
39 to high vulnerability to at least 2 other anthropogenic threats. Twelve of these species breed in the

1 Forth and Tay region (8 of which also overwinter there), with a further 5 species overwintering and
2 7 species being migratory or summer visitors to the area (Table 6). Threats were applicable to
3 species present in the region in both the summer and winter (breeding species: 94% vulnerable to
4 fisheries, 67% to pollutants, 89% to disturbance, 94% to wind farms, 67% to climate; overwintering
5 species: 79% to fisheries, 90% to pollutants, 66% to disturbance, 93% to wind farms, 45% to
6 climate).

7 A breakdown of vulnerability to climate and multiple threats by family and main use of the region
8 is provided in Table 7. Cormorants, grebes, skuas, terns and auks had markedly high percentages of
9 species vulnerable to climate and high or very high population concern to future climate warming
10 ($\geq 50\%$ of species for both; Table 7). All families had high vulnerability to multiple threats with
11 ducks, cormorants, grebes, terns and auks of particularly high population concern to multiple threats
12 ($\geq 75\%$ of species; Table 7). Birds breeding in the region were especially vulnerable to climate, with
13 67% (18 species) in the highest vulnerability category. Overall vulnerability and population concern
14 to multiple threats was high across all use groups with 100% of breeding species and 97% of
15 overwintering species considered vulnerable to multiple threats.

16

1

2 **DISCUSSION**

3 The Forth and Tay region of the North Sea supports a large and diverse community of marine birds
4 throughout the year that are of national and international importance (Söhle et al. 2007, JNCC
5 2013). Sea Surface Temperature has increased rapidly in the region since 1980, comparable to rates
6 observed in the North Atlantic and Pacific (Parry 2007). Our quantitative assessment demonstrated
7 negative correlations between SST and abundance, adult survival and/or productivity of 57% of
8 marine bird species. Combining quantitative and qualitative assessments of climate vulnerability
9 with population and demographic trends, we found that 44% of the 45 study species were of high or
10 very high population concern to rising sea temperatures in the future. Breeding, overwintering and
11 migrating species were all affected, with the largest proportion of high or very high population
12 concern found in the former. Crucially, all species with negative responses to climate change were
13 also vulnerable to at least two other anthropogenic threats operating in the region, with 76% of the
14 45 species of high or very high population concern to multiple threats, potentially impacting the
15 resilience of this marine bird community.

16

17 ***Vulnerability to climate***

18 Globally, seabirds have declined faster than terrestrial bird groups with comparable numbers of
19 species (Croxall et al. 2012), with the majority of trends consistent with climate change
20 (Poloczanska et al. 2013). In accordance with this global picture, we found that only 13% of the
21 marine bird community in the Forth and Tay region was of low or very low population concern to
22 future warming. The effects of climate on lower trophic levels results in complex spatial and
23 temporal variation in prey availability, making it challenging to establish links between top predator
24 abundance or demography and environmental drivers (Le Bohec et al. 2008, Bond et al. 2011,
25 Lahoz-Monfort et al. 2013). It is therefore of considerable concern that negative associations
26 between climate and abundance and demographic rates were so widespread across the community.
27 Synchronous responses to bottom-up processes occur where species are dependent on a common
28 prey base or exhibit similar life-history strategies, and have been demonstrated in seabird species in
29 this region (Lahoz-Monfort et al. 2011, Lahoz-Monfort et al. 2013). We found that cormorants,
30 grebes, skuas, shearwaters, terns, auks and some individual species in other families (e.g. greater
31 scaup and black-legged kittiwake) were particularly vulnerable to increased SST. Many of these
32 species are heavily reliant on lesser sandeels (*Ammodytes marinus*) which are sensitive to changes
33 in SST (Arnott & Ruxton 2002, van Deurs et al. 2009) and have restricted capacity to shift
34 distribution (Wright et al. 2000, Heath et al. 2012). In contrast, divers, sea ducks, gannet, gulls and
35 storm petrels were less vulnerable. This may have arisen because of insufficient resolution in the
36 data or lack of data on demographic rates that are more sensitive to changes in climate. However,
37 several of these groups, in particular sea ducks, gannets and gulls, have more generalist diets which
38 may buffer them from indirect climate impacts. Gulls and gannets exploit fisheries discards, which
39 have provided an alternative source of food to naturally available prey, although this will alter in the
40 coming years with changes in EU policy on discards (Bicknell et al. 2013). Increased abundance of
41 swimming crabs (subfamily Polybiinae) have been associated with climate change and fisheries
42 management (Lindley & Kirby 2010). Crabs are an important dietary component of sea ducks

1 (Ouellet et al. 2013), and have been linked with population increases of lesser black-backed gull
2 (Luczak et al. 2012, Schwemmer et al. 2013).

3 We found that productivity was more sensitive to climate change than count data, in line with other
4 studies (Frederiksen et al. 2007, Cook et al. 2014). This is of particular concern given the
5 international conservation importance of breeding colonies in the region, with many designated as
6 Special Protection Areas. We also found that adult survival rate was sensitive to climate change in 3
7 (European shag, black-legged kittiwake and Atlantic puffin) of the 5 breeding species for which
8 data were available. This is despite the fact that the latter two species have broad overwinter ranges
9 across the North Sea and North Atlantic and hence will be encountering non-local climate at the
10 time when most mortality takes place (Harris et al. 2010, Bogdanova et al. 2011). Factors that
11 impact on adult survival rates are of particular significance since the latter are the key determinant
12 of population size in *K*-selected species such as marine birds (Gaillard et al. 1989). However, our
13 study highlights that survival data are generally lacking. Collection of mark recapture data is
14 difficult and time-consuming, requiring specialised skills for catching and ringing birds at
15 accessible breeding sites, and such data are therefore only available for a limited subset of species.
16 Furthermore, survival analysis from dead recoveries of ringed birds is challenging in marine birds
17 because of poor recovery rates (Robinson 2010). However, there is a need to fill this knowledge
18 gap, especially for the sixteen species wintering in the region and hence likely to be experiencing
19 the main period of mortality.

20
21 In addition to the indirect effects of climate operating via food webs, marine bird species may also
22 be sensitive to direct impacts of climate. Direct climate effects may be particularly important for
23 species wintering in the region, when increased mortality can occur during prolonged periods of
24 poor weather (Frederiksen et al. 2008, Harris & Elkins 2013). Temperature extremes, heavy rainfall
25 or high winds may also affect productivity during the breeding season (Mallory et al. 2009, Oswald
26 & Arnold 2012). These effects may become increasingly important since most climate models
27 predict that future warming will be associated with increasing climate variability and hence
28 frequency of extreme weather events (Solomon 2007, Rahmstorf & Coumou 2011). Furthermore,
29 predicted sea-level rise may lead to loss of suitable foraging habitat for tidally feeding species or
30 breeding habitat for ground-nesting species such as common eider and terns (van de Pol et al.
31 2010). Complementary approaches to our study have used climate envelope models based on air
32 temperature data from a baseline period to assess the climatic suitability of terrestrial grid squares in
33 the UK in 2070-99 (Huntley et al. 2007). Based on these models, which integrate direct and indirect
34 effects of climate, it is predicted that by the end of the century the Forth and Tay region will
35 become climatically unsuitable, or at the southern edge of the breeding range, for 10 of the 18
36 breeding species we considered (Huntley et al. 2007). These include 8 (northern fulmar, European
37 shag, black-legged kittiwake, Atlantic puffin, common tern, Arctic tern, common guillemot and
38 razorbill) of the 11 breeding species identified in our analyses as being of high or very high
39 population concern to future warming. It is therefore possible that direct climate impacts may
40 adversely affect species not currently considered vulnerable to climate as well as exacerbate
41 impacts on species already under threat.

42

43 ***Vulnerability to multiple impacts***

1 Climate change comprised part of a suite of anthropogenic threats to this bird community, with 93%
2 of species vulnerable to multiple anthropogenic threats and 73% considered of high or very high
3 population concern to multiple threats in the future. The threats pertinent to the North Sea are also
4 threatening seabird populations globally, in particular invasive species, pollution, commercial
5 fisheries and human disturbance (Croxall et al. 2012). In contrast to marine birds in many other
6 areas, mammalian predation has not been widely recorded in the Forth and Tay region. However,
7 reintroduction of white-tailed sea-eagles has recently occurred in the region, potentially having a
8 negative impact via predation on breeding seabirds, as observed in Norway (Hipfner et al. 2012).
9 Furthermore, introduced plants can have significant impacts on breeding habitat available for
10 seabirds. Expansion of tree mallow (*Lavatera arborea*) has substantially reduced suitable nesting
11 habitat for Atlantic puffins at several colonies in the region. Moreover, this expansion was in part
12 due to increases in germination opportunity due to higher temperatures (van der Wal et al. 2008),
13 and climate warming may therefore favour further increases. In recent decades, levels of plastic
14 pollution have increased in marine environments and such pollution impairs digestive function and
15 causes reproductive failure (Azzarello & Vanvleet 1987, Avery-Gomm et al. 2012). Furthermore,
16 contaminants such as brominated flame retardants and perfluorinated compounds have increased in
17 tissues of predators (Dietz et al. 2008, Dietz et al. 2013), with negative consequences for survival
18 rates and productivity (Votier et al. 2005, Letcher et al. 2010, Votier et al. 2011, Miljeteig et al.
19 2012). Large scale marine renewable developments are proposed for this region as part of a broader
20 strategy to meet green energy targets, with the potential for negative impacts from collision and
21 displacement (Furness et al. 2013). Although future policy on fisheries for prey of marine birds
22 such as lesser sandeel is hard to predict, upcoming changes in EU policy are expected to reduce
23 fishery discards, which may have a negative impact on scavenging species such as gulls and
24 northern gannet (Bicknell et al. 2013). In contrast, policy changes on seabird bycatch are predicted
25 to reduce mortality. The relative importance of these drivers is therefore predicted to change in
26 future, but the overall threat is likely to remain high.

27 The high vulnerability of the Forth and Tay region marine bird community to multiple threats
28 means that there is an urgent need to evaluate their cumulative impacts in conjunction with climate
29 change. While qualitative approaches such as those undertaken here are undoubtedly useful, they
30 cannot identify whether multiple threats are additive, synergistic or antagonistic. This requires
31 robust, quantitative analyses of the interaction between multiple impacts on marine bird
32 communities. However, this is a huge challenge because potential drivers are difficult to quantify at
33 the appropriate scale and will often co-vary. The few studies that have undertaken quantitative
34 analyses of multiple impacts in wild populations have focused on effects on single species. These
35 studies have shown that interactions between climate and other factors such as fisheries or pollution
36 may be additive or synergistic (Frederiksen et al. 2004, Votier et al. 2005, Ainley & Blight 2009,
37 McKinney et al. 2013). Fisheries may directly compete with marine birds or be beneficial by
38 removing competitors, depending on what species they are harvesting (review in Lewison et al.
39 2012) but interactions with climate are likely to be complex and hard to predict. Impacts of marine
40 renewable developments on bird breeding colonies may change if species adjust foraging ranges
41 due to climate warming, potentially altering overlap. Despite the lack of a strong predictive
42 framework, there are opportunities for quantitative investigation of multiple impacts on marine bird
43 communities. Controlled experiments are an appealing option for establishing causality, but are
44 logistically challenging in marine environments; however, opportunities such as new marine
45 renewable developments or changes in discard policy, would enable marine bird responses to be

1 partitioned unequivocally among drivers, especially in species groups where demographic
2 sensitivity to climate has been demonstrated and which are particularly amenable to study, such as
3 European shag, black-legged kittiwake and auks. Mechanistic studies of diet and foraging
4 energetics would greatly enhance understanding of the impacts of multiple drivers mediated via
5 changes at lower trophic levels (Thaxter et al. 2013), since such studies have proved powerful in
6 elucidating responses of top predators to changing abundance in prey associated with climate
7 change and other drivers such as pollution (Provencher et al. 2012, McKinney et al. 2013, Anderson
8 et al. 2014) . Comparisons of multi-species colonies across broad spatial scales, across a gradient of
9 severity of anthropogenic threats, would be another fruitful avenue of research.

10

11 ***Conclusions***

12 To our knowledge, this study is the first comprehensive assessment of vulnerability to climate
13 change and a suite of anthropogenic threats in a community of marine birds and builds substantially
14 on previous evaluations of species in this assemblage to single stressors such as climate (Sandvik et
15 al. 2005, Frederiksen et al. 2007), fisheries (Furness & Tasker 2000) and marine renewables
16 (Furness et al. 2013). A previous assessment of changes in the size of breeding populations of the
17 UK marine bird community between 1969 and 2002 found that most populations had increased;
18 however, terns and black-legged kittiwakes were notable exceptions, and extensive breeding
19 failures were apparent in several species at the very end of the study period (Grandgeorge et al.
20 2008). Our study extended this time series by almost a decade in the Forth and Tay region, and
21 found that, in addition to terns and black-legged kittiwakes, many other species are now declining
22 and showing evidence of negative associations with climate. These results therefore support the
23 concerns raised by Grandgeorge et al (2008) and indicate that climate change is now having a
24 substantial impact on this marine bird community.

25 Our study highlights the value of long-term demographic studies of marine birds in elucidating
26 anthropogenic threats to species communities and emphasizes the need for continuation and
27 expansion of such studies. However, even in the Forth and Tay region, where spatially and
28 temporally comprehensive data on abundance and demography are available, almost half of the
29 species present had insufficient data to enable associations with climate to be assessed
30 quantitatively.

31 Development of forecasting models to predict the interaction between climate and other drivers on
32 marine bird communities is an important research priority. Progress using this approach is currently
33 hampered by the lack of predicted regional SST data between now and 2070. However, based on
34 our retrospective assessment of impacts of climate and other factors we suggest that the majority of
35 marine birds in the Forth and Tay region of the North Sea face an uncertain future because of
36 simultaneous and likely increasing threats from climate warming and a suite of other anthropogenic
37 stressors. In particular, reductions in discard policy and expansion of marine renewables may
38 impact this bird community further over the coming decades. In conjunction with climate change,
39 such factors may threaten community resilience in the near future.

40

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21

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Figures

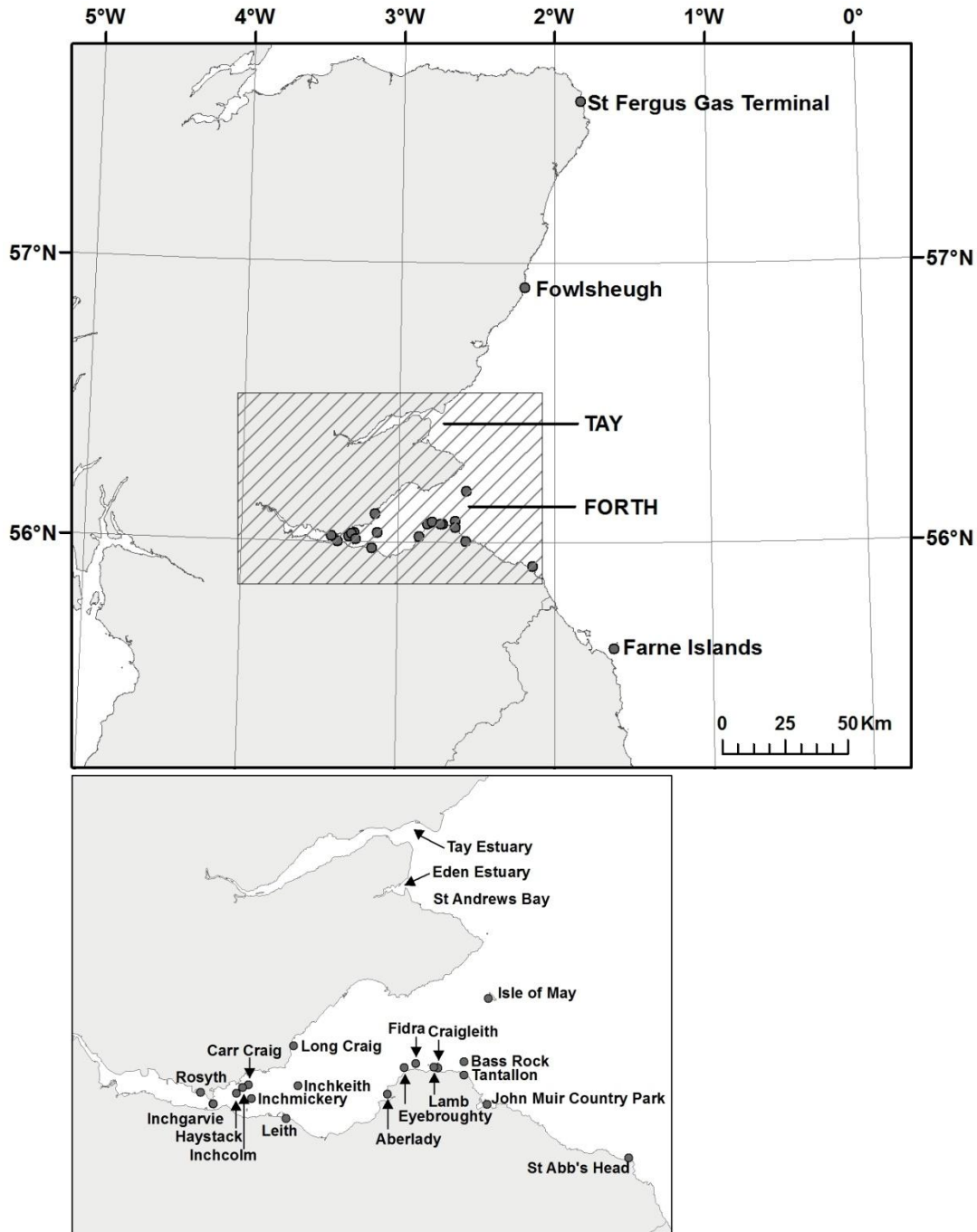


Figure 1: Upper panel: study area indicating the locations of the Forth and Tay estuaries (shaded box) and SMP sites outside the main Forth/Tay region that were included in analysis. The area of the North Sea for which ESAS and SST data were analysed was between 55° - 58°N and 4°W - 0°E. Lower panel: larger scale map of the shaded box in the upper panel, indicating SMP breeding colonies and WeBS estuary sites.

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2 **Table 1:** Index of population concern to future climate warming, calculated according to vulnerability to climate and
3 whether populations or demography showed evidence of increasing, showing no trend or decreasing. The shading
4 indicates the level of the index of population concern, ranging from white (very low concern) to dark grey (very high
5 concern).

		Population and/or demographic rates		
		Increasing	Stable	Declining
Relationship with climate	Positive	Very Low (0)	Low (1)	Moderate (2)
	None	Moderate (2)	Moderate (2)	Moderate (2)
	Negative	Moderate (2)	High (3)	Very High (4)

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2 **Table 2:** Trends in SST: annual (January to December); during winter (December, January and February); spring
3 (March, April and May); summer (June, July and August) and autumn (September, October and November) in the Forth
4 and Tay region between 1980 and 2011 based on linear regressions of SST against year with temporal autocorrelation
5 accounted for.

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Season SST	Estimate (°C per year)	S.E. (°C per year)	t statistic	p value
Annual	0.051	0.010	5.029	0.000
Winter	0.050	0.010	4.858	0.000
Spring	0.056	0.015	3.779	0.001
Summer	0.048	0.013	3.629	0.001
Autumn	0.055	0.012	4.752	0.000

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1 **Table 3:** Quantitative assessment of vulnerability to climate based on relationships with climate and trends in counts
2 and/or demographic rates. We present significant trends in counts and demographic rates and whether relationships with
3 climate are consistent. Finally, we provide an overall index of vulnerability to climate ranging from 1 (positive) to 3
4 (negative) and an index of population concern to future climate based on vulnerability to climate and population trends
5 ranging from 0 (very low) to 4 (very high; see Table S8 in supp. info for a fuller version of this table).

Species	No datasets analysed	Direction of significant trends	Climate regressions consistently in one direction? (no. models)	Climate vulnerability	Index of population concern to future climate
Great crested grebe <i>Podiceps cristatus</i>	1	Decline	yes (13 negative)	3	4
Northern fulmar <i>Fulmarus glacialis</i>	4	Decline (productivity), no trend (counts)	Yes (productivity: 9 negative; ESAS winter 6 negative); No (SMP counts)	3	4
Northern gannet <i>Morus bassanus</i>	2	Increase (ESAS summer)	Yes (ESAS summer 8 positive)	1	0
Great cormorant <i>Phalacrocorax carbo</i>	2	Decline (SMP & WeBS)	Yes (SMP: 1 negative; WeBS 12 positive)	1	2
European shag <i>Phalacrocorax aristotelis</i>	3	Decline (counts), no trend (productivity or survival)	Yes (survival: 4 negative) No (counts: 5 negative & 5 positive)	3	4
Greater scaup <i>Aythya marila</i>	1	Decline	Yes (12 negative)	3	4
Common eider <i>Somateria mollissima</i>	2	No trend	yes (SMP- 2 pos)	1	1
Long-tailed duck <i>Clangula hyemalis</i>	1	No trend	Yes (3 positive)	1	1
Black scoter <i>Melanitta nigra</i>	1	No trend	Yes (7 negative)	3	3
Velvet scoter <i>Melanitta fusca</i>	1	No trend	No significant relationships	2	2
Common goldeneye <i>Bucephala clangula</i>	1	No trend	No significant relationships	2	2
Red-breasted merganser <i>Mergus serrator</i>	2	No trend	Yes (winter: 2 negative)	3	3
Goosander <i>Mergus merganser</i>	1	No trend	No significant relationships	2	2
Black-headed gull <i>Chroicocephalus ridibundus</i>	1	Increasing (SMP)	Yes (3 positive)	1	0
Lesser black-backed gull <i>Larus fuscus</i>	2	Increase (counts), no trend (productivity)	No significant relationships	2	2
Herring gull <i>Larus argentatus</i>	3	No trend (counts or productivity)	Yes (ESAS winter 6 negative)	3	3
Great black-backed gull <i>Larus marinus</i>	3	Increase (SMP), no trend (WeBS; ESAS)	Yes (ESAS 8 negative)	3	2
Black-legged kittiwake <i>Rissa tridactyla</i>	5	Decline (SMP counts, survival & productivity)	Yes (productivity: 7 negative; survival: 7 negative; ESAS counts 75% negative) No (SMP)	3	4
Sandwich tern <i>Sterna sandvicensis</i>	2	Decline (SMP), no trend (WeBS)	No significant relationships	2	2
Common tern <i>Sterna hirundo</i>	3	No trend (counts or productivity)	Yes (productivity: 3 negative)	3	3
Arctic tern <i>Sterna paradisaea</i>	3	No trend (counts or productivity)	Yes (SMP 2 negative; productivity 5 negative)	3	3
Little tern <i>Sternula albifrons</i>	1	No trend	Yes (3 negative)	3	3
Atlantic puffin <i>Fratercula arctica</i>	4	no trend (SMP, productivity or survival)	Yes (productivity: 5 negative), no relationship (counts; survival)	3	3

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1 **Table 4:** Qualitative assessment of vulnerability to climate for species where robust data were not available for
2 quantitative assessment or for species that showed inconsistent quantitative trends. Climate vulnerability was based on
3 published relationships with climate or foraging sensitivity and ranges from 1 (positive response or low foraging
4 sensitivity to climate change) to 3 (negative response or high foraging sensitivity to climate). Climate vulnerability was
5 combined with population trends or, where unavailable, conservation status to provide an index of population concern
6 to future climate ranging from 0 (very low) to 4 (very high).

Species	Scottish or UK* population trend (or conservation status)	Relationships with climate	Foraging sensitivity index	Climate Vulnerability	Index of population concern to future climate
Red-throated diver <i>Gavia stellata</i>	Increasing (Dillon et al. 2009)	Unknown	12	2	2
Black-throated diver <i>Gavia arctica</i>	Unknown (amber)	Unknown	12	2	2
Surf scoter <i>Melanitta perspicillata</i>	Unknown	Unknown	13	2	2
Great northern diver <i>Gavia immer</i>	Unknown (amber)	Unknown	11	2	2
Red-necked grebe <i>Podiceps grisegena</i>	Unknown (amber)	Unknown	14	2	2
Slavonian grebe <i>Podiceps auritus</i>	Declining (Perkins et al. 2005)	Unknown	15	3	4
Black-necked grebe <i>Podiceps nigricollis</i>	Unknown (amber)	Unknown	15	3	3
Sooty shearwater <i>Puffinus griseus</i>	Unknown (amber)	Unknown	4	1	1
Manx shearwater <i>Puffinus puffinus</i>	Unknown (amber)	Negative (Riou et al. 2011, Bicknell et al. 2013)	7	3	3
European storm-petrel <i>Hydrobates pelagicus</i>	Unknown (amber)	Unknown	10	2	2
Leach's storm-petrel <i>Oceanodroma leucorhoa</i>	Declining (Newson et al (2008)	Unknown	10	2	2
Pomarine skua <i>Stercorarius pomarinus</i>	Unknown (green)	Unknown	15	3	2
Arctic skua <i>Stercorarius parasiticus</i>	Declining	Unknown	15	3	4
Long-tailed skua <i>Stercorarius longicaudus</i>	Unknown (green)	Unknown	15	3	2
Great skua <i>Stercorarius skua</i>	Increasing	Negative (Oswald et al. 2008)	13	3	2
Mediterranean gull <i>Ichthyaetus melanocephalus</i>	Increasing*	Unknown	14	2	2
Little gull <i>Hydrocoloeus minutus</i>	Unknown (amber)	Unknown	16	3	3
Common gull <i>Larus canus</i>	Declining	Unknown	14	2	2
Roseate tern <i>Sterna dougallii</i>	Declining	Unknown	22	3	4
Little auk <i>Alle alle</i>	Unknown (green)	Unknown	13	2	2
Common guillemot <i>Uria aalge</i>	Declining	Negative (Votier et al. 2005, Lahoz-Monfort et al. 2011)	9	3	4
Razorbill <i>Alca torda</i>	Declining	Negative (Lahoz-Monfort et al. 2011)	12	3	4

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3 **Table 5:** Vulnerability of species to non-climate threats. Vulnerability to each threat is ranked as 1 (low), 2 (moderate)
4 or 3 (high). Only threats applicable when a species is present in the study area are considered.

Species	Discards	Bycatch	Competition with fisheries	Oil pollution	Contaminants	Plastics	Introduced predators	Disturbance (non-wind farm related)	Collision impacts with wind farms	Displacement and disturbance from wind farms
Red-throated diver	1	2	1	3	1	1	1	2	2	3
Black-throated diver	1	1	1	3	1	1	1	2	2	3
Great northern diver	1	1	1	3	1	1	1	2	2	3
Great crested grebe	1	2	1	3	1	1	1	1	2	2
Red-necked grebe	1	2	1	3	1	1	1	1	2	2
Slavonian grebe	1	2	1	3	1	1	1	1	2	2
Black-necked grebe	1	2	1	3	1	1	1	1	2	2
Northern fulmar	3	2	1	2	2	3	3	2	2	1
Sooty shearwater	2	2	1	2	1	3	1	1	1	1
Manx shearwater	2	2	1	2	1	3	1	1	1	1
European storm-petrel	1	1	1	2	1	2	1	1	1	1
Leach's storm-petrel	1	1	1	2	1	2	1	1	1	1
Northern gannet	3	2	2	2	2	1	1	1	3	1
Great cormorant	1	2	3	2	1	1	3	2	1	2
European shag	1	2	1	2	1	1	3	2	1	2
Greater scaup	1	1	2	3	1	1	1	1	2	3
Common eider	1	2	3	2	1	1	3	2	1	2
Long-tailed duck	1	1	2	3	1	1	1	2	1	2
Black scoter	1	1	2	3	1	1	1	2	1	3
Surf scoter	1	1	2	3	1	1	1	2	1	3
Velvet scoter	1	1	2	3	1	1	1	2	1	3
Common goldeneye	1	1	1	3	1	1	1	2	1	3
Red-breasted merganser	1	1	2	2	1	1	1	1	1	3
Goosander	1	1	3	1	1	1	1	1	1	3
Pomarine skua	3	1	2	1	1	1	1	1	3	1
Arctic skua	1	1	2	1	1	1	2	1	3	1
Long-tailed skua	1	1	2	1	1	1	1	1	3	1
Great skua	3	2	2	1	2	1	1	1	2	1
Mediterranean gull	1	1	1	2	1	1	1	1	3	1
Little gull	1	1	1	2	1	1	1	1	2	1
Black-headed gull	1	1	1	2	2	1	1	1	3	1
Common gull	1	1	1	2	2	1	1	1	3	1
Lesser black-backed gull	3	2	1	2	2	1	2	1	3	1
Herring gull	3	2	1	2	2	1	2	1	3	1
Great black-backed gull	3	2	1	2	2	1	2	1	3	1
Black-legged kittiwake	2	1	3	2	1	1	2	1	3	1
Sandwich tern	2	1	1	1	1	1	3	2	2	1
Roseate tern	2	1	1	1	1	1	3	3	2	1
Common tern	2	1	1	1	1	1	3	3	2	1
Arctic tern	2	1	1	1	1	1	3	3	2	1
Little tern	2	1	1	1	1	1	3	3	2	2
Common guillemot	1	2	2	2	1	1	3	1	1	2
Razorbill	1	2	1	2	1	1	3	1	1	2
Little auk	1	1	1	1	1	1	1	1	1	1
Atlantic puffin	1	1	2	1	1	1	3	2	1	1

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Table 6: Overall summary of vulnerability to multiple anthropogenic threats. The main use of the study area is denoted as B (breeding), OW (over-wintering), SV (summer visitor) or PM (passage migrant). We present the highest vulnerability score per main threat (fisheries, pollutants, disturbance, windfarms and climate). Summed vulnerability is the summed score for the 5 categories (including climate). We indicate the total number of threats the species is vulnerable to (climate scored as 3 or other threats scored as ≥ 2 ; table ordered by this column). The index of population concern to climate and multiple threats incorporated climate vulnerability or number of threats species is vulnerable to and population status respectively.

Species	Main use of study area	fisheries	pollutants	disturbance	windfarms	Climate	Summed vulnerability score	No. Threats vulnerable to	pop trend or status	Index of population concern to climate	Index of population concern to multiple threats
Northern fulmar	B, OW	3	3	3	2	3	14	5	Decline	4	4
European shag	B, OW	2	2	3	2	3	12	5	Decline	4	4
Black scoter	OW	2	3	2	3	3	13	5	No trend	3	3
Herring gull	B, OW	3	2	2	3	3	13	5	No trend	3	3
Great black-backed gull	B, OW	3	2	2	3	3	13	5	Increase	2	2
Black-legged kittiwake	B, OW	3	2	2	3	3	13	5	Decline	4	4
Common guillemot	B, OW	2	2	3	2	3	12	5	Decline	4	4
Razorbill	B, OW	2	2	3	2	3	12	5	Decline	4	4
Red-throated diver	OW	2	3	2	3	2	12	4	Increase	2	2
Great crested grebe	OW	2	3	1	2	3	11	4	Decline	4	4
Slavonian grebe	OW	2	3	1	2	3	11	4	Decline	4	4
Black-necked grebe	PM	2	3	1	2	3	11	4	amber	3	3
Great cormorant	B, OW	3	2	3	2	1	11	4	Decline	2	4
Greater scaup	OW	2	3	1	3	3	12	4	Decline	4	4
Common eider	B, OW	3	2	3	2	1	11	4	No trend	1	3
Long-tailed duck	OW	2	3	2	2	1	10	4	No trend	1	3
Surf scoter	OW	2	3	2	3	2	12	4	No trend	2	3
Velvet scoter	OW	2	3	2	3	2	12	4	No trend	2	3
Red-breasted merganser	OW	2	2	1	3	3	11	4	No trend	3	3
Arctic skua	PM	2	1	2	3	3	11	4	Decline	4	4
Great skua	PM	3	2	1	2	3	11	4	Increase	2	2
Lesser black-backed gull	B, OW	3	2	2	3	2	12	4	No trend	2	3
Roseate tern	B	2	1	3	2	3	11	4	Decline	4	4
Common tern	B	2	1	3	2	3	11	4	No trend	3	3
Arctic tern	B	2	1	3	2	3	11	4	No trend	3	3
Little tern	B	2	1	3	2	3	11	4	No trend	3	3
Black-throated diver	OW	1	3	2	3	2	11	3	amber	2	3
Great northern diver	OW	1	3	2	3	2	11	3	amber	2	3
Red-necked grebe	OW	2	3	1	2	2	10	3	No trend	2	3
Manx shearwater	SV	2	3	1	1	3	10	3	No trend	3	3
Northern gannet	B, OW	3	2	1	3	1	10	3	Increase	0	2
Common goldeneye	OW	1	3	2	3	2	11	3	No trend	2	3
Pomarine skua	PM	3	1	1	3	3	11	3	green	2	2
Long-tailed skua	PM	2	1	1	3	3	10	3	green	2	2
Little gull	PM	1	2	1	2	3	9	3	amber	3	3
Sandwich tern	B	2	1	3	2	2	10	3	Decline	2	4
Atlantic puffin	B, OW	2	1	3	1	3	10	3	No trend	3	3
Sooty shearwater	PM	2	3	1	1	1	8	2	amber	1	3
Goosander	OW	3	1	1	3	2	9	2	No trend	2	3
Mediterranean gull	SV	1	2	1	3	2	9	2	Increase	2	2
Black-headed gull	B, OW	1	2	1	3	1	8	2	Increase	0	2
Common gull	OW	1	2	1	3	2	9	2	Decline	2	4
European storm-petrel	SV	1	2	1	1	2	7	1	amber	2	1
Leach's storm-petrel	SV	1	2	1	1	2	7	1	Decline	2	2
Little auk	OW	1	1	1	1	2	6	0	green	2	0

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Table 7: Vulnerability of birds grouped by family and main use the Forth and Tay area to climate and multiple threats. The five right hand columns indicate the % of species in each family/main use that: are in the highest climate vulnerability category; have high or very high population concern to future climate warming; are vulnerable to multiple threats; have high or very high population concern to multiple threats; or are vulnerable to climate and other threats.

Grouping category	Family/main use	No species	% species with high vulnerability to climate	% species with high or very high population concern to future climate	% species vulnerable to ≥2 threats	% species with high or very high population concern to multiple threats	% species vulnerable to climate and at least 1 other threat
Family	Anatidae	9	33	33	100	100	33
	Gaviidae	3	0	0	100	67	0
	Procellariidae	3	67	67	100	100	67
	Hydrobatidae	2	0	0	0	0	0
	Sulidae	1	0	0	100	0	0
	Phalacrocoracidae	2	50	50	100	100	50
	Podicepsidae	4	75	75	100	100	75
	Stercorariidae	4	100	50	100	25	100
	Laridae	8	50	38	100	63	50
	Sternidae	5	80	80	100	100	80
Alcidae	4	75	75	75	75	75	
Use of study area	Breeding	5	80	80	100	100	80
	Breeding & Overwintering	13	62	54	100	77	62
	Overwintering	16	31	31	94	88	31
	Migrant or summer visitor	11	64	36	73	45	63

9