Seabirds in the North-East Atlantic

Climate Change Vulnerability and Potential Conservation Actions

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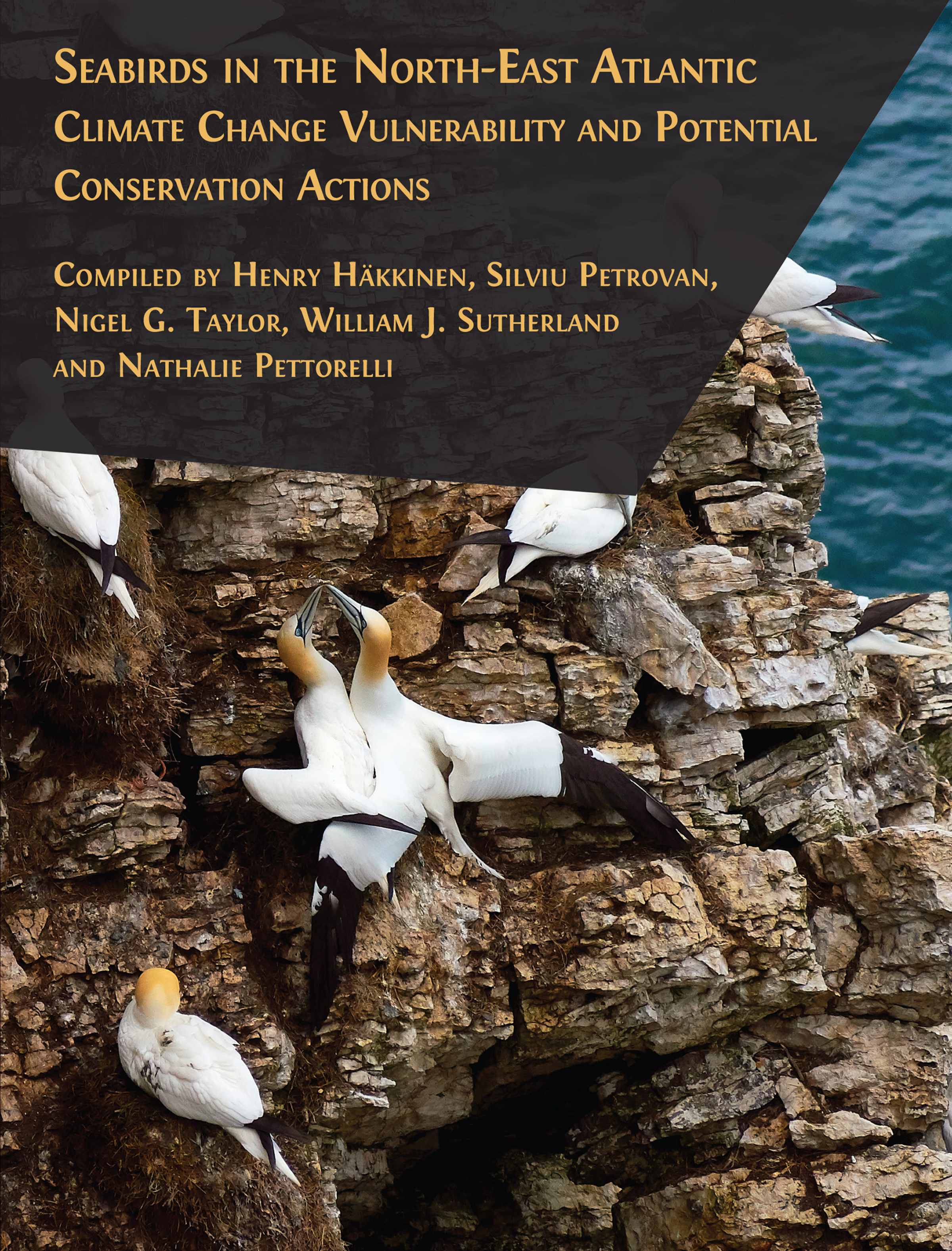

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Appendices

Appendix 1: Auks

Sources and references for vulnerability assessment

1.1 Evidence for exposure (references)

1.1.1 Current impacts attributed to climate change:

Razorbill

1 - Extreme storms during the razorbill breeding season have led to wide-spread nest destruction, nesting failure and a net reduction in annual population production

> **Newell, M., et al. "Effects of an extreme weather event on seabird breeding success at a North Sea colony." Marine Ecology Progress Series 532 (2015): 257-268.** A single extreme summer storm on the Isle of May resulted in wide-spread nest destruction, nesting failure and a net reduction in annual population production. While individual storms cannot be easily be attributed to climate change, severe storms are increasingly frequent in Europe.

2 - As sea temperatures have increased over time, razorbill productivity has decreased, most likely due to changes in prey availability.

> **Lauria, V., et al. "Influence of climate change and trophic coupling across four trophic levels in the Celtic Sea." (2012): e47408.** Razorbill productivity on Skomer Island declined over the study period (1993–2007). Meanwhile, spring sea surface temperature significantly increased. Razorbill productivity was correlated with spring sea surface temperature in the previous year. The study suggests that sea temperature affected the razorbills indirectly, through the availability of forage fish.

3 - Key prey species have shifted their life-cycle, likely in response to climate change, but razorbills have not adjusted in response. There is concern this could result in trophic mismatch, but no overall effect on breeding success has so far been observed.

> **Burthe, S., et al. "Phenological trends and trophic mismatch across multiple levels of a North Sea pelagic food web." Marine Ecology Progress Series 454 (2012): 119-133.** Timing of sandeel growth has changed substantially, but laying date has not in razorbills. This likely has resulted in trophic mismatch. However, to date no overall effect on breeding success has been observed. Seabird observations based mostly on Isle of May.

Little Auk

1 - Warmer temperatures correlate with longer foraging trips and lower little auk productivity, most likely due to decreased prey availability.

Hovinen, J. E. H., et al. "Climate warming decreases the survival of the little auk (Alle alle), a high Arctic avian predator." Ecology and Evolution 4.15 (2014): 3127-3138. At several sites in Svalbard, higher SST is associated with decreased adult survival, probably mediated through prey availability. Suggested mechanism is that an increase in temperature results in a decrease in sea ice and a decrease in ice algal production which in turn results in less food quality and availability. The temperature and inflow of warm Atlantic water to the Arctic increased during the study period.

Hovinen, J. E. H., et al. "Fledging success of little auks in the high Arctic: do provisioning rates and the quality of foraging grounds matter?." Polar Biology 37.5 (2014): 665-674. Higher SST in colonies around Svalbard correlates with lower fledging success, though not with provisioning rate by parents. In at least one colony, this has led to population decline. Most likely linked to higher SST resulting in lower prey availability quality.

Ramírez, F., et al. "Sea ice phenology and primary productivity pulses shape breeding success in Arctic seabirds." Scientific Reports 7.1 (2017): 1-9. As above, warmer years with less sea ice result in changes in timing of key prey species availability. This in turn correlates with lower breeding performance in little auks. Study was based around Spitsbergen, Svalbard.

Jakubas, D., Wojczulanis-Jakubas, K., and Walkusz, W. "Response of dovekie to changes in food availability." Waterbirds 30.3 (2007): 421-428. This study looks at similar effects to those above, they note warmer waters around Spitsbergen means less easily accessible high-quality food, but that adults are able to compensate somewhat with changes in their foraging strategy. Study also notes that the North Atlantic has warmed over recent years.

2 - Little auks are breeding earlier in correlation with warmer temperatures, so far no negative consequence has been observed

Moe, Børge, et al. “Climate change and phenological responses of two seabird species breeding in the high-Arctic.” Marine Ecology Progress Series 393 (2009): 235-246. Little auks on Svalbard are breeding earlier in correlation with increases in air temperature in the spring. The reason for this is not clear, but may be a result of nesting sites being available earlier due to snow melt. This change in phenology may or may not match prey availability, which may lead to trophic mismatch in the future.

3 - Extreme storms during the non-breeding season have led to mass mortality of

little auks ('wrecks')

Clairbaux, M., et al. "North Atlantic winter cyclones starve seabirds." Current Biology 31.17 (2021): 3964-3971. Following heavy storm action, seabird mortality increases due to increased difficulty foraging (rather than increased energetic costs). The authors use a multi-species dataset (puffins, little auks, common murres, and thick-billed murres) over a wide area of the Atlantic basin. They conclude that seabirds around Iceland and the Barents Sea (along with several N. American sites) are particularly vulnerable. Climate change is likely to be a contributing factor to present and future storm mortality.

Black Guillemot

1 - Heavy rainfall events and high water level has led to flooding of nests and lower hatching success in the Baltic. The authors note that such flooding events are likely to further increase. Debris left by storms and flooding can also make large areas of shoreline less suitable for breeding

Hof, A. R., Crombag, J. A. H. M. , and Allen, A. M. "The ecology of Black Guillemot Cepphus grylle grylle chicks in the Baltic Sea region: insights into their diet, survival, nest predation and moment of fledging." Bird Study 65.3 (2018): 357-364. Storms and increased water level leads to flooding of nests and lower breeding success in the Baltic. The authors note that such flooding events are likely to further increase. Information regarding debris comes from personal correspondence with stakeholders.

2 - Range expansion of American mink, partly assisted by climate change, has led to increased rates of predation at guillemot colonies

Buchadas, A. R. C., and Hof, A. R. "Future breeding and foraging sites of a southern edge population of the locally endangered Black Guillemot Cepphus grylle." Bird Study 64.3 (2017): 306-316. Black guillemots are particularly vulnerable to predation by American mink, which is currently increasing in range and abundance in Europe. This range expansion has likely been assisted by climate change and therefore predation is likely to worsen across the species range. The study focusses on the Baltic but suggests anywhere the mink is expanding is likely to have similar issues in the future.

3 - Guillemot have shifted their laying date, most likely linked to an increase in sea surface temperature and prey availability

Greenwood, J. G. "Earlier laying by Black Guillemots Cepphus grylle in Northern Ireland in response to increasing sea-surface temperature." Bird Study 54.3 (2007): 378-379.

Atlantic Puffin

1 - Changes in puffins’ prey availability during breeding season has led to decreased breeding success

Barrett, R. T. "Atlantic puffin Fratercula arctica and common guillemot Uria aalge chick diet and growth as indicators of fish stocks in the Barents Sea." Marine Ecology Progress Series 230 (2002): 275-287. The volume of puffin eggs in two Norwegian populations declined over a roughly 30-year period. Eggs were smaller in years when capelin and herring is less available, which is linked to climate change. This likely is also an indicator of population health and may be driving declines.

Burthe, S. J., et al. "Assessing the vulnerability of the marine bird community in the western North Sea to climate change and other anthropogenic impacts." Marine Ecology Progress Series 507 (2014): 277-295. Puffin productivity and survival has decreased around the Forth and Tay region as temperature has increased. Most likely linked to prey availability. Sea surface temperature has increased in the study region between 1980 and 2011.

Dunn, P. O., and Møller, A. P. (eds). "Effects of Climate Change on Birds" 2nd edition, Oxford, Oxford Academic (2019). Higher water temperature in the Norwegian sea has resulted in a shift in herring stock to the north, and a spatial mismatch between puffins and prey.

Durant, J. M., et al. "Regime shifts in the breeding of an Atlantic puffin population." Ecology Letters 7.5 (2004): 388-394. In the Norwegian sea, long term fluctuations in the winter NAO index have affected food availability and therefore puffin success and breeding timing. Study used a multi-decadal dataset from Hernyken, Northern Norway.

Fauchald, Per, et al. "The status and trends of seabirds breeding in Norway and Svalbard." NINA rapport 1151. Norsk institutt for naturforskning (2015): 1-84. Severe declines of puffins have occurred in most areas of Norway, cause is not known but changes in food abundance and timing are concluded to be the most probable cause.

Fayet, A. L., et al. "Local prey shortages drive foraging costs and breeding success in a declining seabird, the Atlantic puffin." Journal of Animal Ecology 90.5 (2021): 1152-1164. Puffin tracking data has shown that when they are forced to forage further (using data from Iceland, Norway and Wales) breeding success decreases. Changes in food availability – which the study suggests have caused puffins to forage further from the colony and expend more energy at foraging grounds – are closely related to temperature.

Frederiksen, M., et al. "Climate, copepods and seabirds in the boreal

Northeast Atlantic–current state and future outlook." Global Change Biology 19.2 (2013): 364-372. Declines in puffin breeding success on the Isle of May correlate with marine environmental suitability for copepods (a key prey for many fish and seabirds), which has decreased in recent years. The authors found a weaker, non-significant link in Norway.

Hansen, E. S., et al. "Centennial relationships between ocean temperature and Atlantic puffin production reveal shifting decennial trends." Global Change Biology 27 (2021): 3753-3764. Sea surface temperature is a strong predictor of puffin breeding success in a breeding population in Iceland, over both decennial and centennial timescales, most likely through sandeel abundance during the winters. Milder winters result in fewer sandeels in the following summer. Study uses a long term dataset (130 years) based on breeding success in Vestmannaeyjar, Iceland.

2 - Changes in puffins' prey availability during non-breeding season has led to increased mortality and population declines

Anon "Atlantic puffin Fratercula arctica" Scottish Wildlife Trust Report (2018) Available at: https://scottishwildlifetrust.org.uk/wp-content/uploads/2018/01/Puffin.docx. Colony declines on the east coast of Scotland are attributed to lack of prey during the breeding and non-breeding season. The report notes the availability of suitable prey during the non-breeding season is critical for long-term health of puffin populations.

Harris, M. P., et al. "Wintering areas of adult Atlantic puffins Fratercula arctica from a North Sea colony as revealed by geolocation technology." Marine Biology 157.4 (2010): 827-836. Between 1992 and 2008, Isle of May puffins suffered increasing over-winter mortality and shifted their wintering distribution from the North Sea to the Atlantic. The study suggests this might be linked to changes in temperature, plankton populations and fish populations in the North Sea.

3 - Changes in vegetation has led to fewer suitable puffin nest-sites

Burthe, S. J., et al. "Assessing the vulnerability of the marine bird community in the western North Sea to climate change and other anthropogenic impacts." Marine Ecology Progress Series 507 (2014): 277-295. Update on the below item confirming the impacts of tree mallow on puffins and the scale of the problem in Scotland.

Van Der Wal, R., et al. "Multiple anthropogenic changes cause biodiversity loss through plant invasion." Global Change Biology 14.6 (2008): 1428-1436. Expansion of tree mallow Lavatera arboreahas, in part due to climate change, substantially reduced suitable nesting habitat for Atlantic puffins at several colonies in the Forth and Tay region.

4 - Extreme storms during the non-breeding season have led to mass-mortality of puffins (‘wrecks’)

Clairbaux, M., et al. "North Atlantic winter cyclones starve seabirds." Current Biology 31.17 (2021): 3964-3971. Following heavy storm action, seabird mortality increases due to increased difficulty foraging (rather than increased energetic costs). The authors use a multi-species dataset (puffins, little auks, common murres, and thick-billed murres) over a wide area of the Atlantic basin. They conclude that seabirds around Iceland and the Barents Sea (along with several N. American sites) are particularly vulnerable. Climate change is likely to be a contributing factor to present and future storm mortality.

Mitchell, I., et al. "Impacts of climate change on seabirds, relevant to the coastal and marine environment around the UK." (2020): 382-399. Winter storms can cause mass mortality (and have recently in 2013/14 storms), wrecks have been observed off the coast of France and the east coast of England. While individual storms cannot easily be attributed to climate change, most predictions are confident extreme Atlantic storms will become more frequent.

5 - Puffins have changed their wintering range

Harris, M. P., et al. "Wintering areas of adult Atlantic puffins Fratercula arctica from a North Sea colony as revealed by geolocation technology." Marine Biology 157.4 (2010): 827-836. Between 1992 and 2008, Isle of May puffins suffered increasing over-winter mortality and shifted their wintering distribution from the North Sea to the Atlantic. The study suggests this might be linked to changes in temperature, plankton populations and fish populations in the North Sea.

Common Murre

1 - High-wind events in the non-breeding season have led to mass mortality of murres in recent years

Louzao, M., et al. "Threshold responses in bird mortality driven by extreme wind events." Ecological Indicators 99 (2019): 183-192. High wind events in the winter have caused several mass mortality events (“wrecks”) in NE Atlantic, though this study focusses on bodies washed up in Bay of Biscay. Study suggests high wind events are likely to become more common and result in more deaths in the future.

2 - Extreme storms during the non-breeding season have led to mass mortality of murres (‘wrecks’)

Clairbaux, M., et al. "North Atlantic winter cyclones starve seabirds."

Current Biology 31.17 (2021): 3964-3971. Following heavy storm action, seabird mortality increases due to increased difficulty foraging (rather than increased energetic costs). The authors use a multi-species dataset (puffins, little auks, common murres, and thick-billed murres) over a wide area of the Atlantic basin. They conclude that seabirds around Iceland and the Barents Sea (along with several N. American sites) are particularly vulnerable. Climate change is likely to be a contributing factor to present and future storm mortality.

3 - More frequent extreme storms during murres' breeding season has increased foraging difficulty and reduced food fed to chicks

Finney, S. K., Wanless, S., and Harris, M. P. "The effect of weather conditions on the feeding behaviour of a diving bird, the Common Guillemot Uria aalge." Journal of Avian Biology (1999): 23-30. Stormy weather affects the quantity and size of food that adults can provide to chicks, and increases in summer storm frequency may result in lowered foraging efficiency. Study was conducted on Isle of May. Extreme storms in the Atlantic are likely to become more frequent in the future and further disrupt the breeding season.

4 - Extreme storms during murres' breeding season have led to wide-spread nest destruction, nesting failure and a net reduction in annual population production

Newell, M., et al. "Effects of an extreme weather event on seabird breeding success at a North Sea colony." Marine Ecology Progress Series 532 (2015): 257-268. A single extreme summer storm on the Isle of May resulted in wide-spread nest destruction, nesting failure and a net reduction in annual population production. While individual storms cannot be easily be attributed to climate change, it is generally believed that severe storms are becoming more common

5 - Changes in murres' prey availability during the breeding season has led to decreased breeding success

Frederiksen, M., et al. "Climate, copepods and seabirds in the boreal Northeast Atlantic–current state and future outlook." Global Change Biology 19.2 (2013): 364-372. Breeding success on the Isle of May was strongly correlated to suitable climate for local copepods, and increases in temperature have lowered suitability for copepods and therefore breeding success in recent years. Projections also show that this drop in suitability will continue and worsen in the future. Interestingly, the authors did not find evidence of such a link in Rost, Norway.

Irons, D. B., et al. "Fluctuations in circumpolar seabird populations linked to climate oscillations." Global Change Biology 14.7 (2008): 1455-1463. The authors find, using a multi-decade dataset, that murre population size across the Arctic is strongly correlated to sea surface temperature. Rapid temperature shifts (either hotter or cooler) resulted in a decrease in population size. Note: this study does not explicitly investigate anthropogenic climate change, but does show a clear linkage between rapid climate change and population declines.

6 - Murres are more likely to skip breeding in warmer weather, and this behaviour is becoming more frequent. While this is a cause for concern, it is unclear what effect this will have on the population in the long-term

Reed, T. E., Harris, M. P., and Wanless, S. "Skipped breeding in common guillemots in a changing climate: restraint or constraint?" Frontiers in Ecology and Evolution 3 (2015): 1. Murres (aka guillemots) skip breeding more frequently in/following warm years, and sea temperatures have increased in the study area (North Sea) over recent decades. this may increase in the future. However, the long term consequences of this impact on the population are unclear. Study conducted on Isle of May, Scotland.

7 - Heatwaves have resulted in significant murre chick mortality. The frequency and severity of heatwaves is likely to increase

Ballstaedt, Elmar (personal correspondance); See also https://www.jordsand.eu/2018/08/14/bruterfolg-deutscher-seev%C3%B6gel-durch-wetterkapriolen-schlecht-wie-lange-nicht-mehr The heatwave of summer 2018 resulted in fewer breeding attempts and increased chick mortality in many species on Helgoland, most likely due to heat stress. Many seabirds on Helgoland are declining which could in part be due to climate change.

8 - Common murres have changed their phenology, potentially in response to climate change but the mechanism is unclear

Wanless, S., et al. "Later breeding in northern gannets in the eastern Atlantic." Marine Ecology Progress Series 370 (2008): 263-269. Over a period of roughly 30 years, the laying date of common murres in the North Sea (Isle of May and Farne Islands) became significantly later. The study did not identify a mechanism for delayed breeding in a warming North Sea, but did find a correlation between combined auk/kittiwake laying dates and the winter NAO index.

9 - A shift towards warmer, drier and calmer conditions has correlated with higher population abundance. Mechanism unknown, but likely mediated through prey availability and lower energetic costs.

Hemery, G., et al. "Detecting the impact of oceano-climatic changes on marine ecosystems using a multivariate index: the case of the Bay of

Biscay (North Atlantic-European Ocean)." Global Change Biology 14.1 (2008): 27-38. Abundance of common murres in the Bay of Biscay increased from 1974 to 2000. Annual abundance (at-sea counts) was positively correlated with a local multivariate climate index (combining 11 oceanic and atmospheric variables) and the large-scale winter NAO index. Murres appear to benefit from a trend towards warmer, drier years with calmer sea surface conditions.

Thick-billed Murre

1 - Changes in thick-billed murres' prey availability during the non-breeding season has led to increased mortality

Descamps, S., Strøm, H., and Steen, H.. "Decline of an arctic top predator: synchrony in colony size fluctuations, risk of extinction and the subpolar gyre." Oecologia 173.4 (2013): 1271-1282. Many colonies in Svalbard are declining, and if trends continue there is a risk of local extinction. Declines strongly correlate with marine change, though the exact mechanism is unknown. Authors suggest that deterioration of the feeding conditions in the winter affected bird survival, particularly juvenile survival, and that local variations in spring and summer conditions affected breeding propensity and breeding success of murres.

Sandvik, H., et al. "The effect of climate on adult survival in five species of North Atlantic seabirds." Journal of Animal Ecology 74.5 (2005): 817-831. Authors found that both the common murres (guillemots) and thick-billed murres (Brünnich's guillemots) were negatively affected by warmer temperatures causing alterations to their food webs, they note that these trends are likely to continue. The data spanned 14 years of observation at a colony on Hornøya, off Northern Norway in the western Barents Sea

2 - Changes in thick-billed murres' prey availability during the breeding season has led to decreased breeding success

Descamps, S., Strøm, H., and Steen, H.. "Decline of an arctic top predator: synchrony in colony size fluctuations, risk of extinction and the subpolar gyre." Oecologia 173.4 (2013): 1271-1282. Local variations in Svalbard spring and summer conditions affected breeding propensity and breeding success of murres. See 1) for more details.

Garðarsson, A., Guðmundsson, G. A., and Lilliendahl, K. "Svartfugl í íslenskum fuglabjörgum 2006–2008." Bliki 33 (2019): 35-46. Reviews the population trends in various seabird species in Iceland. Particularly highlights the drastic decline of thick-billed murres (Brünnich's guillemots) across Iceland. Sharp declines correspond to crash in key prey species and changes in marine ecosystems linked to rapid temperature change.

3 - Changes in thick-billed murres' prey availability during the breeding season has led to increased mortality

Fluhr, J., et al. "Weakening of the subpolar gyre as a key driver of North Atlantic seabird demography: a case study with Brünnich's guillemots in Svalbard." Marine Ecology Progress Series 563 (2017): 1-11. An update and expansion on the previous paper, focussing on murres on Bear Island, Svalbard. Confirms strong correlation of adult annual survival and the strength of Atlantic subpolar gyre.

4 - Thick-billed murre populations are typically smaller and decline in areas with increasing sea temperatures. Mechanism unclear.

Bonnet-Lebrun, A. S., et al. "Cold comfort: Arctic seabirds find refugia from climate change and potential competition in marginal ice zones and fjords." Ambio 51.2 (2022): 345-354. Thick-billed murres (Brünnich's guillemots) populations in Iceland have declined in correlation with rising sea surface temperatures. In addition, populations associated with higher sea temperatures have declined faster and tend to be smaller than those near refugia of cold water. The authors investigate the role of competition (with little significant effect), but link to various Icelandic studies which provide evidence for prey availability being the main reason behind the declines

Irons, D. B., et al. "Fluctuations in circumpolar seabird populations linked to climate oscillations." Global Change Biology 14.7 (2008): 1455-1463. The authors find, using a multi-decade dataset, that murre population size across its range in the Arctic is strongly correlated to sea surface temperature. Rapid temperature shifts (either hotter or cooler) resulted in a decrease in population size, probably mediated through changes in underlying food-webs. Note: this study does not explicitly investigate anthropogenic climate change, but does show a clear linkage between rapid climate change and population declines.

5 - Extreme storms during the non-breeding season have led to mass mortality of murres ('wrecks')

Clairbaux, M., et al. "North Atlantic winter cyclones starve seabirds." Current Biology 31.17 (2021): 3964-3971. Following heavy storm action, seabird mortality increases due to increased difficulty foraging (rather than increased energetic costs). The authors use a multi-species dataset (puffins, little auks, common murres, and thick-billed murres) over a wide area of the Atlantic basin. They conclude that seabirds around Iceland and the Barents Sea (along with several N. American sites) are particularly vulnerable. Climate change is likely to be a contributing factor to present and future storm mortality.

1.1.2 Change in European range size between present day and 2100:

Using a species distribution model (SDM) we correlated species occurrence during the breeding season with a number of terrestrial and marine environmental variables. Species range data came from the European Breeding Bird Atlas (EBBA2) database. Present-day and 2100 terrestrial data were downloaded from the WorldClim database. We used data from the MRI-ESM2 general circulation model (GCM), which is a high-performing model over Europe. Present-day and 2100 marine data were downloaded from the Bio-Oracle database which averages predictions of marine variables from several different atmospheric-oceanic general circulation models (AOGCMS; for full details see Assis et al., 2017). For the map presented in the summary we used representative concentration pathway (RCP) 4.5, which is an “intermediate” emissions scenario. All data were at 5-minute resolution.

For razorbill, little auk, black guillemot, Atlantic puffin, common murre, and thick-billed murre we included the following terrestrial variables: mean temperature of the warmest month, precipitation during breeding season, isolation of landmass, area of landmass, distance to sea.

For razorbill, little auk, black guillemot, Atlantic puffin, common murre, and thick-billed murre we included the following marine variables: sea surface temperature (during the winter), salinity, maximum chlorophyll concentration, bathymetry (depth and variance).

After running our model we generated a present-day map where every grid-cell is given a habitat suitability score between 0 and 1, where 1 is very suitable habitat and 0 is not at all suitable. We then compared this with a corresponding map built with 2100 data, and highlighted currently inhabited areas where 1) suitability drops sharply (i.e. by more than 0.1) and 2) suitability drops below a probability threshold set by the model. Conversely we also highlighted areas where suitability rose sharply and above a given threshold. While a drop in habitat suitability is likely to result in population declines, it is not a certainty, and it does not mean that a population will be extinct in 2100 or that a population is doomed to extinction. With conservation action and careful management, along with changes in human behaviour, such declines may be mitigated or in some cases prevented. For a full explanation of the model see the accompanying ‘Methodology’ folder in Appendix 2.

Underlying data were downloaded from:

> **Keller, V., et al. "European Breeding Bird Atlas 2: Distribution, Abundance and Change." European Bird Census Council & Lynx Edicions, Barcelona (2020).** Source of range data

Fick, S. E., and Hijmans, R. J. "WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas." International Journal of Climatology 37.12 (2017): 4302-4315. Source of present-day and 2100 terrestrial data.

Assis, J., et al. "Bio-ORACLE v2. 0: Extending marine data layers for bioclimatic modelling." Global Ecology and Biogeography 27.3 (2018): 277-284. Source of present-day and 2100 marine data

1.1.3 Changes in key prey species:

We first identified the key prey species for each species. This can be variable across a species' range, but if available evidence suggested at least one major population is highly dependent on a particular prey species, then typically this species would be included. Lists of prey species were compiled from published sources, then verified and expanded following consultation with conservation practitioners. Afterwards we compiled current and projected maps of prey ranges to assess where key prey species may become less common in the near future. If any of the key species are predicted to vanish or drastically reduce in abundance in the current foraging range a given species, we marked this on the summary map.

We used several sources to collate range information, but for preference we used data from COPERNICUS as they include projected abundance. For species where this was not available we used habitat suitability instead. In all cases we used RCP 4.5, which is an "intermediate" emissions scenario. For species in the COPERNICUS database we used the 0.6 maximum sustainable yield parameter, which assumes international co-operation to work towards fish-stock sustainability. Our assessment is therefore relatively conservative in terms of changes in prey species.

Razorbill key prey species: sandeel species (*Ammodytes marinus* and *Ammodytes tobianus*), herring (*Clupea harengus*), capelin (*Mallotus villosus*) and sprat (*Sprattus sprattus*). Prey species list was compiled from:

Barrett, R. T. "The diet, growth and survival of Razorbill Alca torda chicks in the southern Barents Sea." Ornis Norvegica 38 (2015): 25-31.

Fauchald, Per, et al. "The status and trends of seabirds breeding in Norway and Svalbard." NINA rapport 1151. Norsk institutt for naturforskning (2015): 1-84.

Little Auk key prey species: *Calanus glacialis*, *Calanus hyperboreus* and *Apherusa glacialis*. Note that since data regarding climate change and copepod range shifts are not readily available, a full prey loss assessment could not be carried out for this species. Prey species list was compiled from:

Amélineau, F., et al. "Arctic climate change and pollution impact little auk foraging and fitness across a decade." Scientific reports 9.1 (2019): 1-15.

Harding, A. M. A., et al. "Estimating prey capture rates of a planktivorous seabird, the little auk (Alle alle), using diet, diving behaviour, and energy consumption." Polar Biology 32.5 (2009): 785-796.

Black Guillemot key prey species: sandeel species (*Ammodytes marinus*), butterfish (*Pholis gunnellus*), eelpout (*Zoarces viviparus*) and sea scorpion (*Taurulus bubalis*). Prey species list was compiled from:

Barrett, R. T., and Anker-Nilssen, T. "Egg-laying, chick growth and food of Black Guillemots Cepphus grylle in North Norway." Fauna Norvegica, Series C 20.2 (1997): 69-79.

BirdLife International. "Species factsheet: Cepphus grylle." (2021) Downloaded from http://www.birdlife.org on 01/06/2021.

Ewins, P. J. "The diet of black guillemots Cepphus grylle in Shetland." Ecography 13.2 (1990): 90-97.

Fauchald, Per, et al. "The status and trends of seabirds breeding in Norway and Svalbard." NINA rapport 1151. Norsk institutt for naturforskning (2015): 1-84.

Hario, M. "Chick growth and nest departure in Baltic Black Guillemots Cepphus grylle." Ornis Fennica 78.3 (2001): 97-108.

Hof, A. R., Crombag, J. A. H. M. , and Allen, A. M. "The ecology of Black Guillemot Cepphus grylle grylle chicks in the Baltic Sea region: insights into their diet, survival, nest predation and moment of fledging." Bird Study 65.3 (2018): 357-364.

Atlantic Puffin key prey species: sandeel species (*Ammodytes marinus* and *Ammodytes tobianus*), herring (*Clupea harengus*), capelin (*Mallotus villosus*) and sprat (*Sprattus sprattus*). Prey species list was compiled from:

BirdLife International. "Species factsheet: Fratercula arctica." (2021) Downloaded from http://www.birdlife.org on 01/06/2021.

Fayet, A. L., et al. "Local prey shortages drive foraging costs and breeding success in a declining seabird, the Atlantic puffin." Journal of Animal Ecology 90.5 (2021): 1152-1164.

Common Murre key prey species: sprat (*Sprattus sprattus*), sandeels species (*Ammodytes marinus* and *Ammodytes tobianus*), capelin (*Mallotus villosus*), herring

(*Clupea harengus*), Atlantic cod (*Gadus morhua)*, saithe (*Pollachius virens*) and haddock (*Melanogrammus aeglefinus*). Prey species list was compiled from:

Ainley, D. G., Nettleship, D. N., and Storey, A. E. “Common Murre (Uria aalge), version 2.0.” In Birds of the World (S. M. Billerman, P. G. Rodewald, and B. K. Keeney, Editors). Cornell Lab of Ornithology, Ithaca, NY, USA (2021).

BirdLife International. “Species factsheet: Uria aalge.” (2021) Downloaded from http://www.birdlife.org on 01/06/2021.

Fauchald, Per, et al. "The status and trends of seabirds breeding in Norway and Svalbard." NINA rapport 1151. Norsk institutt for naturforskning (2015): 1-84.

Thick-billed Murre key prey species: sandeel species (*Ammodytes marinus* and *Ammodytes tobianus*), herring (*Clupea harengus*), capelin (*Mallotus villosus*), Atlantic cod (*Gadus morhua*) and polar cod (*Boreogadus saida*). Prey species list was compiled from:

Fauchald, Per, et al. "The status and trends of seabirds breeding in Norway and Svalbard." NINA rapport 1151. Norsk institutt for naturforskning (2015): 1-84.

Prey range information for all species were compiled from:

Kesner-Reyes, K., et al. "AquaMaps: Predicted range maps for aquatic species." In FishBase: R. Froese & D. Pauly (Eds.) (2019). Available at: https://www.aquamaps.org

Sailley, S., et al. "Fish abundance and catch data for the Northwest European Shelf and Mediterranean Sea from 2006 to 2098 derived from climate projections". Copernicus Climate Change Service (C3S) Climate Data Store (CDS) (2021). https://doi.org/10.24381/cds.39c97304.

1.1.4 Climate change impacts outside of Europe

Little Auk

Loss of sea ice and new prey items due to climate change has led to increased little auk breeding success in Greenland

Amélineau, F., et al. “Arctic climate change and pollution impact little auk foraging and fitness across a decade.” Scientific reports 9.1 (2019): 1-15.

Atlantic Puffin

Some colonies in North America have changed their laying phenology, presumably in response to temperature and/or prey availability. Some recent observations have reported this has also occurred in Europe.

Major, H. L., et al. “Contrasting phenological and demographic responses of Atlantic Puffin (Fratercula arctica) and Razorbill (Alca torda) to climate change in the Gulf of Maine.” Elem Sci Anth 9.1 (2021): 00033.
Erpur Hansen (Personal Correspondence)

Thick-billed Murre

Thick-billed murres are known to be impacted by climate change outside of Europe. Impacts include increased predation by polar bears, increased parasitism by mosquitoes (leading to breeding failure), and increased mortality caused by algal blooms. Changes in the marine ecosystem in the canadian high Arctic, driven by climate change, has resulted in higher concentrations of mercury bioaccumulated in thick-billed murres. No long-term impact on population health has been observed so far.

Braune, B. M., et al. “Changes in food web structure alter trends of mercury uptake at two seabird colonies in the Canadian Arctic.” Environmental science & technology 48.22 (2014): 13246-13252.

Gaston, A. J., and Elliott, K. H. “Effects of climate-induced changes in parasitism, predation and predator-predator interactions on reproduction and survival of an Arctic marine bird.” Arctic (2013): 43-51.

Kuletz, K. et al. “Chapter 3.5: Seabirds” in “State of the Arctic Marine Biodiversity Report”. Conservation of Arctic Flora and Fauna International Secretariat (2017): 129-147.

1.2 Sensitivity (references)

We used a list of candidate traits based on that in Foden & Young (2016) that indicate high sensitivity and identified which, if any, auks possessed. In brief, we consulted published literature as well as expert knowledge and online databases such as Birdlife (http://datazone.birdlife.org/) and Birds of the World (https://birdsoftheworld.org), to assess whether auks have either 1) Specialised habitat and/or microhabitat requirement 2) Environmental tolerances or thresholds (at any life stage) that are likely to be exceeded due to climate change 3) Dependence on environmental triggers that are likely to be disrupted by climate change, 4) Dependence on interspecific interactions that are likely to be disrupted by climate change or 5) High rarity.

For more detail and a full list of traits see:

> Foden, W. B. and Young, B. E. (eds.). "IUCN SSC Guidelines for Assessing Species' Vulnerability to Climate Change. Version 1.0." Occasional Paper of the IUCN Species Survival Commission No. 59 (2016). Cambridge, UK and Gland, Switzerland: IUCN Species Survival Commission. x+114pp.

1.3 Adaptive capacity (references)

We used a list of candidate traits based on that in Foden & Young (2016) that indicate adaptive capacity and identified which, if any, auks possessed. In brief, we consulted published literature as well as expert knowledge and online databases such as Birdlife (http://datazone.birdlife.org/) and Birds of the World (https://birdsoftheworld.org), to assess whether auks have either: 1) High phenotypic plasticity. 2) High dispersal ability or 3) High evolvability.

For more detail and a full list of traits see:

> Foden, W. B. and Young, B. E. (eds.). "IUCN SSC Guidelines for Assessing Species' Vulnerability to Climate Change. Version 1.0." Occasional Paper of the IUCN Species Survival Commission No. 59 (2016). Cambridge, UK and Gland, Switzerland: IUCN Species Survival Commission. x+114pp.

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Appendix 1: Ducks and Phalaropes

Sources and references for vulnerability assessment

1.1 Evidence for exposure (references)

1.1.1 Current impacts attributed to climate change:

Long-tailed Duck

1 - Wintering populations in Europe have declined due to climate change-driven changes in predation in breeding areas outside of Europe.

Hario, M., Rintala, J., and Nordenswan, G. "Dynamics of wintering long-tailed ducks in the Baltic Sea–the connection with lemming cycles, oil disasters, and hunting." Suomen Riista 55 (2009): 83-96. Wintering populations in the Baltic have rapidly declined, in part because of the effects of climate change on key breeding sites outside of Europe. Due to changes in lemming availability, predators such as Arctic foxes have swapped to preying on duck eggs and young as alternative prey which, in turn, has resulted in decreased breeding success of long-tailed duck Clangula hyemalis on the Taimyr Peninsula.

Hearn, R. D., Harrison, A. L., and Cranswick, P. A. "International single species action plan for the conservation of the long-tailed duck Clangula hyemalis, 2016–2025." AEWA Technical Series Species Action Plan: 57 (2015). Expands and updates the work above, the authors believe changes in predation have affected populations across western Siberia and northern Europe

2 - Range expansion of red foxes following milder winters has led to predation of ducks much further north than previously, and may be threatening the viability of northern populations.

Hearn, R. D., Harrison, A. L., and Cranswick, P. A. "International single species action plan for the conservation of the long-tailed duck Clangula hyemalis, 2016–2025." AEWA Technical Series Species Action Plan: 57 (2015). Range expansion of predators such as red fox (Vulpes vulpes) may be influencing predator-prey relationships in the Arctic breeding grounds, and appears to be threatening the viability of the small Finnish Lapland breeding population of long-tailed ducks. Additional information on the risk and spread of red foxes due to climate change was provided by stakeholders.

3 - Competition with non-native gobies has caused long-tailed ducks to switch prey, though there has been no observed change in mortality or condition. Goby invasion

may have been assisted by climate change, though currently this is speculative.

Behrens, J. W., et al. “Seasonal depth distribution and thermal experience of the non-indigenous round goby Neogobius melanostomus in the Baltic Sea: implications to key trophic relations.” Biological Invasions 24.2 (2022): 527-541. This study does not make a link directly to seabirds, but is provided as supplementary information making the link between gobies and climate change clearer. Gobies strongly prefer warm water, which explain why they have now colonised the Baltic as climate change has resulted in warmer winters. It also suggests further climate change will assist further spread.

Skabeikis, A., et al. “Effect of round goby (Neogobius melanostomus) invasion on blue mussel (Mytilus edulis trossulus) population and winter diet of the long-tailed duck (Clangula hyemalis).” Biological Invasions 21.3 (2019): 911-923. The benthic round goby has recently colonised the Baltic, which may have been facilitated by climate change (Ramunas Žydelis, personal communication), as gobies strongly prefer warmer water (see Behrens et al. 2022 below). Competition with gobies has caused long-tailed ducks to switch prey, and there has been no observed change in mortality or condition. However, further climate change could promote goby expansion and further competition.

Harlequin Duck

1 - Population has redistributed, with some populations growing and others shrinking, most likely due to shifts in prey species caused by climate change

Gardarsson, A. “Harlequin Ducks in Iceland.” Waterbirds 31.sp2 (2008): 8-14.

Gardarsson, A., and Einarsson, Á. "Relationships among food, reproductive success and density of harlequin ducks on the River Laxá at Myvatn, Iceland (1975-2002)." Waterbirds 31.sp2 (2008): 84-91. Using a multidecade dataset the authors conclude that southern populations in Iceland have decreased 1961-2001 while northern populations have increased. This is likely due to changes in blackfly abundance, which in turn is at least partly due to warmer springs and summers

Velvet Scoter

1 - Scoters are starting their autumn migration significantly later in response to changing climate.

Lehikoinen, A., and Jaatinen, K. "Delayed autumn migration in northern European waterfowl." Journal of Ornithology 153.2 (2012): 563-570. Scoter phenology changed between 1979 and 2009, consistent with expectations under a warming local climate. Autumn migration is occurring later, birds are arriving later. Study carried out using long term data from Hanko Observatory, southern Finland

2 - Wintering populations have redistributed, most likely due to lack of prey caused at least partly by climate change.

Tolon, V., et al. "Etat des populations de macreuses en Europe, en France et en Basse-Normandie et analyse des principaux facteurs de distribution". Report for Maison de l'Estuaire (2013). Wintering populations of scoters off the coast of France are declining and in some cases have disappeared. Cause is uncertain, but probably they have redistributed rather than died, and have shifted in response to reduced prey availability. There are several underlying causes, but climate change is likely to be a contributing factor.

Common Scoter

1 - Wintering populations have redistributed, most likely due to lack of prey caused at least partly by climate change.

Tolon, V., et al. "Etat des populations de macreuses en Europe, en France et en Basse-Normandie et analyse des principaux facteurs de distribution". Report for Maison de l'Estuaire (2013). Wintering populations of scoters off the coast of France are declining and in some cases have disappeared. Cause is uncertain, but probably they have redistributed rather than died, and have shifted in response to reduced prey availability. There are several underlying causes, but climate change is likely to be a contributing factor.

Red-necked Phalarope

1 - Red-necked phalaropes have shifted north in Finland, the most southerly populations are declining while northerly populations are increasing. This shift is in correlation with climate change, but the underlying mechanism is not certain

Virkkala, R., et al. "Matching trends between recent distributional changes of northern-boreal birds and species-climate model predictions." Biological Conservation 172 (2014): 124-127. Red-necked phalaropes have shifted north in Finland, the central density of the population has shifted significantly northwards. This shift is in correlation with climate change, but the underlying mechanism is not certain.

Steller's Eider

1 - Many Steller's eiders in the Baltic have changed wintering area to the White Sea, most likely due to decreases in sea ice. This may also be associated with an overall population decline, but this is uncertain

Aarvak, T., et al. "The European wintering population of Steller's Eider Polysticta stelleri reassessed." Bird Conservation International 23.3 (2013):

337-343. The number of Steller’s eiders wintering in the Baltic has dropped sharply. This is likely due to both a decrease in population size and a redistribution of wintering area to the White sea, most likely due to decreases in sea ice and a greater area of open water.

Žydelis, R., et al. “Recent changes in the status of Steller’s Eider Polysticta stelleri wintering in Europe: a decline or redistribution?.” Bird Conservation International 16.3 (2006): 217-236. This paper precedes the one above and concludes that although there was a redistribution towards the Kola Peninsula, the population may be declining as a whole.

Common Eider

1 - Milder winter and summer weather have resulted in better average adult condition, and therefore better breeding success. In some areas this has resulted in local populations increases.

D’Alba, L., Monaghan, P., and Nager, R. G. "Advances in laying date and increasing population size suggest positive responses to climate change in common eiders Somateria mollissima in Iceland." Ibis 152.1 (2010): 19-28. Using a 30 year dataset in Iceland, the authors believe climate change is a major driver behind the population increase. Milder summers mean more nests, because fewer females skip breeding (as they are in higher condition)

2 - Eiders have shifted their phenology in response to milder winters and lay earlier.

D’Alba, L., Monaghan, P., and Nager, R. G. "Advances in laying date and increasing population size suggest positive responses to climate change in common eiders Somateria mollissima in Iceland." Ibis 152.1 (2010): 19-28. In Iceland, eiders laid earlier following warmer winters. The exact reason is uncertain but could be because adults are in better condition following winter, or because key prey species (especially mussels) are available earlier in milder winters.

3 - Due to a lack of sea ice driven by climate change, polar bears are becoming more numerous around bird colonies during the summer and are more heavily predating on eider populations

Prop, J., et al. “Climate change and the increasing impact of polar bears on bird populations.” Frontiers in Ecology and Evolution 3 (2015): 33. Study conducted on Svalbard, polar bears appear to be swapping prey species from seals due to a lack of sea ice. Several bird species are increasingly predated, prominently eiders.

4 - Earlier melt of sea ice in spring has resulted in a decrease in predation by Arctic

foxes, as they cannot access breeding colonies without the presence of sea ice

Hanssen, S. A., et al. "A natural antipredation experiment: predator control and reduced sea ice increases colony size in a long-lived duck." Ecology and Evolution 3.10 (2013): 3554-3564. Across two eider colonies in Spitsbergen, population density is greater in years with less sea ice in April. The study suggests this provides earlier/longer access to food and reduces predation by Arctic foxes. The study used a 30-year dataset, and notes that April sea ice cover has declined over this period.

5 - Earlier melt of sea ice in spring has resulted in an increase in eider population density, as eiders have earlier and longer access to high-quality prey.

Hanssen, S. A., et al. "A natural antipredation experiment: predator control and reduced sea ice increases colony size in a long-lived duck." Ecology and Evolution 3.10 (2013): 3554-3564. Across two eider colonies in Spitsbergen, population density is greater in years with less sea ice in April. The study suggests this provides earlier/longer access to food and reduces predation by Arctic foxes. The study used a 30-year dataset, and notes that April sea ice cover has declined over this period.

1.1.2 Change in European range size between present day and 2100:

Using a species distribution model (SDM) we correlated species occurrence during the breeding season with a number of terrestrial and marine environmental variables. Species range data came from the European Breeding Bird Atlas (EBBA2) database. Present-day and 2100 terrestrial data were downloaded from the WorldClim database. We used data from the MRI-ESM2 general circulation model (GCM), which is a high-performing model over Europe. Present-day and 2100 marine data were downloaded from the Bio-Oracle database which averages predictions of marine variables from several different atmospheric-oceanic general circulation models (AOGCMS; for full details see Assis et al., 2017). For the map presented in the summary we used representative concentration pathway (RCP) 4.5, which is an “intermediate” emissions scenario. All data were at 5-minute resolution.

For long-tailed duck, harlequin duck, velvet scoter, common scoter, red-breasted merganser, red phalarope, and red-necked phalarope we included the following terrestrial variables: Mean temperature of the warmest month, precipitation during breeding season, distance to sea

For Steller’s eider, common eider, and king eider we included the following terrestrial variables: mean temperature of the warmest month, precipitation during breeding season, isolation of landmass, area of landmass, distance to sea.

For Steller's eider, common eider, and king eider we included the following marine variables: sea surface temperature (during the winter), salinity, maximum chlorophyll concentration, bathymetry (depth and variance).

Several other variables may strongly influence the distribution of ducks and phalaropes and it is not possible to include all possible variables in a given model. However the following variables have previously been found to be important to predicting the distribution of ducks and phalaropes in Europe: freshwater depth, freshwater ph, freshwater chlorophyll concentration, seabed substrate (sediment granulometry). For local assessments of climate change, we recommend these variables are strongly considered. We hope to incorporate these variables into future versions of this resource.

After running our model we generated a present-day map where every grid-cell is given a habitat suitability score between 0 and 1, where 1 is very suitable habitat and 0 is not at all suitable. We then compared this with a corresponding map built with 2100 data, and highlighted currently inhabited areas where 1) suitability drops sharply (i.e. by more than 0.1) and 2) suitability drops below a probability threshold set by the model. Conversely we also highlighted areas where suitability rose sharply and above a given threshold. While a drop in habitat suitability is likely to result in population declines, it is not a certainty, and it does not mean that a population will be extinct in 2100 or that a population is doomed to extinction. With conservation action and careful management, along with changes in human behaviour, such declines may be mitigated or in some cases prevented. For a full explanation of the model see the accompanying 'Methodology' folder in Appendix 2.

Underlying data were downloaded from:

Keller, V., et al. "European Breeding Bird Atlas 2: Distribution, Abundance and Change." European Bird Census Council & Lynx Edicions, Barcelona (2020). Source of range data

Fick, S. E., and Hijmans, R. J. "WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas." International Journal of Climatology 37.12 (2017): 4302-4315. Source of present-day and 2100 terrestrial data.

Assis, J., et al. "Bio-ORACLE v2. 0: Extending marine data layers for bioclimatic modelling." Global Ecology and Biogeography 27.3 (2018): 277-284. Source of present-day and 2100 marine data

1.1.3 Changes in key prey species:

We first identified the key prey species for each species. This can be variable across a species' range, but if available evidence suggested at least one major population is highly dependent on a particular prey species, then typically this species would be included. Lists of prey species were compiled from published sources, then verified and expanded following consultation with conservation practitioners. Afterwards we compiled current and projected maps of prey ranges to assess where key prey species may become less common in the near future. If any of the key species are predicted to vanish or drastically reduce in abundance in the current foraging range a given species, we marked this on the summary map.

We used several sources to collate range information, but for preference we used data from COPERNICUS as they include projected abundance. For species where this was not available we used habitat suitability instead. In all cases we used RCP 4.5, which is an "intermediate" emissions scenario. For species in the COPERNICUS database we used the 0.6 maximum sustainable yield parameter, which assumes international co-operation to work towards fish-stock sustainability. Our assessment is therefore relatively conservative in terms of changes in prey species.

Long-tailed Duck key prey species: This species relies on predominantly aquatic invertebrates on breeding grounds, and a variety of invertebrates, notably Mytilus species, and fish in winter. No key species could be identified so currently there is no key prey assessment for this species

Harlequin Duck key prey species: In summer, this species preys mainly on various midges, blackfly and caddis flies. In winter, no key species could be identified as diet is extremely varied. Currently this species does not have a key prey assessment

Velvet Scoter key prey species: *Mya arenaria, Cerastoderma glaucum, Saduria entomon, Euspira nitida, Macoma baltica, Cerastoderma lamarcki and Spisula subtruncata.* Prey species list was compiled from:

Morkune, R., et al. "Triple stable isotope analysis to estimate the diet of the Velvet Scoter (Melanitta fusca) in the Baltic Sea." PeerJ 6 (2018): e5128.

Durinck, J, et al. "Diet of the common scoter Melanitta nigra and velvet scoter Melanitta fusca wintering in the North Sea." Ornis Fennica 70.4 (1993): 215-218.

Stempniewicz, L. "The food intake of two Scoters Melanitta fusca and M. nigra wintering in the Gulf of Gdańsk, Polish Baltic coast." Vår Fågelv., Suppl 11 (1986): 211-214..

Common Scoter key prey species: *Spisula subtruncata, Mya truncata, Macoma* *balthica, Mytilis edulis and Donax vittatus*. This species also preys on insects, especially chironomid larvae and cladocerans. Presently these are not included in the key prey assessment, due to data limitations.. Prey species list was compiled from:

> Carboneras, C. and Kirwan, G. M. "Common Scoter (Melanitta nigra), version 1.0." In Birds of the World (J. del Hoyo, A. Elliott, J. Sargatal, D. A. Christie, and E. de Juana, Editors). Cornell Lab of Ornithology, Ithaca, NY, USA (2020).
>
> Durinck, J., et al. "Diet of the common scoter Melanitta nigra and velvet scoter Melanitta fusca wintering in the North Sea." Ornis Fennica 70.4 (1993): 215-218.
>
> Hartley, C. "Status and distribution of Common Scoters on the Solway Firth." British Birds 100.5 (2007): 280.
>
> Stempniewicz, L. "The food intake of two Scoters Melanitta fusca and M. nigra wintering in the Gulf of Gdansk, Polish Baltic coast." Vår Fågelv., Suppl 11 (1986): 211-214.

Red-breasted Merganser key prey species: stickleback (*Gasterosteus aculeatus*). This species consumes a wide variety of fish species, both marine and freshwater. Freshwater species, especially *Salmo salar,* are likely very important but freshwater species are currently not included in the key prey assessment. While it preys on other marine species, no other key species could be identified. Prey species list was compiled from:

> Bengtson, S.-A. "Food and feeding of diving ducks breeding at Lake Myvatn, Iceland." Ornis Fennica Vol. 48 (1971): 77-92.
>
> Craik, S., Pearce, J., and Titman, R. D. "Red-breasted Merganser (Mergus serrator), version 1.0." In Birds of the World (S. M. Billerman, Editor). Cornell Lab of Ornithology, Ithaca, NY, USA (2020).
>
> Feltham, M. "The diet of red-breasted mergansers (Mergus serrator) during the smolt run in NE Scotland: the importance of salmon (Salmo salar) smolts and parr." Journal of Zoology 222.2 (1990): 285-292.

Red Phalarope key prey species: This species has a broad diet of invertebrates, that varies across populations. Key species groups include marine copepods and amphipods, as well as adult and larval midges, gnats and craneflies. Currently there is no key prey assessment, due to lack of data.

Red-necked Phalarope key prey species: During the breeding species this species feed primarily on midges (adults and larvae), along with many other insect species. At sea, it feeds mostly on copepods and krill species. Currently there is no key prey assessment for this species

Steller's Eider key prey species: *Margarites helicinus, Skeneopsis planorbis, Mytilus edulis, Turtonia minuta, Gammarus oceanicus, Ampithoe rubricata, Idotea emarginata and Idotea granulosa*. This species also preys on various midge and cranefly larvae, especially during the breeding season. These terrestrial species are not included in the key prey assessment. Prey species list was compiled from

Bustnes, Jan O., et al. "The diet of Steller's Eiders wintering in Varangerfjord, northern Norway." The Wilson Journal of Ornithology 112.1 (2000): 8-13.

Fredrickson, L. H. "Steller's Eider (Polysticta stelleri), version 1.0." In Birds of the World (S. M. Billerman, Editor). Cornell Lab of Ornithology, Ithaca, NY, USA (2020).

Nygård, T., Frantzen, B., and Švažas, Saulius. "Steller's Eiders Polysticta stelleri wintering in Europe: numbers, distribution and origin." Wildfowl 46.46 (1995): 140-156.

Common Eider key prey species: *Mytilus edulis, Modiolus modiolus, Tonicella marmorea, Buccinum undatum, Hyas araneus and Lacuna vincta*. Prey species list was compiled from:

Bustnes, J. O., and Erikstad, K. E. "The diets of sympatric wintering populations of Common Eider Somateria mollissima and King Eider S. spectabilis in Northern Norway." Ornis Fennica 65.4 (1988): 163-168.

Goudie, R. I., Robertson, G. J., and Reed, A. "Common Eider (Somateria mollissima), version 1.0". In Birds of the World (S. M. Billerman, Editor). Cornell Lab of Ornithology, Ithaca, NY, USA (2020).

Kristjánsson, T. Ö., Jónsson, J. E., and Svavarsson, J. "Spring diet of common eiders (Somateria mollissima) in Breiðafjörður, West Iceland, indicates non-bivalve preferences." Polar Biology 36.1 (2013): 51-59.

King Eider key prey species: *Ophiopholis aculeata, Strongylocentrotus droebachiensis, Asterias rubens, Boreotrophon clathratus, Musculus discors, Modiolaria modiolus, Chlamys islandica, Mya truncata, Mytilus edulis, Ciliatocardium ciliatum and Hiatella arctica.* Prey species list was compiled from:

Powell, A. N. and Suydam, R. S. "King Eider (Somateria spectabilis), version 1.0." In Birds of the World (S. M. Billerman, Editor). Cornell Lab of

Ornithology, Ithaca, NY, USA (2020).

Frimer, O. “Diet of moulting king eiders Somateria spectabilis at Disko Island, West Greenland.” Ornis Fennica 74 (1997): 187-194.

Merkel, F. R., et al. “The diet of king eiders wintering in Nuuk, Southwest Greenland, with reference to sympatric wintering common eiders.” Polar Biology 30.12 (2007): 1593-1597.

Prey range information for all species were compiled from:

Kesner-Reyes, K., et al. "AquaMaps: Predicted range maps for aquatic species." In FishBase: R. Froese & D. Pauly (Eds.) (2019). Available at: https://www.aquamaps.org

Sailley, S., et al. "Fish abundance and catch data for the Northwest European Shelf and Mediterranean Sea from 2006 to 2098 derived from climate projections". Copernicus Climate Change Service (C3S) Climate Data Store (CDS) (2021). https://doi.org/10.24381/cds.39c97304.

Velvet Scoter

Climate change has contributed to declines of scoter populations in North America. Earlier spring snow melt has likely led to a trophic mismatch and lower breeding success in scoters.

Drever, M. C., et al. “Population vulnerability to climate change linked to timing of breeding in boreal ducks.” Global Change Biology 18.2 (2012): 480-492.

Common Scoter

Climate change has contributed to declines of scoter populations in North America. Earlier spring snow melt has likely led to a trophic mismatch and lower breeding success in scoters.

Drever, M. C., et al. “Population vulnerability to climate change linked to timing of breeding in boreal ducks.” Global Change Biology 18.2 (2012): 480-492.

Red Phalarope

In Alaska red phalaropes now lay smaller eggs on average, presumably due to lower condition. This is likely due to delayed snow melt due to higher precipitation, despite the general warming trend. Across California red phalaropes have declined across their wintering areas. This is likely due to changes in ocean currents and declines in prey abundance. Populations around Alaska have declined in some areas, or possibly redistributed, due to changes in sea ice and in key copepod prey species

Gall, A. E., et al. “Ecological shift from piscivorous to planktivorous seabirds in the Chukchi Sea, 1975–2012.” Polar Biology 40.1 (2017): 61-78.

Martin, J.-L., et al. "Late snowmelt can result in smaller eggs in Arctic shorebirds." Polar Biology 41.11 (2018): 2289-2295.

Sydeman, W. J., et al. “Climate–ecosystem change off southern California: time-dependent seabird predator–prey numerical responses.” Deep Sea Research Part II: Topical Studies in Oceanography 112 (2015): 158-170.

Red-necked Phalarope

A study in Alaska found that phalaropes have changed their laying date in response to changes in snow melt. Phalaropes have responded to changes in oceanic patterns in the Indian ocean and changed their foraging areas and patterns in response.

Liebezeit, J. R., et al. “Phenological advancement in arctic bird species: relative importance of snow melt and ecological factors.” Polar Biology 37.9 (2014): 1309-1320.

Nussbaumer, R., et al. “Investigating the influence of the extreme Indian Ocean Dipole on the 2020 influx of Red-necked Phalaropes Phalaropus lobatus in Kenya.” Ostrich (2021): 1-9.

Common Eider

Known to be affected by climate change in other parts of their range. They suffer increased predation from Arctic foxes due to prey switching following a collapse in lemming breeding cycles in northern Canada. In addition Canadian populations have suffered due to changes in weather in the breeding season, especially increased rain, either directly through exposure or indirectly through changes in predation.

Iles, D. T., et al. “Predators, alternative prey and climate influence annual breeding success of a long-lived sea duck.” Journal of Animal Ecology 82.3 (2013): 683-693.

King Eider

Increase in ice break-up, and increased variability of break-up, caused by climate change has resulted in significant damage to benthic prey and has caused local shifts in prey availability. Currently this has only a small impact on king eiders, but impacts could become significant in the future.

Lovvorn, J. R., et al. “Limits to benthic feeding by eiders in a vital Arctic migration corridor due to localized prey and changing sea ice.” Progress in Oceanography 136 (2015): 162-174.

1.2 Sensitivity (references)

We used a list of candidate traits based on that in Foden & Young (2016) that indicate high sensitivity and identified which, if any, sea ducks and phalaropes possessed. In brief, we consulted published literature as well as expert knowledge and online databases such as Birdlife (http://datazone.birdlife.org/) and Birds of the World (https://birdsoftheworld.org), to assess whether sea ducks and phalaropes have either 1) Specialised habitat and/or microhabitat requirement 2) Environmental tolerances or thresholds (at any life stage) that are likely to be exceeded due to climate change 3) Dependence on environmental triggers that are likely to be disrupted by climate change, 4) Dependence on interspecific interactions that are likely to be disrupted by climate change or 5) High rarity.

For more detail and a full list of traits see:

> Foden, W. B. and Young, B. E. (eds.). "IUCN SSC Guidelines for Assessing Species' Vulnerability to Climate Change. Version 1.0." Occasional Paper of the IUCN Species Survival Commission No. 59 (2016). Cambridge, UK and Gland, Switzerland: IUCN Species Survival Commission. x+114pp.

1.3 Adaptive capacity (references)

We used a list of candidate traits based on that in Foden & Young (2016) that indicate adaptive capacity and identified which, if any, sea ducks and phalaropes possessed. In brief, we consulted published literature as well as expert knowledge and online databases such as Birdlife (http://datazone.birdlife.org/) and Birds of the World (https://birdsoftheworld.org), to assess whether sea ducks and phalaropes have either: 1) High phenotypic plasticity. 2) High dispersal ability or 3) High evolvability.

For more detail and a full list of traits see:

> Foden, W. B. and Young, B. E. (eds.). "IUCN SSC Guidelines for Assessing Species' Vulnerability to Climate Change. Version 1.0." Occasional Paper of the IUCN Species Survival Commission No. 59 (2016). Cambridge, UK and Gland, Switzerland: IUCN Species Survival Commission. x+114pp.

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Appendix 1: Gannets and Cormorants

Sources and references for vulnerability assessment

1.1 Evidence for exposure (references)

1.1.1 Current impacts attributed to climate change:

Northern Gannet

1 - Gannets are undertaking longer foraging trips, most likely in response to prey shortages due to climate change. Although this likely increases the energetic costs of foraging, there have so far been no observed impacts on breeding success or mortality.

> **Davies, R. D., et al. "Density-dependent foraging and colony growth in a pelagic seabird species under varying environmental conditions." Marine Ecology Progress Series 485 (2013): 287-294.** Gannets are undertaking longer and longer foraging trips Celtic and Irish Seas. This is presumably due to food shortages closer to the colony, and climate change is likely one driver of this. Colonies are still growing and expanding, but at a slower rate than colonies elsewhere in the UK. This likely means these colonies will be more sensitive in future to climate change, but at the moment this is not classed as a negative impact.

2 - Gannets have established new colonies as key prey species have shifted further north.

> **Barrett, R. T., Strøm, H., and Melnikov, M. "On the polar edge: the status of the northern gannet (Morus bassanus) in the Barents Sea in 2015-16." Polar Research 36.1 (2017): 1390384.** Since 2011 gannets have established colonies in the Barents Sea (first on Bear Island), thought to be associated with a warming of the Barents Sea and the northward spread of common prey species.

European Shag

1 - Shags have advanced their laying date, most likely due to changes in marine and terrestrial temperatures and subsequently in prey availability

> **Álvarez, D., and Pajuelo, M. A. F. "Southern populations of European shag Phalacrocorax a. aristotelis advance their laying date in response to local weather conditions but not to large-scale climate." Ardeola 58.2 (2011):**

239-250. Laying dates for shags in northern Spain have changed drastically, advancing by almost 40 days in only 10 years. This is in correlation with an increase in local land and ocean temperatures, which is also the most likely reason behind this change in phenology.

2 - The diet composition of shags has changed a great deal, likely in response to climate change driven changes in the marine ecosystem

Howells, R. J., et al. "Pronounced long-term trends in year-round diet composition of the European shag Phalacrocorax aristotelis." Marine Biology 165.12 (2018): 1-15. Diet composition has changed, most likely in response to climate change. No known impact on population. Study on the Isle of May
Howells, R. J., et al. "From days to decades: short-and long-term variation in environmental conditions affect offspring diet composition of a marine top predator." Marine Ecology Progress Series 583 (2017): 227-242. Diet composition has changed, in correlation to climate change and change in sandeel abundance. Study on the Isle of May.

3 - Extreme storms during the shag breeding season have led to wide-spread nest destruction, nesting failure and a net reduction in annual population production

Newell, M., et al. "Effects of an extreme weather event on seabird breeding success at a North Sea colony." Marine Ecology Progress Series 532 (2015): 257-268 A single extreme summer storm on the Isle of May resulted in wide-spread nest destruction, nesting failure and a net reduction in annual population production. While individual storms cannot be easily be attributed to climate change, it is generally believed that severe storms are becoming more common

4 - Recent declines in shag populations because of high adult mortality are most likely because of increasingly severe winter storms.

Heubeck, M., et al. "Population and breeding dynamics of European Shags Phalacrocorax aristotelis at three major colonies in Shetland, 2001-15." Seabird 28 (2015): 55-77. Populations in the Shetlands have markedly declined, likely due to high mortality from winter storms. While individual extreme weather events are difficult to attribute to climate change, the frequency and severity of extreme weather events is likely increasing.

5 - Shags breed later as winters have become colder

Lorentsen, S.-H., et al. "Forage fish abundance is a predictor of timing of breeding and hatching brood size in a coastal seabird." Marine Ecology Progress Series 519 (2015): 209-220. Median hatch date became later over the study period (1989–2009). This was partially explained by a decline in the wNAO index, indicating colder conditions. This relationship was only observed at one of two studied colonies (Røst). It is unclear if or how this change affects the population

Great Cormorant

1 - Cormorants that migrate to coastal areas during the winter are now migrating later, most likely due to less and later ice on freshwater feeding areas.

Trella, M., and Wołos, A.. "Opinions of Owners and Managers of Fishing Entities in Central and Eastern Europe on the Impact of Climate Change on Lake Fisheries Management." Fisheries & Aquatic Life 29.4 (2021): 189-201. In Poland, observational surveys show that cormorants stay later in freshwater habitats during winter than previously, due to shorter ice-cover duration. Populations are shifting to relying more heavily on freshwater, and away from coastal and marine habitats.

2 - Cormorants are expanding their range due to increased availability of prey, in large part due to declines in competing marine predators, which in turn are partially driven by climate change.

van Eerden, M. R., et al. "Expanding East: Great Cormorants Phalacrocorax carbo Thriving in the Eastern Baltic and Gulf of Finland." Ardea 109.3 (2022): 313-326. Large marine predators have declined in part due to climate change (in particular due to warmer waters and increased eutrophication), along with several other major factors, which has resulted in an increase in smaller prey. This is likely a major factor contributing to major growth in cormorant populations in southern Finland, Estonia, Lithuania and across the eastern Baltic area, which are now breeding in areas they were never historically associated with.

1.1.2 Change in European range size between present day and 2100:

Using a species distribution model (SDM) we correlated species occurrence during the breeding season with a number of terrestrial and marine environmental variables. Species range data came from the European Breeding Bird Atlas (EBBA2) database. Present-day and 2100 terrestrial data were downloaded from the WorldClim database. We used data from the MRI-ESM2 general circulation model (GCM), which is a high-performing model over Europe. Present-day and 2100 marine data were downloaded from the Bio-Oracle database which averages predictions of marine variables from several different atmospheric-oceanic general circulation models (AOGCMS; for full details see Assis et al., 2017). For the map presented in the summary we used representative concentration pathway (RCP) 4.5, which is an "intermediate" emissions scenario. All data were at 5-minute resolution.

For European shag, and northern gannet we included the following terrestrial variables: Mean temperature of the warmest month, precipitation during breeding season, isolation of landmass, area of landmass, distance to sea.

For great cormorant we included the following terrestrial variables: mean temperature of the warmest month, precipitation during breeding season, distance to sea.

For European shag, and northern gannet we included the following marine variables: sea surface temperature (during the winter), salinity, maximum chlorophyll concentration, bathymetry (depth and variance).

Several other variables may strongly influence the distribution of gannets and cormorants and it is not possible to include all possible variables in a given model. However the following variables have previously been found to be important to predicting the distribution of gannets and cormorants in Europe: average wind speed during breeding season, sea surface height, seabed substrate, average wind speed during breeding season, presence of stable ocean fronts (or bathymetric proxy)distance to fresh water, freshwater depth, freshwater ph, freshwater chlorophyll concentration, land “roughness” index. For local assessments of climate change, we recommend these variables are strongly considered. We hope to incorporate these variables into future versions of this guidance resource.

After running our model we generated a present-day map where every grid-cell is given a habitat suitability score between 0 and 1, where 1 is very suitable habitat and 0 is not at all suitable. We then compared this with a corresponding map built with 2100 data, and highlighted currently inhabited areas where 1) suitability drops sharply (i.e. by more than 0.1) and 2) suitability drops below a probability threshold set by the model. Conversely we also highlighted areas where suitability rose sharply and above a given threshold. While a drop in habitat suitability is likely to result in population declines, it is not a certainty, and it does not mean that a population will be extinct in 2100 or that a population is doomed to extinction. With conservation action and careful management, along with changes in human behaviour, such declines may be mitigated or in some cases prevented. For a full explanation of the model see the accompanying ‘Methodology’ folder in Appendix 2.

Underlying data were downloaded from:

> **Keller, V., et al. "European Breeding Bird Atlas 2: Distribution, Abundance and Change." European Bird Census Council & Lynx Edicions, Barcelona (2020).** Source of range data

Fick, S. E., and Hijmans, R. J. "WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas." International Journal of Climatology 37.12 (2017): 4302-4315. Source of present-day and 2100 terrestrial data.

Assis, J., et al. "Bio-ORACLE v2. 0: Extending marine data layers for bioclimatic modelling." Global Ecology and Biogeography 27.3 (2018): 277-284. Source of present-day and 2100 marine data

1.1.3 Changes in key prey species:

We first identified the key prey species for each species. This can be variable across a species' range, but if available evidence suggested at least one major population is highly dependent on a particular prey species, then typically this species would be included. Lists of prey species were compiled from published sources, then verified and expanded following consultation with conservation practitioners. Afterwards we compiled current and projected maps of prey ranges to assess where key prey species may become less common in the near future. If any of the key species are predicted to vanish or drastically reduce in abundance in the current foraging range a given species, we marked this on the summary map.

We used several sources to collate range information, but for preference we used data from COPERNICUS as they include projected abundance. For species where this was not available we used habitat suitability instead. In all cases we used RCP 4.5, which is an “intermediate” emissions scenario. For species in the COPERNICUS database we used the 0.6 maximum sustainable yield parameter, which assumes international co-operation to work towards fish-stock sustainability. Our assessment is therefore relatively conservative in terms of changes in prey species.

Northern Gannet key prey species: herring (*Clupea harengus*), saithe (*Pollachius virens*), mackerel (*Scomber scombrus*), sandeel species (*Ammodytes marinus* and *Ammodytes tobianus*), capelin (*Mallotus villosus*), sprat (*Sprattus sprattus)*, haddock (*Melanogrammus aeglefinus*) and garfish (*Belone belone*). This species will also take many other species where available, it will also forage fishery discards. Prey species list was compiled from:

Le Bot, T., et al. “Fishery discards do not compensate natural prey shortage in Northern gannets from the English Channel.” Biological conservation 236 (2019): 375-384.

Mowbray, T. B. “Northern Gannet (Morus bassanus), version 1.0.” In Birds of the World (S. M. Billerman, Editor). Cornell Lab of Ornithology, Ithaca, NY, USA (2020).

Pettex, E., et al. “Multi-scale foraging variability in Northern gannet (Morus bassanus) fuels potential foraging plasticity.” Marine Biology 159.12 (2012): 2743-2756.

European Shag key prey species: sandeel species (*Ammodytes marinus* and *Ammodytes tobianus*), saith (*Pollachius virens*), cod (*Gadus morhua*), poor cod (*Trisopterus minutus*) and capelin (*Mallotus villosus*). Prey species list was compiled from:

Harris, M. P., and Wanless, S. "The diet of shags Phalacrocorax aristotelis during the chick-rearing period assessed by three methods." Bird study 40.2 (1993): 135-139.

Hillersøy, G., and Lorentsen, S-H. "Annual variation in the diet of breeding European shag (Phalacrocorax aristotelis) in Central Norway." Waterbirds 35.3 (2012): 420-429.

Lorentsen, S-H., Mattisson, J., and Christensen-Dalsgaard, S. "Reproductive success in the European shag is linked to annual variation in diet and foraging trip metrics." Marine Ecology Progress Series 619 (2019): 137-147.

Great Cormorant key prey species: sandeel species (*Ammodytes marinus* and Ammodytes tobianus), capelin (*Mallotus villosus*), flounder (Platichthys flesus), saithe (*Pollachius virens*), sea scorpion (*Taurulus bubalis*), sole (*Solea solea*), eelpout (*Zoarces viviparu*s) and sprat (*Sprattus sprattus*). This species also feeds on freshwater species, notably brown trout (*Salmo trutta*), salmon parr, European eel (*Anguilla anguilla*), roach (*Rutilus rutilus*), perch (*Perca fluviatilis*) and minnow (*Phoxinus phoxinus*), but these were not included in this analysis. Prey species list was compiled from:

Hatch, J. J., et al. “Great Cormorant (Phalacrocorax carbo), version 1.0.” In Birds of the World (S. M. Billerman, Editor). Cornell Lab of Ornithology, Ithaca, NY, USA (2020).

van Eerden, M. R., et al. “Expanding East: Great Cormorants Phalacrocorax carbo Thriving in the Eastern Baltic and Gulf of Finland.” Ardea 109.3 (2022): 313-326.

Lehikoinen, A., Heikinheimo, O., and Lappalainen, A. "Temporal changes in the diet of great cormorant (Phalacrocorax carbo sinensis) on the southern coast of Finland-comparison with available fish data." Boreal environment research 16 (suppl. B) (2011): 61–70.

Prey range information for all species were compiled from:

Kesner-Reyes, K., et al. "AquaMaps: Predicted range maps for aquatic species." In FishBase: R. Froese & D. Pauly (Eds.) (2019). Available at: https://www.aquamaps.org

Sailley, S., et al. "Fish abundance and catch data for the Northwest European Shelf and Mediterranean Sea from 2006 to 2098 derived from climate projections". Copernicus Climate Change Service (C3S) Climate Data Store (CDS) (2021). https://doi.org/10.24381/cds.39c97304.

1.1.4 Climate change impacts outside of Europe

Northern Gannet

Marine heatwaves in North America have resulted in wide-spread breeding failure and in some cases temporary desertion of colonies. Most likely because of prey shortages, but heat stress could play a role as well. It is difficult to attribute individual climate events to climate change, but heatwaves are becoming more common and more extreme, and will likely continue to do so. Lack of key prey species (mackerel) due to warmer average marine temperatures and over-exploitation has caused low breeding success in a southern population of gannets in Canada.

Franci, C. D., et al. “Nutritional stress in Northern gannets during an unprecedented low reproductive success year: Can extreme sea surface temperature event and dietary change be the cause?.” Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology 181 (2015): 1-8

d’Entremont, K. J. N., et al. “Northern Gannets (Morus bassanus) breeding at their southern limit struggle with prey shortages as a result of warming waters.” ICES Journal of Marine Science 79.1 (2022): 50-60.

Montevecchi, W. A., et al. “Ocean heat wave induces breeding failure at the southern breeding limit of the Northern Gannet Morus bassanus.” Marine Ornithology 49 (2021): 71-78.

Great Cormorant

Cormorants in Greenland have spread their summer range further north, most likely due to warmer sea temperatures and changes in food availability. However, this has also likely increased the costs of migration, as cormorants have further to travel to reach ice-free areas in winter.

White, C. R., et al. “Energetic constraints may limit the capacity of visually guided predators to respond to Arctic warming." Journal of Zoology 289.2 (2013): 119-126.

1.2 Sensitivity (references)

We used a list of candidate traits based on that in Foden & Young (2016) that indicate high sensitivity and identified which, if any, gannets and cormorants possessed. In brief, we consulted published literature as well as expert knowledge and online databases such as Birdlife (http://datazone.birdlife.org/) and Birds of the World (https://birdsoftheworld.org), to assess whether gannets and cormorants have either 1) Specialised habitat and/or microhabitat requirement 2) Environmental tolerances or thresholds (at any life stage) that are likely to be exceeded due to climate change 3) Dependence on environmental triggers that are likely to be disrupted by climate change, 4) Dependence on interspecific interactions that are likely to be disrupted by climate change or 5) High rarity.
For more detail and a full list of traits see:

Foden, W. B. and Young, B. E. (eds.). "IUCN SSC Guidelines for Assessing Species' Vulnerability to Climate Change. Version 1.0." Occasional Paper of the IUCN Species Survival Commission No. 59 (2016). Cambridge, UK and Gland, Switzerland: IUCN Species Survival Commission. x+114pp.

1.3 Adaptive capacity (references)

We used a list of candidate traits based on that in Foden & Young (2016) that indicate adaptive capacity and identified which, if any, gannets and cormorants possessed. In brief, we consulted published literature as well as expert knowledge and online databases such as Birdlife (http://datazone.birdlife.org/) and Birds of the World (https://birdsoftheworld.org), to assess whether gannets and cormorants have either: 1) High phenotypic plasticity. 2) High dispersal ability or 3) High evolvability.
For more detail and a full list of traits see:

Foden, W. B. and Young, B. E. (eds.). "IUCN SSC Guidelines for Assessing Species' Vulnerability to Climate Change. Version 1.0." Occasional Paper of the IUCN Species Survival Commission No. 59 (2016). Cambridge, UK and Gland, Switzerland: IUCN Species Survival Commission. x+114pp.


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Appendix 1: Gulls

Sources and references for vulnerability assessment

1.1 Evidence for exposure (references)

1.1.1 Current impacts attributed to climate change:

European Herring Gull

1 - Changes in mercury cycling (due to increased sea temperatures) has led to increased exposure to mercury, with negative impacts on herring gull health

Bełdowska, M., et al. "Mercury concentration in the coastal zone of the Gulf of Gdansk as a function of changing climate—preliminary results." Baltic Sea Science Congress: new horizons for Baltic Sea science. Klaipeda University CORPI, Klaipeda 140 (2013). This paper does not specifically address bioaccumulation in gulls, but provides supporting information for the other references for this impact. Overview of how climate change can lead to changes in mercury concentration in Baltic.

Beldowska, M., et al. "Macrophyta as a vector of contemporary and historical mercury from the marine environment to the trophic web." Environmental Science and Pollution Research 22.7 (2015): 5228-5240. This paper does not specifically address bioaccumulation in gulls, but provides supporting information for the other references for this impact. Overview of how mercury concentration in the Baltic cycles into seabird tissues and how it affects ecosystem health

Saniewska, D., et al. "Climate change and its impact on the mercury cycling in the southern Baltic Sea." Ecosystem dynamics in the Baltic Sea in a climate change perspective, 03.2015. Conference Umeå, Sweden, (2015). Climate change is likely leading to increased mercury concentration cycling in the southern Baltic, this is leading to higher concentrations of mercury in herring gull tissues. While this has not been shown to be affecting the population in the Baltic, it is known that mercury poisoning can severely affect herring gull health.

Lesser Black-backed Gull

1 - Increased prey availability during the breeding season has led to population growth

Luczak, C., et al. "North Sea ecosystem change from swimming crabs to seagulls." Biology letters 8.5 (2012): 821-824. Increased numbers of swimming crabs significantly correlate with sea surface temperature increases and changes in the abundance of lesser black-backed gulls at 21 major North Sea breeding colonies (across northern France and Belgium). Though note there is some debate on whether an increase in crabs is actually the cause of the population increase.

Glaucous Gull

1 - There has been increased predation by polar bears, most likely due to reduction in sea ice and therefore a lack of alternative prey. In some years this has severely affected breeding success.

Prop, J., et al. "Climate change and the increasing impact of polar bears on bird populations." Frontiers in Ecology and Evolution 3 (2015): 33. Polar bears are swapping prey due to lack of sea ice and prey more heavily on glaucous gulls (amongst other seabirds). In some years it severely affects reproductive success in Svalbard and Greenland.

2 - Climate change is likely contributing to higher concentrations of contaminents ingested by glaucous gulls. The overall effect on the population is unknown, but presumably negative.

Alava, J. J., et al. "Climate change–contaminant interactions in marine food webs: Toward a conceptual framework." Global Change Biology 23.10 (2017): 3984-4001. Potential exacerbation of POPs and mercury in marine food webs due to climate change (i.e., increasing temperatures). Glaucous gulls appear to have high accumulation of compounds, but there's no established negative effect on populations. Study was conducted across their range, especially around Greenland.

3 - Climate change has contributed to a range shift in several helminth parasites, which has led to glaucous gulls being exposed to novel parasites, as well as increased parasite load. Effect on population is unknown, but presumably negative

Galaktionov, K. V. "Patterns and processes influencing helminth parasites of Arctic coastal communities during climate change." Journal of Helminthology 91.4 (2017): 387-408. Review of helminth parasites across the Arctic, especially in seabirds. Notes that several parasites have been recorded in species they have never been associated with before. Most likely because boreal crustaceans are shifting north, along with associated parasites. Notable species are glaucous gulls and black-legged kittiwakes which now have significant new parasites at rapidly increasing loads.

Great Black-backed Gull

1 - Higher sea temperatures correlate with lower breeding success. Mechanism unknown, but likely mediated through prey availability

Burthe, S. J., et al. "Assessing the vulnerability of the marine bird community in the western North Sea to climate change and other anthropogenic impacts." Marine Ecology Progress Series 507 (2014): 277-295. Greater black-backed gull productivity decreases as sea surface temperature gets higher. Probably due to prey availability, study focusses on seabirds in Forth and Tay region.

Ivory Gull

1 - Ivory gulls are heavily reliant on sea ice for breeding and hunting, recent decreases in sea ice are leading to rapid changes in population size and range.

Gilg, O., et al. "Living on the edge of a shrinking habitat: the ivory gull, Pagophila eburnea, an endangered sea-ice specialist." Biology letters 12.11 (2016): 20160277. Demonstrates how closely linked Ivory gull ranges are to sea ice availability across its range, including Greenland, Svalbard, Russia and Canada. Also notes that their range is shrinking due to changes in sea ice.

2 - As a secondary impact of sea ice loss, Ivory gulls face more competition from other Ivory gulls and from other species for resources.

Hamilton, C. D., et al. "Spatial overlap among an Arctic predator, prey and scavenger in the marginal ice zone." Marine Ecology Progress Series 573 (2017): 45-59. Decreasing area of sea ice mean less area for ivory gulls, polar bears and ringed seals (both of which commonly scavenge in similar areas). This leads to increased intra- and inter- specific competition.

Black-legged Kittiwake

1 - Decreased prey availability due to warmer seas has led to lower breeding success

Sandvik, H., et al. "The decline of Norwegian kittiwake populations: modelling the role of ocean warming." Climate Research 60.2 (2014): 91-102. The study find a correlation between lower breeding success and sea surface temperature along Norwegian coast. The suggested mechanism is through prey availability as this is known to affect breeding success in various parts of their range.

2 - Kittiwake diet has changed significantly due to climate-change driven shift in prey assemblage. However, so far this has not resulted in any demonstrated change in breeding success.

Vihtakari, M., et al. "Black-legged kittiwakes as messengers of Atlantification in the Arctic." Scientific Reports 8.1 (2018): 1-11. Kittiwake diet in Svalbard changed significantly over a 10-year period (2006-2016), from predominantly Arctic species to species more associated with warmer Atlantic waters, in correlation with increase in ocean temperature and loss of sea ice. There were, however, no significant changes in clutch size or breeding success during this time.

3 - Kittiwake populations have shifted their range in response to changes in distribution of key prey species.

Garðarsson, A., Guðmundsson, G. A., and Lilliendahl, K. "Framvinda íslenskra ritubyggða." Bliki 32 (2013): 1-10. Kittiwakes have redistributed across Iceland. Populations in the north have decreased, and populations in the west have increased. The population in general is relatively stable. The authors hypothesise this is likely due to redistribution of capelin, a key prey species of kittiwakes in Iceland.

4 - Climate change has contributed to a range shift in several helminth parasites, which has led to kittiwakes being exposed to novel parasites, as well as increased parasite load. Effect on population is unknown, but most likely negative

Galaktionov, K. V. "Patterns and processes influencing helminth parasites of Arctic coastal communities during climate change." Journal of Helminthology 91.4 (2017): 387-408. Review of helminth parasites across the Arctic, especially in seabirds. Notes that several parasites have been recorded in species they have never been associated with before. Most likely because boreal crustaceans are shifting north, along with associated parasites. Notable species are glaucous gulls and black-legged kittiwakes which now have significant new parasites at rapidly increasing loads.

5 - Higher sea temperatures correlate with lower breeding success. Mechanism unknown, but potentially mediated through prey availability. Alternative theories suggest fishery pressure has been a large contributing factor.

Burthe, S. J., et al. "Assessing the vulnerability of the marine bird community in the western North Sea to climate change and other anthropogenic impacts." Marine Ecology Progress Series 507 (2014): 277-295. Kittiwake productivity has decreased as sea surface temperature has increased. Probably due to prey availability, study focusses on seabirds in Forth and Tay region.

Carroll, M. J., et al. "Effects of sea temperature and stratification changes on seabird breeding success." Climate Research 66.1 (2015): 75-89. Across 11 colonies in the UK and Ireland, kittiwake breeding success was lower in years with higher spring sea surface temperatures (and strong ocean stratification in the preceding winter). Both variables increased over the study period. However, key drivers of productivity varied between colonies. Environmental variables were taken from the observed foraging areas of the kittiwakes. The study suggests a food-web-based mechanism for impact.

Frederiksen, M., et al. "Regional and annual variation in black-legged kittiwake breeding productivity is related to sea surface temperature." Marine Ecology Progress Series 350 (2007): 137-143. Over the study period (mid-1980s to mid-2000s, February/March sea surface temperature increased around six of six colonies in the UK and Ireland – although only significantly so in two. Breeding productivity negatively related to SST across all colonies, and for two of six individual colonies. The study suggests the mechanism is unclear, but likely operates through effects on sandeels.

6 - Kittiwake colonies have declined during periods of rapid ocean warming. Mechanism unknown, but likely due to rapid changes in marine ecosystems and prey availability

Descamps, S., et al. "Circumpolar dynamics of a marine top-predator track ocean warming rates." Global Change Biology 23.9 (2017): 3770-3780. Rapid increases in SST around circumpolar kittiwake colonies in the 1990s conicided with steep declines in colony size. The suggested mechanism is abrupt "regime shifts" that changed prey availability.

7 - Extreme storms during the non-breeding season have led to mass mortality of kittiwakes ('wrecks')

Clairbaux, M., et al. "North Atlantic winter cyclones starve seabirds." Current Biology 31.17 (2021): 3964-3971. Following heavy storm action, seabird mortality increases due to increased difficulty foraging (rather than increased energetic costs). The authors use a multi-species dataset (puffins, little auks, common murres, and thick-billed murres) over a wide area of the Atlantic basin. They conclude that seabirds around Iceland and the Barents Sea (along with several N. American sites) are particularly vulnerable. Climate change is likely to be a contributing factor to present and future storm mortality.

8 - Extreme storms during the kittiwake breeding season have led to wide-spread nest destruction, nesting failure and a net reduction in annual population production

Newell, M., et al. "Effects of an extreme weather event on seabird breeding success at a North Sea colony." Marine Ecology Progress Series 532 (2015): 257-268. A single extreme summer storm on the Isle of May resulted in wide-spread nest destruction, nesting failure and a net reduction in annual population production. While individual storms cannot be easily be attributed to climate change, it is generally believed that severe storms are becoming more common.

Yellow-legged Gull

1 - Changes in prey availability have caused species to swap prey

Calado, J. G., et al. "Anthropogenic food resources, sardine decline and environmental conditions have triggered a dietary shift of an opportunistic seabird over the last 30 years on the northwest coast of Spain." Regional Environmental Change 20.1 (2020): 1-13. Yellow-legged gulls have changed their diet following declines in sardine populations, driven by climate change and fishery activity. Study based on several populations on the north-west coast of Spain.

1.1.2 Change in European range size between present day and 2100:

Using a species distribution model (SDM) we correlated species occurrence during the breeding season with a number of terrestrial and marine environmental variables. Species range data came from the European Breeding Bird Atlas (EBBA2) database. Present-day and 2100 terrestrial data were downloaded from the WorldClim database. We used data from the MRI-ESM2 general circulation model (GCM), which is a high-performing model over Europe. Present-day and 2100 marine data were downloaded from the Bio-Oracle database which averages predictions of marine variables from several different atmospheric-oceanic general circulation models (AOGCMS; for full details see Assis et al., 2017). For the map presented in the summary we used representative concentration pathway (RCP) 4.5, which is an "intermediate" emissions scenario. All data were at 5-minute resolution.

For European herring gull, Audouin's gull, lesser black-backed gull, glaucous gull, great black-backed gull, ivory gull, black-legged kittiwake, and Sabine's gull we included the following terrestrial variables: Mean temperature of the warmest month, precipitation during breeding season, isolation of landmass, area of landmass, distance to sea

For Caspian gull, and yellow-legged gull we included the following terrestrial variables: mean temperature of the warmest month, precipitation during breeding season, distance to sea.

For Audouin's gull, lesser black-backed gull, glaucous gull, great black-backed gull, ivory gull, black-legged kittiwake, and Sabine's gull we included the following marine variables: sea surface temperature (during the winter), salinity, maximum chlorophyll concentration, bathymetry (depth and variance).

Several other variables may strongly influence the distribution of gulls and it is not possible to include all possible variables in a given model. However the following variables have previously been found to be important to predicting the distribution of gulls in Europe: sea level height. For local assessments of climate change, we recommend these variables are strongly considered. We hope to incorporate these variables into future versions of this guidance resource.

After running our model we generated a present-day map where every grid-cell is given a habitat suitability score between 0 and 1, where 1 is very suitable habitat and 0 is not at all suitable. We then compared this with a corresponding map built with 2100 data, and highlighted currently inhabited areas where 1) suitability drops sharply (i.e. by more than 0.1) and 2) suitability drops below a probability threshold set by the model. Conversely we also highlighted areas where suitability rose sharply and above a given threshold. While a drop in habitat suitability is likely to result in population declines, it is not a certainty, and it does not mean that a population will be extinct in 2100 or that a population is doomed to extinction. With conservation action and careful management, along with changes in human behaviour, such declines may be mitigated or in some cases prevented. For a full explanation of the model see the accompanying 'Methodology' folder in Appendix 2.

Underlying data were downloaded from:

Keller, V., et al. "European Breeding Bird Atlas 2: Distribution, Abundance and Change." European Bird Census Council & Lynx Edicions, Barcelona (2020). Source of range data

Fick, S. E., and Hijmans, R. J. "WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas." International Journal of Climatology 37.12 (2017): 4302-4315. Source of present-day and 2100 terrestrial data.

Assis, J., et al. "Bio-ORACLE v2. 0: Extending marine data layers for bioclimatic modelling." Global Ecology and Biogeography 27.3 (2018): 277-284. Source of present-day and 2100 marine data

1.1.3 Changes in key prey species:

We first identified the key prey species for each species. This can be variable across a species' range, but if available evidence suggested at least one major population is highly dependent on a particular prey species, then typically this species would be included. Lists of prey species were compiled from published sources, then verified and expanded following consultation with conservation practitioners. Afterwards we compiled current and projected maps of prey ranges to assess where key prey species may become less common in the near future. If any of the key species are predicted to vanish or drastically reduce in abundance in the current foraging range a given species, we marked this on the summary map. We used several sources to collate range information, but for preference we used data from COPERNICUS as they include projected abundance. For species where this was not available we used habitat suitability instead. In all cases we used RCP 4.5, which is an "intermediate" emissions scenario. For species in the COPERNICUS database we used the 0.6 maximum sustainable yield parameter, which assumes international co-operation to work towards fish-stock sustainability. Our assessment is therefore relatively conservative in terms of changes in prey species.

European Herring Gull key prey species: This species has a very varied diet, including fish, discards, bivalves, gastropods, crustaceans, squid, insects, refuse and other seabirds, among many other food sources. No key species were identified, so the key prey assessment is not complete

Audouin's Gull key prey species: sardines (*Sardina pilchardus*), Atlantic saury (*Scomberesox saurus*) and blue whiting (*Micromesistius poutassou*). This species is also known to feed on various other demersal and pelagic fish, as well as various terrestrial food sources, but no other species could be firmly identified as key prey species. Prey species list was compiled from:

> Burger, J., et al. "Audouin's Gull (Ichthyaetus audouinii), version 1.0." In Birds of the World (J. del Hoyo, A. Elliott, J. Sargatal, D. A. Christie, and E. de Juana, Editors). Cornell Lab of Ornithology, Ithaca, NY, USA (2020)
>
> Calado, J. G., et al. "Seasonal and annual differences in the foraging ecology of two gull species breeding in sympatry and their use of fishery discards." Journal of Avian Biology 49.1 (2018).

Caspian Gull key prey species: This species has a varied diet of invertebrates. No key species were identified and so the key prey assessment is not complete

Lesser Black-backed Gull key prey species: herring (*Clupea harengus*), saithe (*Pollachius virens*) and sandeel species (*Ammodytes marinus* and *Ammodytes tobianus*). Many populations also rely heavily on discards, refuse and egg/chick predation. These food sources were not included in this assessment. Prey species list was compiled from:

> Burger, J., et al. "Lesser Black-backed Gull (Larus fuscus), version 1.0." In Birds of the World (J. del Hoyo, A. Elliott, J. Sargatal, D. A. Christie, and E. de Juana, Editors). Cornell Lab of Ornithology, Ithaca, NY, USA (2020).
>
> Bustnes, J. O., Barrett, R. T., and Helberg, M. "Northern Lesser Black-Backed Gulls: What do They Eat?." Waterbirds 33.4 (2010): 534-540.

Glaucous Gull key prey species: Arctic cod (*Boreogadus saida*), cod (*Gadus morhua*), sandeel species (*Ammodytes marinus* and *Ammodytes tobianus*), capelin (*Mallotus villosus*) and herring (*Clupea harengus*). Prey species list was compiled from:

> Weiser, E. and Gilchrist, H. G. "Glaucous Gull (Larus hyperboreus), version 1.0." In Birds of the World (S. M. Billerman, Editor). Cornell Lab of Ornithology, Ithaca, NY, USA (2020).

Great Black-backed Gull key prey species: capelin (*Mallotus villosus*), cod *(Gadus morhua*), mackerel (*Scomber scombrus*) and herring (*Clupea harengus*). Some populations also rely on other seabirds (including eggs, chicks and adults) as an important prey source. These were not included in the key prey assessment. Prey species list was compiled from:

> Good, T. P. "Great Black-backed Gull (Larus marinus), version 1.0." In Birds of the World (S. M. Billerman, Editor). Cornell Lab of Ornithology, Ithaca, NY, USA (2020).

Ivory Gull key prey species: Arctic cod (*Boreogadus saida*). This species also preys frequently on invertebrates and other fish, however these were not included in the assessment. Prey species list was compiled from:

> Mallory, M. L., et al. "Ivory Gull (Pagophila eburnea), version 1.0." In Birds of the World (S. M. Billerman, Editor). Cornell Lab of Ornithology, Ithaca, NY, USA (2020).

Black-legged Kittiwake key prey species: sandeel species (*Ammodytes marinus* and *Ammodytes tobianu*s), sprat (*Sprattus sprattus*), Arctic cod (*Boreogadus saida*), capelin (*Mallotus villosus*) and herring (*Clupea harengus*). Prey species list was compiled from:

> Hatch, S. A., Robertson, G. J., and Baird, P. H. "Black-legged Kittiwake (Rissa tridactyla), version 1.0." In Birds of the World (S. M. Billerman, Editor). Cornell Lab of Ornithology, Ithaca, NY, USA (2020).
>
> Fauchald, Per, et al. "The status and trends of seabirds breeding in Norway and Svalbard." NINA rapport 1151. Norsk institutt for naturforskning (2015): 1-84.
>
> Johansen M., et al. "International Black-legged Kittiwake Conservation Strategy and Action Plan" Circumpolar Seabird Expert Group. Conservation of Arctic Flora and Fauna, Akureyri, Iceland (2020).

Sabine's Gull key prey species: This species has a varied diet of invertebrates and fish. No key species were identified and so the key prey assessment is not complete

Yellow-legged Gull key prey species: Henslow's swimming crab (*Polybius henslowii*), sardines (*Sardina pilchardus*), chub mackeral (*Scomber colias*), blue whiting (*Micromesistius poutassou*) and hake (*Merluccius merluccius*). This species has a varied diet of pelagic and demersal fish, as well as several terrestrial food sources. Note that several of the fish species here may be from fishery discards. Prey species list was compiled from:

> del Hoyo, J., et al. "Yellow-legged Gull (Larus michahellis), version 1.0." In Birds of the World (J. del Hoyo, A. Elliott, J. Sargatal, D. A. Christie, and E. de Juana, Editors). Cornell Lab of Ornithology, Ithaca, NY, USA (2020).

Prey range information for all species were compiled from:

> Kesner-Reyes, K., et al. "AquaMaps: Predicted range maps for aquatic species." In FishBase: R. Froese & D. Pauly (Eds.) (2019). Available at: https://www.aquamaps.org

> Sailley, S., et al. "Fish abundance and catch data for the Northwest European Shelf and Mediterranean Sea from 2006 to 2098 derived from climate projections". Copernicus Climate Change Service (C3S) Climate Data Store (CDS) (2021). https://doi.org/10.24381/cds.39c97304.

1.1.4 Climate change impacts outside of Europe

European Herring Gull

Increased flooding due to sea level rise has led to the reduction or destruction of several populations in the US.

> Burger, J., and Gochfeld, M. "Habitat, population dynamics, and metal levels in colonial waterbirds: a food chain approach." CRC Pres, New York (2016).

Glaucous Gull

Glaucous gull colonies display higher rates of cannabalism and lower breeding success in response to higher sea temperatures. This is presumably due to lack of marine prey, and is likely to be excerabated with further climate change.

> Hayward, J. L., et al. "Egg cannibalism in a gull colony increases with sea surface temperature." The Condor 116.1 (2014): 62-73.

Ivory Gull

Climate change is known to have several other impacts in other parts of the species range, in particular through changing winter food supplies, increasing competition with other marine birds, and increased predation due to increased access to previously isolated colonies.

Gilchrist, H. G., and Mallory, M. L. "Declines in abundance and distribution of the ivory gull (Pagophila eburnea) in Arctic Canada." Biological Conservation 121.2 (2005): 303-309.

Hamilton, C. D., et al. “Spatial overlap among an Arctic predator, prey and scavenger in the marginal ice zone.” Marine Ecology Progress Series 573 (2017): 45-59.

Yannic, G., et al. “Complete breeding failures in ivory gull following unusual rainy storms in North Greenland.” Polar Research 33.1 (2014): 22749.

Black-legged Kittiwake

Recent heatwaves in the North Pacific have resulted in mass mortality and widespread breeding failure at kittiwake colonies

Johansen M., et al. "International Black-legged Kittiwake Conservation Strategy and Action Plan" Circumpolar Seabird Expert Group. Conservation of Arctic Flora and Fauna, Akureyri, Iceland (2020). Note: data not provided in report.

1.2 Sensitivity (references)

We used a list of candidate traits based on that in Foden & Young (2016) that indicate high sensitivity and identified which, if any, gulls possessed. In brief, we consulted published literature as well as expert knowledge and online databases such as Birdlife (http://datazone.birdlife.org/) and Birds of the World (https://birdsoftheworld.org), to assess whether gulls have either 1) Specialised habitat and/or microhabitat requirement 2) Environmental tolerances or thresholds (at any life stage) that are likely to be exceeded due to climate change 3) Dependence on environmental triggers that are likely to be disrupted by climate change, 4) Dependence on interspecific interactions that are likely to be disrupted by climate change or 5) High rarity.

For more detail and a full list of traits see:

Foden, W. B. and Young, B. E. (eds.). "IUCN SSC Guidelines for Assessing Species’ Vulnerability to Climate Change. Version 1.0." Occasional Paper of the IUCN Species Survival Commission No. 59 (2016). Cambridge, UK and Gland, Switzerland: IUCN Species Survival Commission. x+114pp.

1.3 Adaptive capacity (references)

We used a list of candidate traits based on that in Foden & Young (2016) that indicate adaptive capacity and identified which, if any, gulls possessed. In brief, we consulted published literature as well as expert knowledge and online databases such as Birdlife (http://datazone.birdlife.org/) and Birds of the World (https://birdsoftheworld.org), to assess whether gulls have either: 1) High phenotypic plasticity. 2) High dispersal ability or 3) High evolvability.

For more detail and a full list of traits see:

> Foden, W. B. and Young, B. E. (eds.). "IUCN SSC Guidelines for Assessing Species' Vulnerability to Climate Change. Version 1.0." Occasional Paper of the IUCN Species Survival Commission No. 59 (2016). Cambridge, UK and Gland, Switzerland: IUCN Species Survival Commission. x+114pp.

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Appendix 1: Loons/Divers and Grebes

Sources and references for vulnerability assessment

1.1 Evidence for exposure (references)

1.1.1 Current impacts attributed to climate change:

No impacts were recorded for Loons/Divers and Grebes in Europe

1.1.2 Change in European range size between present day and 2100:

Using a species distribution model (SDM) we correlated species occurrence during the breeding season with a number of terrestrial and marine environmental variables. Species range data came from the European Breeding Bird Atlas (EBBA2) database. Present-day and 2100 terrestrial data were downloaded from the WorldClim database. We used data from the MRI-ESM2 general circulation model (GCM), which is a high-performing model over Europe. Present-day and 2100 marine data were downloaded from the Bio-Oracle database which averages predictions of marine variables from several different atmospheric-oceanic general circulation models (AOGCMS; for full details see Assis et al., 2017). For the map presented in the summary we used representative concentration pathway (RCP) 4.5, which is an “intermediate” emissions scenario. All data were at 5-minute resolution.

For Arctic loon, common loon, horned grebe, and red-necked grebe we included the following terrestrial variables: Mean temperature of the warmest month, precipitation during breeding season, distance to sea

For red-throated loon we included the following terrestrial variables: Mean temperature of the warmest month, precipitation during breeding season, isolation of landmass, area of landmass, distance to sea

No marine variables were included for this species group, as they are predominantly terrestrial during the breeding season.

Several other variables may strongly influence the distribution of loons, divers and grebes and it is not possible to include all possible variables in a given model. However the following variables have previously been found to be important to predicting the distribution of loons, divers and grebes in Europe: distance to fresh water, freshwater depth, freshwater ph, freshwater chlorophyll concentration, land “roughness” index. For local assessments of climate change, we recommend these variables are strongly considered. We hope to incorporate these variables into future versions of this guidance resource.

After running our model we generated a present-day map where every grid-cell is given a habitat suitability score between 0 and 1, where 1 is very suitable habitat and 0 is not at all suitable. We then compared this with a corresponding map built with 2100 data, and highlighted currently inhabited areas where 1) suitability drops sharply (i.e. by more than 0.1) and 2) suitability drops below a probability threshold set by the model. Conversely we also highlighted areas where suitability rose sharply and above a given threshold. While a drop in habitat suitability is likely to result in population declines, it is not a certainty, and it does not mean that a population will be extinct in 2100 or that a population is doomed to extinction. With conservation action and careful management, along with changes in human behaviour, such declines may be mitigated or in some cases prevented. For a full explanation of the model see the accompanying ‘Methodology’ folder in Appendix 2.

Underlying data were downloaded from:

> **Keller, V., et al. "European Breeding Bird Atlas 2: Distribution, Abundance and Change." European Bird Census Council & Lynx Edicions, Barcelona (2020).** Source of range data
>
> **Fick, S. E., and Hijmans, R. J. "WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas." International Journal of Climatology 37.12 (2017): 4302-4315.** Source of present-day and 2100 terrestrial data.
>
> **Assis, J., et al. "Bio-ORACLE v2. 0: Extending marine data layers for bioclimatic modelling." Global Ecology and Biogeography 27.3 (2018): 277-284.** Source of present-day and 2100 marine data

1.1.3 Changes in key prey species:

We first identified the key prey species for each species. This can be variable across a species’ range, but if available evidence suggested at least one major population is highly dependent on a particular prey species, then typically this species would be included. Lists of prey species were compiled from published sources, then verified and expanded following consultation with conservation practitioners. Afterwards we compiled current and projected maps of prey ranges to assess where key prey species may become less common in the near future. If any of the key species are predicted to vanish or drastically reduce in abundance in the current foraging range a given species, we marked this on the summary map.

We used several sources to collate range information, but for preference we used data from COPERNICUS as they include projected abundance. For species where this was not available we used habitat suitability instead. In all cases we used RCP 4.5, which is an “intermediate” emissions scenario. For species in the COPERNICUS database we used the 0.6 maximum sustainable yield parameter, which assumes international co-operation to work towards fish-stock sustainability. Our assessment is therefore relatively conservative in terms of changes in prey species.

Arctic Loon key prey species: herring (*Clupea harengus*), sprat (*Sprattus sprattus*) and cod (*Gadus morhua*). This species will also prey on freshwater fish, especially during the breeding season, notably salmonids, perch, roach, minnows and sticklebacks. However, freshwater species were not included in the key prey assessment. Prey species list was compiled from:

> Jackson, D. B. "Environmental correlates of lake occupancy and chick survival of black-throated divers Gavia arctica in Scotland." Bird Study 52.3 (2005): 225-236.
>
> Russell, R. W. “Arctic Loon (Gavia arctica), version 1.0.” In Birds of the World (S. M. Billerman, Editor). Cornell Lab of Ornithology, Ithaca, NY, USA (2020).
>
> Söderlund, E. Effects of whitefish speciation on piscivorous birds. A dietary study of piscivorous birds in central and northern Sweden. Umeå University (2021). MSc Thesis.

Common Loon key prey species: During the breeding season this species preys primarily on salmonids. However, freshwater species are not assessed as part of the key prey assessment. Also feeds on a wide variety of marine species, however no key prey species were identified. Currently there is no key prey assessment for this species

Red-throated Loon key prey species: herring (*Clupea harengus*), sprat (*Sprattus sprattus*), sandeels (*Ammodytes marinus*), cod (*Gadus morhua*) and smelt (*Osmerus eperlanus*). This species also commonly preys on freshwater fish, especially during the breeding season, however these were not included in the key prey assessment. Prey species list was compiled from:

> Eriksson, M. O. G., and Paltto, H. "Vattenkemi och fiskbeståndens sammansättning i storlommens Gavia arctica häckningssjöar, samt en jämförelse med smålommens Gavia stellata fiskesjöar." Ornis Svecica 20.1 (2010): 3-30.
>
> Rizzolo, D. J., et al. “Red-throated Loon (Gavia stellata), version 2.0.” In

Birds of the World (P. G. Rodewald and B. K. Keeney, Editors). Cornell Lab of Ornithology, Ithaca, NY, USA (2020).

Horned Grebe key prey species: three-spined sticklebacks (*Gasterosteus aculeatus*) and smelt (*Osmerus eperlanus*). This species also preys on small aquatic and airborne arthropods, particularly during the breeding season (beetles, dragonflies and damselflies, mayflies etc.). Invertebrates are not currently included in key prey assessments. While this species does prey on other fish species, none were identified as key species so were not included. Prey species list was compiled from:

Dillon, I. A., Hancock, M. H. , and Summers, R. W. "Provisioning of Slavonian Grebe Podiceps auritus chicks at nests in Scotland." Bird Study 57.4 (2010): 563-567.

Piersma, T. “Body size, nutrient reserves and diet of Red-necked and Slavonian Grebes Podiceps grisegena and P. auritus on Lake IJsselmeer, The Netherlands.” Bird Study 35.1 (1988): 13-24.

Sonntag, N., Garthe, S., and Adler, S. "A freshwater species wintering in a brackish environment: Habitat selection and diet of Slavonian grebes in the southern Baltic Sea." Estuarine, Coastal and Shelf Science 84.2 (2009): 186-194.

Stedman, S. J. (2020). “Horned Grebe (Podiceps auritus), version 1.0.” In Birds of the World (S. M. Billerman, Editor). Cornell Lab of Ornithology, Ithaca, NY, USA (2020).

Red-necked Grebe key prey species: Smelt (*Osmerus eperlanus*), pilchard (*Gasterosteus aculeatus*), three-spined stickleback (*Crangon crangon*) and prawns. This species feeds on various fish and invertebrates, including many freshwater species (dragonfly and caddis fly larvae among many others). Freshwater species were not included in the key prey assessment. Prey species list was compiled from:

Stout, B. E. and Nuechterlein, G. L. “Red-necked Grebe (Podiceps grisegena), version 1.0.” In Birds of the World (S. M. Billerman, Editor). Cornell Lab of Ornithology, Ithaca, NY, USA (2020).

Piersma, T. “Body size, nutrient reserves and diet of Red-necked and Slavonian Grebes Podiceps grisegena and P. auritus on Lake IJsselmeer, The Netherlands.” Bird Study 35.1 (1988): 13-24.

Prey range information for all species were compiled from:

Kesner-Reyes, K., et al. "AquaMaps: Predicted range maps for aquatic

species." In FishBase: R. Froese & D. Pauly (Eds.) (2019). Available at: https://www.aquamaps.org

Sailley, S., et al. "Fish abundance and catch data for the Northwest European Shelf and Mediterranean Sea from 2006 to 2098 derived from climate projections". Copernicus Climate Change Service (C3S) Climate Data Store (CDS) (2021). https://doi.org/10.24381/cds.39c97304.

1.1.4 Climate change impacts outside of Europe

Common Loon

Several impacts of climate change have been noted in North American populations, including decreased brood size, changes in migration patterns, increased energetic stress due to higher temperatures, and an increase in exposure to mercury.

Paruk, J. D., et al. “Common Loon (Gavia immer), version 2.0.” In Birds of the World (P. G. Rodewald and B. K. Keeney, Editors). Cornell Lab of Ornithology, Ithaca, NY, USA (2021).

Bianchini, K., et al. “Drivers of declines in Common Loon (Gavia immer) productivity in Ontario, Canada.” Science of the Total Environment 738 (2020): 139724.

Red-throated Loon

Red-throated Loon been caused by “red tides” (mass growth of red algae). It is difficult to attribute one event to climate change, but red tides have become more common and more widespread in California and globally, which has been linked to the effects of climate change.

Jessup, D. A., et al. “Mass stranding of marine birds caused by a surfactant-producing red tide.” PLoS One 4.2 (2009): e4550.

1.2 Sensitivity (references)

We used a list of candidate traits based on that in Foden & Young (2016) that indicate high sensitivity and identified which, if any, loons, divers and grebes possessed. In brief, we consulted published literature as well as expert knowledge and online databases such as Birdlife (http://datazone.birdlife.org/) and Birds of the World (https://birdsoftheworld.org), to assess whether loons, divers and grebes have either 1) Specialised habitat and/or microhabitat requirement 2) Environmental tolerances or thresholds (at any life stage) that are likely to be exceeded due to climate change 3) Dependence on environmental triggers that are likely to be disrupted by climate change, 4) Dependence on interspecific interactions that are likely to be disrupted by climate change or 5) High rarity.

For more detail and a full list of traits see:

> Foden, W. B. and Young, B. E. (eds.). "IUCN SSC Guidelines for Assessing Species' Vulnerability to Climate Change. Version 1.0." Occasional Paper of the IUCN Species Survival Commission No. 59 (2016). Cambridge, UK and Gland, Switzerland: IUCN Species Survival Commission. x+114pp.

1.3 Adaptive capacity (references)

We used a list of candidate traits based on that in Foden & Young (2016) that indicate adaptive capacity and identified which, if any, loons, divers and grebes possessed. In brief, we consulted published literature as well as expert knowledge and online databases such as Birdlife (http://datazone.birdlife.org/) and Birds of the World (https://birdsoftheworld.org), to assess whether loons, divers and grebes have either: 1) High phenotypic plasticity. 2) High dispersal ability or 3) High evolvability.

For more detail and a full list of traits see:

> Foden, W. B. and Young, B. E. (eds.). "IUCN SSC Guidelines for Assessing Species' Vulnerability to Climate Change. Version 1.0." Occasional Paper of the IUCN Species Survival Commission No. 59 (2016). Cambridge, UK and Gland, Switzerland: IUCN Species Survival Commission. x+114pp.

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Appendix 1: Petrels and Shearwaters

Sources and references for vulnerability assessment

1.1 Evidence for exposure (references)

1.1.1 Current impacts attributed to climate change:

Cory's Shearwater

1 - New colonies have been established outside of the species' normal range. The cause is uncertain, but likely related to prey range shifts and warming conditions.

> **Munilla, Ignacio, et al. "Colony foundation in an oceanic seabird." PloS one 11.2 (2016): e0147222.** Cory's shearwaters have established several breeding colonies in Galicia, an area they have never historically been associated with. The authors note this is a rare event, as, like most shearwaters, Cory's shearwaters have high site fidelity. The cause is unknown, but the authors hypothesis the underlying cause is generally warming condition and shift of warm-water prey species north.

Northern Fulmar

1 - Warmer winters have resulted in lower adult survival and lower reproductive success in the following year. Mechanism unknown, potentially could be related to marine productivity

> **Grosbois, V., and Thompson, P. M.. "North Atlantic climate variation influences survival in adult fulmars." Oikos 109.2 (2005): 273-290.** Adult survival decreased over the study period, in correlation with winter climate conditions (WNAO). Mechanism unknown. Study in Eynhallow, Orkneys.
>
> **Lewis, S., et al. "Effects of extrinsic and intrinsic factors on breeding success in a long lived seabird." Oikos 118.4 (2009): 521-528.** Confirms the former using data from the same population (Eynhallow, Orkneys). Effects of NAO (and increased winter SST) have a negative, lagged impact on fulmar breeding success.

2 - Higher sea temperatures typically correlate with lower breeding success. Mechanism unknown, but likely mediated through prey availability. Continued warming may cause long-term declines in populations.

> **Burthe, S. J., et al. "Assessing the vulnerability of the marine bird community in the western North Sea to climate change and other anthropogenic impacts." Marine Ecology Progress Series 507 (2014): 277-**

295. Fulmar productivity decreases as sea surface temperature gets higher. Probably due to prey availability, study focusses on seabirds in Forth and Tay region.

European Storm-petrel

1 - High winds and storms in the non-breeding season causes increased mortality, lower body condition, and reduced breeding success. While individual extreme climate events are difficult to attribute to climate change, it is likely that climate change is driving an increase in their frequency and/or intensity.

Zuberogoitia, I., et al. "Assessing the impact of extreme adverse weather on the biological traits of a European storm petrel colony." Population ecology 58.2 (2016): 303-313. Reproductive breeding success was lower, moulting occurred later and more skipped breeding occurred in years following a winter with adverse weather. Protracted periods of continuous gale-force winds prevents petrels from feeding, and they become exhausted and severely weakened. Study was in Aketx colony (Biscay, north of Spain).

2 - A shift towards warmer, drier and calmer conditions has resulted in lower storm petrel abundance. The mechanism is unknown, but likely related to changes in marine ecosystem and key prey availability.

Hemery, G., et al. "Detecting the impact of oceano-climatic changes on marine ecosystems using a multivariate index: the case of the Bay of Biscay (North Atlantic-European Ocean)." Global Change Biology 14.1 (2008): 27-38. Abundance of European storm-petrels in the Bay of Biscay declined from 1974 to 2000. The number of breeding pairs per year was negatively correlated with a local multivariate climate index (combining 11 oceanic and atmospheric variables). Storm petrels seem to have suffered locally from a trend towards warmer, drier years with calmer sea surface conditions.

Manx Shearwater

1 - Reduced prey availability during the breeding season has led to longer foraging trips and lower condition in adults and chicks

Riou, S., et al. "Recent impacts of anthropogenic climate change on a higher marine predator in western Britain." Marine Ecology Progress Series 422 (2011): 105-112. In warmer years, prey is less available and adults must forage further to find prey. As a result, adults breed later and chicks reach lower peak and fledgling status. Study conducted on Skomer Island over several breeding seasons.

1.1.2 Change in European range size between present day and 2100:

Using a species distribution model (SDM) we correlated species occurrence during the breeding season with a number of terrestrial and marine environmental variables. Species range data came from the European Breeding Bird Atlas (EBBA2) database. Present-day and 2100 terrestrial data were downloaded from the WorldClim database. We used data from the MRI-ESM2 general circulation model (GCM), which is a high-performing model over Europe. Present-day and 2100 marine data were downloaded from the Bio-Oracle database which averages predictions of marine variables from several different atmospheric-oceanic general circulation models (AOGCMS; for full details see Assis et al., 2017). For the map presented in the summary we used representative concentration pathway (RCP) 4.5, which is an "intermediate" emissions scenario. All data were at 5-minute resolution.

For Cory's shearwater, northern fulmar, band-rumped storm-petrel, Leach's storm-petrel, European storm-petrel, and Manx shearwater we included the following terrestrial variables: mean temperature of the warmest month, precipitation during breeding season, isolation of landmass, area of landmass, distance to sea.

For Cory's shearwater, northern fulmar, band-rumped storm-petrel, Leach's storm-petrel, European storm-petrel, and Manx shearwater we included the following marine variables: sea surface temperature (during the winter), salinity, maximum chlorophyll concentration, bathymetry (depth and variance).

Several other variables may strongly influence the distribution of petrels and shearwaters and it is not possible to include all possible variables in a given model. However the following variables have previously been found to be important to predicting the distribution of petrels and shearwaters in Europe: average wind speed during breeding season, presence of stable ocean fronts (or bathymetric proxy). For local assessments of climate change, we recommend these variables are strongly considered. We hope to incorporate these variables into future versions of this guidance resource.

After running our model we generated a present-day map where every grid-cell is given a habitat suitability score between 0 and 1, where 1 is very suitable habitat and 0 is not at all suitable. We then compared this with a corresponding map built with 2100 data, and highlighted currently inhabited areas where 1) suitability drops sharply (i.e. by more than 0.1) and 2) suitability drops below a probability threshold set by the model. Conversely we also highlighted areas where suitability rose sharply and above a given threshold. While a drop in habitat suitability is likely to result in population declines, it is not a certainty, and it does not mean that a population will be extinct in 2100 or that a population is doomed to extinction. With conservation action and careful management, along with changes in human behaviour, such declines may be mitigated or in some cases prevented. For a full explanation of the model see the accompanying 'Methodology' folder in Appendix 2.

Underlying data were downloaded from:

> **Keller, V., et al. "European Breeding Bird Atlas 2: Distribution, Abundance and Change." European Bird Census Council & Lynx Edicions, Barcelona (2020).** Source of range data
>
> **Fick, S. E., and Hijmans, R. J. "WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas." International Journal of Climatology 37.12 (2017): 4302-4315.** Source of present-day and 2100 terrestrial data.
>
> **Assis, J., et al. "Bio-ORACLE v2. 0: Extending marine data layers for bioclimatic modelling." Global Ecology and Biogeography 27.3 (2018): 277-284.** Source of present-day and 2100 marine data

1.1.3 Changes in key prey species:

We first identified the key prey species for each species. This can be variable across a species' range, but if available evidence suggested at least one major population is highly dependent on a particular prey species, then typically this species would be included. Lists of prey species were compiled from published sources, then verified and expanded following consultation with conservation practitioners. Afterwards we compiled current and projected maps of prey ranges to assess where key prey species may become less common in the near future. If any of the key species are predicted to vanish or drastically reduce in abundance in the current foraging range a given species, we marked this on the summary map.

We used several sources to collate range information, but for preference we used data from COPERNICUS as they include projected abundance. For species where this was not available we used habitat suitability instead. In all cases we used RCP 4.5, which is an "intermediate" emissions scenario. For species in the COPERNICUS database we used the 0.6 maximum sustainable yield parameter, which assumes international co-operation to work towards fish-stock sustainability. Our assessment is therefore relatively conservative in terms of changes in prey species.

Cory's Shearwater key prey species: saury (*Scombresox saurus*), chub mackerel (*Scomber colias*), sardines (*Sardina pilchardus*) and garfish (*Belone belone*). This species also preys frequently on cephalopods and other fish, however these were not included in the assessment. Prey species list was compiled from:

> **Alonso, H., et al. "Parent–offspring dietary segregation of Cory's shearwaters breeding in contrasting environments." Marine Biology 159.6**

(2012): 1197-1207.

Northern Fulmar key prey species: Atlantic cod (*Mallotus villosus*), sandeel species (*Ammodytes marinus* and *Ammodytes tobianus*), herring (*Clupea harengus*), Norway pout (*Trisopterus esmarkii*), whiting (*Merlangius merlangus*), squid (*Gonatus fabricii*) and crustaceans. This species also heavily preys on various crustacean and cephalopod species, as well as fishery discards. However currently these are not included in the key prey assessment. Prey species list was compiled from:

Phillips, R. A., et al. “Diet of the northern fulmar Fulmarus glacialis: reliance on commercial fisheries?.” Marine Biology 135.1 (1999): 159-170.

Mallory, M. L., Hatch, S. A., And Nettleship, D. N. “Northern Fulmar (Fulmarus glacialis), version 1.0.” In Birds of the World (S. M. Billerman, Editor). Cornell Lab of Ornithology, Ithaca, NY, USA (2020).

Band-rumped Storm-petrel key prey species: blue whiting (*Micromesistius poutassou*) and poor cod (*Trisopterus minutus* along with other *Trisopterus* sp.). The diet of this species is poorly characterised in Europe, it may have other key prey species that have yet to be identified, and may in addition rely on discards in some populations. Prey species list was compiled from:

Carreiro, A. R., et al. “Metabarcoding, stables isotopes, and tracking: unraveling the trophic ecology of a winter-breeding storm petrel (Hydrobates castro) with a multimethod approach.” Marine Biology 167.2 (2020): 1-13.

Leach’s Storm-petrel key prey species: glacier lantern fish (*Benthosema glaciale*) and Arctic telescope (*Protomyctophum arcticum*). Prey species list was compiled from:

Hedd, A., and Montevecchi, W. A. "Diet and trophic position of Leach’s storm-petrel Oceanodroma leucorhoa during breeding and moult, inferred from stable isotope analysis of feathers." Marine Ecology Progress Series 322 (2006): 291-301.

European Storm-petrel key prey species: sprat (*Sprattus sprattus*) and sandeels (*Ammodytes marinus*). This species commonly preys on crustaceans, zooplankton and other marine invertebrates, these are a major component of diet in many populations. However, presently these species are not included in the key prey assessment. Prey species list was compiled from:

Carboneras, C., Jutglar, F., and Kirwan (2021), G. M. “European Storm-Petrel (Hydrobates pelagicus), version 1.1.” In Birds of the World (Editor not available). Cornell Lab of Ornithology, Ithaca, NY, USA (2020)

D'Elbee, J., and Hemery, G. "Diet and foraging behaviour of the British Storm Petrel Hydrobates pelagicus in the Bay of Biscay during summer." Ardea 86.1 (1998): 1-10.

Manx Shearwater key prey species: herring (*Clupea harengus*), sprat (*Sprattus sprattus*), sardines (*Sardina pilchardus*), anchovies (*Engraulis encrasicolus*) and sandeels (*Ammodytes marinus*). This species also heavily preys on cephalopod species, however these are poorly characterised so were not included in this analysis. Prey species list was compiled from:

Riou, S., et al. “Recent impacts of anthropogenic climate change on a higher marine predator in western Britain.” Marine Ecology Progress Series 422 (2011): 105-112.

Lee, D. S., et al. “Manx Shearwater (Puffinus puffinus), version 1.0.” In Birds of the World (S. M. Billerman, Editor). Cornell Lab of Ornithology, Ithaca, NY, USA (2020).

Prey range information for all species were compiled from:

Kesner-Reyes, K., et al. "AquaMaps: Predicted range maps for aquatic species." In FishBase: R. Froese & D. Pauly (Eds.) (2019). Available at: https://www.aquamaps.org

Sailley, S., et al. "Fish abundance and catch data for the Northwest European Shelf and Mediterranean Sea from 2006 to 2098 derived from climate projections". Copernicus Climate Change Service (C3S) Climate Data Store (CDS) (2021). https://doi.org/10.24381/cds.39c97304.

1.1.4 Climate change impacts outside of Europe

Leach’s Storm-petrel

Leach’s storm-petrels in North America have changed their prey species and foraging strategy in response to shifts in the marine ecosystem partially driven by climate change. Heatwaves in North America have impacted storm-petrel colonies and resulted in changes in diet, loss of condition and wrecks. While individual heatwaves are difficult to attribute to climate change, it is likely the frequency and intensity of such events is increasing. Leach’s storm-petrel reproductive success in Canada has been linked to global temperature. Warmer temperatures result in higher reproductive success, up until a certain threshold after which it decreases.

The mechanism is unknown.

Hedd, A., et al. “Diets and distributions of Leach’s storm-petrel (Oceanodroma leucorhoa) before and after an ecosystem shift in the Northwest Atlantic.” Canadian Journal of Zoology 87.9 (2009): 787-801.

D’Entremont, K., et al. “On-land foraging by Leach’s Storm Petrels Oceanodroma leucorhoa coincides with anomalous weather conditions.” Marine Ornithology 49 (2021): 247-252.

Mauck, R. A., Dearborn, D. C., and Huntington, C. E. "Annual global mean temperature explains reproductive success in a marine vertebrate from 1955 to 2010." Global Change Biology 24.4 (2018): 1599-1613.

Manx Shearwater

Manx shearwaters are known to be sensitive to climate change in the tropics, particularly to wrecks caused by storms, which are becoming more common due to changes in the El Nino cycle

Tavares, D. C., et al. “Mortality of seabirds migrating across the tropical Atlantic in relation to oceanographic processes.” Animal Conservation 23.3 (2020): 307-319.

1.2 Sensitivity (references)

We used a list of candidate traits based on that in Foden & Young (2016) that indicate high sensitivity and identified which, if any, petrels and shearwaters possessed. In brief, we consulted published literature as well as expert knowledge and online databases such as Birdlife (http://datazone.birdlife.org/) and Birds of the World (https://birdsoftheworld.org), to assess whether petrels and shearwaters have either 1) Specialised habitat and/or microhabitat requirement 2) Environmental tolerances or thresholds (at any life stage) that are likely to be exceeded due to climate change 3) Dependence on environmental triggers that are likely to be disrupted by climate change, 4) Dependence on interspecific interactions that are likely to be disrupted by climate change or 5) High rarity.
For more detail and a full list of traits see:

Foden, W. B. and Young, B. E. (eds.). "IUCN SSC Guidelines for Assessing Species’ Vulnerability to Climate Change. Version 1.0." Occasional Paper of the IUCN Species Survival Commission No. 59 (2016). Cambridge, UK and Gland, Switzerland: IUCN Species Survival Commission. x+114pp.

1.3 Adaptive capacity (references)

We used a list of candidate traits based on that in Foden & Young (2016) that indicate adaptive capacity and identified which, if any, petrels and shearwaters possessed. In brief, we consulted published literature as well as expert knowledge and online databases such as Birdlife (http://datazone.birdlife.org/) and Birds of the World (https://birdsoftheworld.org), to assess whether petrels and shearwaters have either: 1) High phenotypic plasticity. 2) High dispersal ability or 3) High evolvability.

For more detail and a full list of traits see:

Foden, W. B. and Young, B. E. (eds.). "IUCN SSC Guidelines for Assessing Species' Vulnerability to Climate Change. Version 1.0." Occasional Paper of the IUCN Species Survival Commission No. 59 (2016). Cambridge, UK and Gland, Switzerland: IUCN Species Survival Commission. x+114pp.

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Appendix 1: Skuas

Sources and references for vulnerability assessment

1.1 Evidence for exposure (references)

1.1.1 Current impacts attributed to climate change:

Great Skua

1 - Hotter summers result in increased heat stress in adults and chicks. Adults more frequently leave nests unattended to thermoregulate, which exacerbates chick heat stress

> **Oswald, S. A., et al. "Heat stress in a high-latitude seabird: effects of temperature and food supply on bathing and nest attendance of great skuas Catharacta skua." Journal of Avian Biology 39.2 (2008): 163-169.** In hot summers prey availability is typically lower, so nesting adults need to leave the nest to forage for longer periods of time. They also bath more regularly to thermoregulate. This results in lower fledgling rates as chicks are unattended for longer and left vulnerable to heat stress. Study was conducted on Foula, Shetlands. Note that study does not investigate a trend in temperature over its 3 study years, but presents evidence that temperature increases and prey shortages are linked and are driven by climate change

2 - In hotter summers, adults more frequently leave nests unattended due to prey shortages and to thermoregulate, which results in higher chick mortality due to predation

> **Oswald, S. A., et al. "Heat stress in a high-latitude seabird: effects of temperature and food supply on bathing and nest attendance of great skuas Catharacta skua." Journal of Avian Biology 39.2 (2008): 163-169.** In hot summers prey availability is typically lower, so nesting adults need to leave the nest to forage for longer periods of time. They also bathe more regularly to thermoregulate. This results in lower fledgling rates as chicks are unattended for longer and left vulnerable to predation. Study was conducted on Foula, Shetlands. Note that study does not investigate a trend in temperature over its 3 study years, but presents evidence that temperature increases and prey shortages are linked and are driven by climate change.

3 - Changes in prey availability during the breeding season have led to decreased fledgling success

> **Oswald, S. A., et al. "Heat stress in a high-latitude seabird: effects of**

temperature and food supply on bathing and nest attendance of great skuas Catharacta skua." Journal of Avian Biology 39.2 (2008): 163-169. Lower food availability (particularly sandeels) means adults must forage for longer, resulting in the same problem as for heat stress: chicks are left unattended and vulnerable. Study on Foula, Shetlands. Note that study does not investigate a trend in temperature over its 3 study years, but presents evidence that temperature increases and prey shortages are linked and are driven by climate change.

4 - Changes in prey availability has led to increased population size

Descamps, S., et al. "Climate change impacts on wildlife in a High Arctic archipelago–Svalbard, Norway." Global Change Biology 23.2 (2017): 490-502. Great skuas were first observed breeding on Svalbard in 1970, and their numbers have increased rapidly in recent years. This is most likely driven by range shifts in prey species and because of general warming of the climate.

Long-tailed Jaeger

1 - Southern populations are becoming less populous or going extinct in correlation with rising temperatures. Exact mechanism unknown, probably related to prey availability or heat stress.

Virkkala, R. and Rajasärkkä, A. "Northward density shift of bird species in boreal protected areas due to climate change." Boreal Environment Research 16 (suppl. B) (2011): 2–13. Long-tailed skuas have drastically reduced in range and density in Finland due to climate change, density in 2000-2009 was <50% of what it was in censuses carried out 1981–1999. Seems to be part of a range shift north. Exact mechanism unknown, probably related to prey availability or heat stress.

Arctic Jaeger

1 - Changes in prey availability have led to declines in key seabird species that Arctic skuas parasitise, thus leading to population declines in skuas.

Perkins, A., et al. "Combined bottom-up and top-down pressures drive catastrophic population declines of Arctic skuas in Scotland." Journal of Animal Ecology 87.6 (2018): 1573-1586. Arctic skuas in Scotland are declining drastically, there are multiple potential causes behind this. One likely driver is the decline of other seabirds due to climate change, which are important sources of food for skuas (usually by stealing their prey). Study looks at multiple colonies across Shetlands and Orkney Islands.

2 - Increased competition and predation from Great skuas, due to an increasing population size and prey swapping.

Perkins, A., et al. “Combined bottom-up and top-down pressures drive catastrophic population declines of Arctic skuas in Scotland.” Journal of Animal Ecology 87.6 (2018): 1573-1586. Great skuas are increasing in number and have swapped their diet from predominantly fish to predominantly preying on other birds. Greater numbers of great skua lead to lower fledgling survival rate in arctic skuas. Study looks at multiple colonies across Shetlands and Orkney Islands.

Dawson, N. M., et al. “Interactions with Great Skuas Stercorarius skua as a factor in the long-term decline of an Arctic Skua Stercorarius parasiticus population.” Ibis 153.1 (2011): 143-153. Arctic skua range is contracting across the Shetlands as great skua populations grow and expand. The overall decline in Arctic skua seems to be driven by this and lower density of sandeels, and both patterns are partially driven by climate change.

1.1.2 Change in European range size between present day and 2100:

Using a species distribution model (SDM) we correlated species occurrence during the breeding season with a number of terrestrial and marine environmental variables. Species range data came from the European Breeding Bird Atlas (EBBA2) database. Present-day and 2100 terrestrial data were downloaded from the WorldClim database. We used data from the MRI-ESM2 general circulation model (GCM), which is a high-performing model over Europe. Present-day and 2100 marine data were downloaded from the Bio-Oracle database which averages predictions of marine variables from several different atmospheric-oceanic general circulation models (AOGCMS; for full details see Assis et al., 2017). For the map presented in the summary we used representative concentration pathway (RCP) 4.5, which is an “intermediate” emissions scenario. All data were at 5-minute resolution.

For great skua and Arctic jaeger we included the following terrestrial variables: Mean temperature of the warmest month, precipitation during breeding season, isolation of landmass, area of landmass, distance to sea.

For long-tailed jaeger we included the following terrestrial variables: mean temperature of the warmest month, precipitation during breeding season, distance to sea.

For great skua and Arctic jaeger we included the following marine variables: sea surface temperature (during the winter), salinity, maximum chlorophyll concentration, bathymetry (depth and variance).

After running our model we generated a present-day map where every grid-cell is given a habitat suitability score between 0 and 1, where 1 is very suitable habitat and 0 is not at all suitable. We then compared this with a corresponding map built with 2100 data, and highlighted currently inhabited areas where 1) suitability drops sharply (i.e. by more than 0.1) and 2) suitability drops below a probability threshold set by the model. Conversely we also highlighted areas where suitability rose sharply and above a given threshold. While a drop in habitat suitability is likely to result in population declines, it is not a certainty, and it does not mean that a population will be extinct in 2100 or that a population is doomed to extinction. With conservation action and careful management, along with changes in human behaviour, such declines may be mitigated or in some cases prevented. For a full explanation of the model see the accompanying 'Methodology' folder in Appendix 2.

Underlying data were downloaded from:

> **Keller, V., et al. "European Breeding Bird Atlas 2: Distribution, Abundance and Change." European Bird Census Council & Lynx Edicions, Barcelona (2020).** Source of range data
>
> **Fick, S. E., and Hijmans, R. J. "WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas." International Journal of Climatology 37.12 (2017): 4302-4315.** Source of present-day and 2100 terrestrial data.
>
> **Assis, J., et al. "Bio-ORACLE v2. 0: Extending marine data layers for bioclimatic modelling." Global Ecology and Biogeography 27.3 (2018): 277-284.** Source of present-day and 2100 marine data

1.1.3 Changes in key prey species:

We first identified the key prey species for each species. This can be variable across a species' range, but if available evidence suggested at least one major population is highly dependent on a particular prey species, then typically this species would be included. Lists of prey species were compiled from published sources, then verified and expanded following consultation with conservation practitioners. Afterwards we compiled current and projected maps of prey ranges to assess where key prey species may become less common in the near future. If any of the key species are predicted to vanish or drastically reduce in abundance in the current foraging range a given species, we marked this on the summary map.

We used several sources to collate range information, but for preference we used data from COPERNICUS as they include projected abundance. For species where this was not available we used habitat suitability instead. In all cases we used RCP 4.5, which is an "intermediate" emissions scenario. For species in the COPERNICUS database we used the 0.6 maximum sustainable yield parameter, which assumes international co-operation to work towards fish-stock sustainability. Our assessment is therefore relatively conservative in terms of changes in prey species.

Great Skua key prey species: whiting (*Merlangius merlangus*), blue whiting (*Micromesistius poutassou*), haddock (*Melanogrammus aeglefinus*) and pout (*Trisopterus esmarkii)*. Some populations rely heavily on predation of other seabirds (such as fulmars, kittiwakes and puffins) and on fishery discards. These were not included in our prey assessment. Prey species list was compiled from:

> Jones, T., et al. “Breeding performance and diet of Great Skuas Stercorarius skua and Parasitic Jaegers (Arctic Skuas) S. parasiticus on the west coast of Scotland.” Bird Study 55.3 (2008): 257-266.
>
> Votier, S. C., et al. “Predation by great skuas at a large Shetland seabird colony.” Journal of Applied Ecology 41.6 (2004): 1117-1128.

Long-tailed Jaeger key prey species: collared lemming (*Dichrostonyx groenlandicus*), gray-sided vole (*Clethrionomys rufocanus*) and Norway lemming (*Lemmus lemmus*). Breeding populations rely heavily on rodents, including collared lemmings, gray-sided voles and Norway lemmings. Where rodents are not common, some populations rely on kleptoparasitism. These species were not included in our prey assessment. Prey species list was compiled from:

> Dekorte, J., And Wattel, J. “Food and breeding success of the long-tailed skua at Scoresby Sund, Northeast Greenland.” Ardea 76.1 (1988): 27-41.
>
> Andersson, M. “Population ecology of the long-tailed skua (Stercorarius longicaudus Vieill.).” The Journal of Animal Ecology (1976): 537-559.

Arctic Jaeger key prey species: sandeel species (*Ammodytes marinus* and *Ammodytes tobianus*). Prey species list was compiled from:

> Phillips, R. A., Caldow, R. W. G., and Furness, R. W. "The influence of food availability on the breeding effort and reproductive success of Arctic Skuas Stercorarius parasiticus." Ibis 138.3 (1996): 410-419.

Prey range information for all species were compiled from:

> Kesner-Reyes, K., et al. "AquaMaps: Predicted range maps for aquatic species." In FishBase: R. Froese & D. Pauly (Eds.) (2019). Available at: https://www.aquamaps.org
>
> Sailley, S., et al. "Fish abundance and catch data for the Northwest European Shelf and Mediterranean Sea from 2006 to 2098 derived from climate projections". Copernicus Climate Change Service (C3S) Climate

Data Store (CDS) (2021). https://doi.org/10.24381/cds.39c97304.

1.1.4 Climate change impacts outside of Europe

Long-tailed Jaeger

Skuas have been heavily affected by climate change in Greenland, in particular due to lack of prey and increased predation due to other species prey-switching

Schmidt, N. M., et al. "Response of an arctic predator guild to collapsing lemming cycles." Proceedings of the Royal Society B: Biological Sciences 279.1746 (2012): 4417-4422.

Barraquand, F., et al. "Demographic responses of a site-faithful and territorial predator to its fluctuating prey: long-tailed skuas and arctic lemmings." Journal of Animal Ecology 83.2 (2014): 375-387.

1.2 Sensitivity (references)

We used a list of candidate traits based on that in Foden & Young (2016) that indicate high sensitivity and identified which, if any, skuas possessed. In brief, we consulted published literature as well as expert knowledge and online databases such as Birdlife (http://datazone.birdlife.org/) and Birds of the World (https://birdsoftheworld.org), to assess whether skuas have either 1) Specialised habitat and/or microhabitat requirement 2) Environmental tolerances or thresholds (at any life stage) that are likely to be exceeded due to climate change 3) Dependence on environmental triggers that are likely to be disrupted by climate change, 4) Dependence on interspecific interactions that are likely to be disrupted by climate change or 5) High rarity.

For more detail and a full list of traits see:

Foden, W. B. and Young, B. E. (eds.). "IUCN SSC Guidelines for Assessing Species' Vulnerability to Climate Change. Version 1.0." Occasional Paper of the IUCN Species Survival Commission No. 59 (2016). Cambridge, UK and Gland, Switzerland: IUCN Species Survival Commission. x+114pp.

1.3 Adaptive capacity (references)

We used a list of candidate traits based on that in Foden & Young (2016) that indicate adaptive capacity and identified which, if any, skuas possessed. In brief, we consulted published literature as well as expert knowledge and online databases such as Birdlife (http://datazone.birdlife.org/) and Birds of the World (https://birdsoftheworld.org), to assess whether skuas have either: 1) High phenotypic plasticity. 2) High dispersal ability or 3) High evolvability.

For more detail and a full list of traits see:

Foden, W. B. and Young, B. E. (eds.). "IUCN SSC Guidelines for Assessing Species' Vulnerability to Climate Change. Version 1.0." Occasional Paper of the IUCN Species Survival Commission No. 59 (2016). Cambridge, UK and Gland, Switzerland: IUCN Species Survival Commission. x+114pp.

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Appendix 1: Terns

Sources and references for vulnerability assessment

1.1 Evidence for exposure (references)

1.1.1 Current impacts attributed to climate change:

Arctic Tern

1 - Changes in prey availability during the breeding season have led to population declines (debated).

> **Lindegren, M., et al. "Productivity and recovery of forage fish under climate change and fishing: North Sea sandeel as a case study." Fisheries Oceanography 27.3 (2018): 212-221.** Severe decline in sandeels, which Arctic terns are heavily dependent on in the UK, has led to population declines across the Shetlands. The decline in sandeels is likely linked to fisheries rather than climate change, but it is believed climate change may be hindering recovery of sandeel populations. Sandeel abundance is lower in warmer temperatures, so it is plausible that climate change will have a negative effect on sandeel availability.

2 - Changes in prey availability during the breeding season have led to population declines.

> **Vigfusdottir, F. "Drivers of productivity in a subarctic seabird: Arctic Terns in Iceland." University of East Anglia (2012). PhD Dissertation.** Increasing sea temperatures around Iceland have been linked to reduced sandeel recruitment, which is the likely cause behind recent population declines
> **Petersen, A., et al. "Annual survival of Arctic terns in western Iceland." Polar Biology 43.11 (2020): 1843-1849.** Updated evidence supporting the above study, Arctic terns in Iceland are declining and likely cause is collapse of sandeel populations related to climate change

3 - Arctic terns are arriving from migration and breeding earlier

> **Wanless, S., et al. "Long-term changes in breeding phenology at two seabird colonies in the western North Sea." Ibis 151.2 (2009): 274-285.** Arctic terns on the Farne Islands are arriving and breeding earlier. Study used a 35-year dataset. The study suggests climatic conditions in wintering grounds or during the spring migration may have driven phenological change.
> **Møller, A. P., Flensted-Jensen, E., and Mardal, W. "Rapidly advancing laying date in a seabird and the changing advantage of early reproduction." Journal of Animal Ecology (2006): 657-665.** Arctic terns in Demark are

arriving and breeding earlier. Strong correlation with changes in NAO and temperature.

4 - Juvenile Arctic terns have begun to disperse further, distance has increased in correlation with warmer winters. Mechanism unknown, but likely mediated through prey availability

Møller, A. P., Flensted-Jensen, E., and Mardal, W. "Dispersal and climate change: a case study of the Arctic tern Sterna paradisaea." Global Change Biology 12.10 (2006): 2005-2013. Between 1933 and 1997, the mean natal dispersal distance of Danish Arctic terns increased from around 10 km to around 100 km. (Natal dispersal is the movement from birth site to first breeding site.) The winter NAO index increased over the same period. The study suggests the wNAO may affect dispersal decision through effects on the marine ecosystem, and that increased natal dispersal distances have a fitness cost because they delay breeding and therefore reduce recruitment probability.

Little Tern

1 - Little tern nests are frequently washed away by tidal surges, such events are becoming more frequent or extensive due to rising sea levels

Johnson, C., Sullivan, I., and Newton, S. "Tern Colony Management and Protection at Kilcoole 2017." Department of Arts, Heritage and the Gaeltacht: BirdWatch Ireland (2017). Little tern nests in the UK are frequently washed away by tidal surges (personal correspondence), which has strongly contributed to successive years of poor breeding and subsequent population decline in the UK. Rising sea level exacerbates these effects and reduces the amount of safe breeding habitat available.

2 - As sea temperature has increased over time, tern productivity has decreased. Mechanism unknown, but likely mediated through prey availability

Burthe, S. J., et al. “Assessing the vulnerability of the marine bird community in the western North Sea to climate change and other anthropogenic impacts.” Marine Ecology Progress Series 507 (2014): 277-295. Tern productivity is lower when the sea surface temperature is higher. Mechanism probably linked to prey availability. Local sea surface temperature increased over the study duration. Study focusses on seabirds in Forth and Tay region.

Sandwich Tern

1 - Sandwich terns are changing their migration timing and arriving earlier to breeding sites

Wanless, S., et al. “Long-term changes in breeding phenology at two

seabird colonies in the western North Sea." Ibis 151.2 (2009): 274-285. Sandwich terns in the Farne Islands are arriving earlier, likely in response to changing environmental cues in wintering grounds or on the spring migration route. However, there was no significant advancement in laying date. Study used a roughly 30-year dataset.

2 - Sandwich terns are changing their migration timing, both migration and breeding events are occurring later, making the breeding season shorter

Møller, A. P., et al. "Climate change affects the duration of the reproductive season in birds." Journal of animal ecology 79.4 (2010): 777-784. Breeding season is now significantly shorter in Denmark than it was in 1970 (by approx. 36 days). This is in correlation with rising spring temperatures, is likely in response to changes in environmental conditions

1.1.2 Change in European range size between present day and 2100:

Using a species distribution model (SDM) we correlated species occurrence during the breeding season with a number of terrestrial and marine environmental variables. Species range data came from the European Breeding Bird Atlas (EBBA2) database. Present-day and 2100 terrestrial data were downloaded from the WorldClim database. We used data from the MRI-ESM2 general circulation model (GCM), which is a high-performing model over Europe. Present-day and 2100 marine data were downloaded from the Bio-Oracle database which averages predictions of marine variables from several different atmospheric-oceanic general circulation models (AOGCMS; for full details see Assis et al., 2017). For the map presented in the summary we used representative concentration pathway (RCP) 4.5, which is an "intermediate" emissions scenario. All data were at 5-minute resolution.

For Caspian tern, roseate tern, Arctic tern, little tern, and Sandwich tern we included the following terrestrial variables: Mean temperature of the warmest month, precipitation during breeding season, isolation of landmass, area of landmass, distance to sea.

For Caspian tern, roseate tern, little tern, and Sandwich tern we included the following marine variables: sea surface temperature (during the winter), salinity, maximum chlorophyll concentration, bathymetry (depth and variance)

After running our model we generated a present-day map where every grid-cell is given a habitat suitability score between 0 and 1, where 1 is very suitable habitat and 0 is not at all suitable. We then compared this with a corresponding map built with 2100 data, and highlighted currently inhabited areas where 1) suitability drops sharply (i.e. by more than 0.1) and 2) suitability drops below a probability threshold set by the model. Conversely we also highlighted areas where suitability rose sharply and above a given threshold. While a drop in habitat suitability is likely to result in population declines, it is not a certainty, and it does not mean that a population will be extinct in 2100 or that a population is doomed to extinction. With conservation action and careful management, along with changes in human behaviour, such declines may be mitigated or in some cases prevented. For a full explanation of the model see the accompanying 'Methodology' folder in Appendix 2.

Underlying data were downloaded from:

Keller, V., et al. "European Breeding Bird Atlas 2: Distribution, Abundance and Change." European Bird Census Council & Lynx Edicions, Barcelona (2020). Source of range data

Fick, S. E., and Hijmans, R. J. "WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas." International Journal of Climatology 37.12 (2017): 4302-4315. Source of present-day and 2100 terrestrial data.

Assis, J., et al. "Bio-ORACLE v2. 0: Extending marine data layers for bioclimatic modelling." Global Ecology and Biogeography 27.3 (2018): 277-284. Source of present-day and 2100 marine data

1.1.3 Changes in key prey species:

We first identified the key prey species for each species. This can be variable across a species' range, but if available evidence suggested at least one major population is highly dependent on a particular prey species, then typically this species would be included. Lists of prey species were compiled from published sources, then verified and expanded following consultation with conservation practitioners. Afterwards we compiled current and projected maps of prey ranges to assess where key prey species may become less common in the near future. If any of the key species are predicted to vanish or drastically reduce in abundance in the current foraging range a given species, we marked this on the summary map.
We used several sources to collate range information, but for preference we used data from COPERNICUS as they include projected abundance. For species where this was not available we used habitat suitability instead. In all cases we used RCP 4.5, which is an "intermediate" emissions scenario. For species in the COPERNICUS database we used the 0.6 maximum sustainable yield parameter, which assumes international co-operation to work towards fish-stock sustainability. Our assessment is therefore relatively conservative in terms of changes in prey species.

Arctic Tern key prey species: sandeel species (*Ammodytes marinus* and

Ammodytes tobianus), herring (*Clupea harengus*) and stickleback (*Gasterosteus aculeatus)*. This species also preys on small invertebrates (larval fish, shrimp, idotea, etc.). These are poorly characterised so have not been included in the prey assessment. Prey species list was compiled from:

> Hatch, J. J., et al. "Arctic Tern (Sterna paradisaea), version 1.0." In Birds of the World (S. M. Billerman, Editor). Cornell Lab of Ornithology, Ithaca, NY, USA (2020).
>
> Eglington, S., and Perrow, M. R. "Literature review of tern (Sterna & Sternula spp.) foraging ecology". ECON Ecological Consultancy Limited (2014).

Little Tern key prey species: sandeel species (*Ammodytes marinus* and *Ammodytes tobianus*), herring (*Clupea harengus*), sprat (*Sprattus sprattus*), sand-smelt (*Atherina presbyter*), sardines (*Sardina pilchardus*) and goby species. Prey species list was compiled from:

> Shealer, D., et al. "Sandwich Tern (Thalasseus sandvicensis), version 1.0." In Birds of the World (S. M. Billerman, Editor). Cornell Lab of Ornithology, Ithaca, NY, USA (2020).
>
> Eglington, S., and Perrow, M. R. "Literature review of tern (Sterna & Sternula spp.) foraging ecology". ECON Ecological Consultancy Limited (2014).

Roseate Tern key prey species: sprat (*Sprattus sprattus*) and sandeel species (*Ammodytes marinus* and *Ammodytes tobianus*). Prey species list was compiled from:

> Green, E. "Tern diet in the UK and Ireland: a review of key prey species and potential impacts of climate change." RSPB Report (2017).
>
> Eglington, S., and Perrow, M. R. "Literature review of tern (Sterna & Sternula spp.) foraging ecology". ECON Ecological Consultancy Limited (2014).

Sandwich Tern key prey species: sandeel species (*Ammodytes marinus* and *Ammodytes tobianus*), herring (*Clupea harengus*), sprat (*Sprattus sprattus*), anchovy (*Engraulis encrasicholus*) and sardine (*Sardina pilchardus*). Prey species list was compiled from:

> Shealer, D., et al. "Sandwich Tern (Thalasseus sandvicensis), version 1.0." In Birds of the World (S. M. Billerman, Editor). Cornell Lab of Ornithology, Ithaca, NY, USA (2020).

Eglington, S., and Perrow, M. R. "Literature review of tern (Sterna & Sternula spp.) foraging ecology". ECON Ecological Consultancy Limited (2014).

Caspian Tern key prey species: herring (*Clupea harengus*). Prey species list was compiled from:

Cuthbert, F. J. and Wires, L. R. "Caspian Tern (Hydroprogne caspia), version 1.0." In Birds of the World (S. M. Billerman, Editor). Cornell Lab of Ornithology, Ithaca, NY, USA (2020).

Prey range information for all species were compiled from:

Kesner-Reyes, K., et al. "AquaMaps: Predicted range maps for aquatic species." In FishBase: R. Froese & D. Pauly (Eds.) (2019). Available at: https://www.aquamaps.org

Sailley, S., et al. "Fish abundance and catch data for the Northwest European Shelf and Mediterranean Sea from 2006 to 2098 derived from climate projections". Copernicus Climate Change Service (C3S) Climate Data Store (CDS) (2021). https://doi.org/10.24381/cds.39c97304.

1.1.4 Climate change impacts outside of Europe

Caspian Tern

Caspian terns in North America have been negatively affected by heatwaves, warming seas, severe storms, and increased frequency of flooding, all of which are linked to climate change.

Suzuki, Y., et al. "Colony connectivity and the rapid growth of a Caspian Tern (Hydroprogne caspia) colony on Alaska's Copper River Delta, USA." Waterbirds 42.1 (2019): 1-7.

1.2 Sensitivity (references)

We used a list of candidate traits based on that in Foden & Young (2016) that indicate high sensitivity and identified which, if any, terns possessed. In brief, we consulted published literature as well as expert knowledge and online databases such as Birdlife (http://datazone.birdlife.org/) and Birds of the World (https://birdsoftheworld.org), to assess whether terns have either 1) Specialised habitat and/or microhabitat requirement 2) Environmental tolerances or thresholds (at any life stage) that are likely to be exceeded due to climate change 3) Dependence on environmental triggers that are likely to be disrupted by climate change, 4) Dependence on interspecific interactions that are likely to be disrupted by climate change or 5) High rarity.

For more detail and a full list of traits see:

> Foden, W. B. and Young, B. E. (eds.). "IUCN SSC Guidelines for Assessing Species' Vulnerability to Climate Change. Version 1.0." Occasional Paper of the IUCN Species Survival Commission No. 59 (2016). Cambridge, UK and Gland, Switzerland: IUCN Species Survival Commission. x+114pp.

1.3 Adaptive capacity (references)

We used a list of candidate traits based on that in Foden & Young (2016) that indicate adaptive capacity and identified which, if any, terns possessed. In brief, we consulted published literature as well as expert knowledge and online databases such as Birdlife (http://datazone.birdlife.org/) and Birds of the World (https://birdsoftheworld.org), to assess whether terns have either: 1) High phenotypic plasticity. 2) High dispersal ability or 3) High evolvability.

For more detail and a full list of traits see:

> Foden, W. B. and Young, B. E. (eds.). "IUCN SSC Guidelines for Assessing Species' Vulnerability to Climate Change. Version 1.0." Occasional Paper of the IUCN Species Survival Commission No. 59 (2016). Cambridge, UK and Gland, Switzerland: IUCN Species Survival Commission. x+114pp.

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Appendix 2: Sources and references for conservation action assessment

Due to the volume of data involved, we have placed our supporting information detailing our full methodology and list of references into a separate resource. It is available to download here: https://doi.org/10.11647/OBP.0343.

Methodology

If you would like to see our full methodology, please see the accompanying "Methodology" folder. This folder contains information on:

- How we compiled our climate change impacts list for all species
- How we compiled our conservation action evidence base
- How we assessed effectiveness of conservation actions
- How we scored strength, transparency and relevance of conservation actions
- Additional methodology on modelling approach and generating outputs

References

If you would like a full reference list of all studies in our evidence base, as well as the raw data for the evidence base please see the "References" folder. This folder contains:

- All references relevant to climate change impacts, and each species' sensitivity and adaptive capacity to climate change
- All references used to assess species diet
- The full citation of each paper included in the conservation action evidence base and additional details. Additional details include the focal species of each study, the sample size and location of each study, what the metric of success was for each study, whether each study had published and replicable methodology, whether we considered that each study had a clear justification of their method, whether we considered that each study had a clear outcome, the form of each study, and each study's experimental design
- Links to relevant Conservation Evidence website data (where applicable)
- Additional details on ex-situ populations, rehabilitation and release.

Version History

This guidance is continually updated, we include a brief version history here to inform readers on changes between versions. This version is v1.2. If you would like to see the full online version please visit this address: https://doi.org/10.11647/OBP.0343.

Version 1:

v1.0: Full initial release.

v1.1: Minor fixes. Error found and now fixed on ivory gull vulnerability map. Additional labels added to photos. Version history page added.

v1.2: Information from EAZA Charadriiformes TAG incorporated. Includes additional information on seabird ex-situ population sizes, breeding success, rehabilitation and release, and overview of head-starting for different species.