Linking climate change vulnerability research and evidence on conservation action effectiveness to safeguard seabird populations in Western Europe

Hakkinen H.[1], Petrovan S.O.[2], Sutherland W.J.[2,3], Dias M.P.[4,5], Ameca E.I.[6,7], Oppel S.[8], Ramirez I.[9], Lawson B.[1], Lehikoinen A.[10], Bowgen K.M.[11], Taylor N.G.[2,12], Pettorelli N.[1]

[1]Institute of Zoology, Zoological Society of London, Regent's Park, NW1 4RY London, UK

[2]Department of Zoology, Cambridge University, the David Attenborough Building, Pembroke Street, Cambridge CB2 3QZ, UK

[3]Biosecurity Research Initiative at St Catharine's (BioRISC), St Catharine's College, University of Cambridge, Cambridge, CB2 1RL, UK

[4]BirdLife International, The David Attenborough Building, Pembroke Street, Cambridge CB2 3QZ, UK

[5]Departamento de Biologia Animal, Faculdade de Ciências da Universidade de Lisboa, Edifício C2, Campo Grande, 1749-016 Lisboa, Portugal

[6]MOE Key Laboratory for Biodiversity Science and Ecological Engineering, Beijing Normal University. 100875, Beijing, China.

[7]Climate Change Specialist Group, Species Survival Commission, International Union for Conservation of Nature, 1196, Gland, Switzerland.

[8]RSPB Centre of Conservation Science, David Attenborough Building, Pembroke Street, Cambridge, Cambridgeshire, CB2 3QZ, UK

[9]Convention on Migratory Species, United Campus in Bonn, Platz der Vereinten Nationen 1, Bonn, 53113, Germany

[10]LUOMUS, Finnish Museum of Natural History, P.O. Box 17, Helsinki, Finland.

[11]British Trust for Ornithology, The Nunnery, Thetford, Norfolk, IP24 2PU, UK

[12]Ecological Consultant, Cambridge CB4 1LA, UK

Biosketches: *Henry Hakkinen* is a scientist interested in assessing the risks that climate change poses to European seabirds. *Silviu Petrovan, Nigel Taylor* and *William Sutherland* are researchers interested in improving evidence-based solutions for biodiversity conservation. *Maria Dias* is the marine science coordinator at BirdLife International. *Eric Ameca* is a member of the IUCN SSC Climate Change Specialist Group (Impacts Theme co-lead). *Steffen Oppel* is a scientist at the RSPB Centre for Conservation Science. *Ivan Ramirez* is the Head of the Avian Unit at the Convention on the Conservation of Migratory Species (CMS). *Becki Lawson* is a researcher whose main area of interest is the study of disease effects on free-ranging wildlife populations. *Aleksi Lehikoinen* coordinates the Finnish common bird monitoring schemes and leads the Helsinki Lab of Ornithology research group. *Katharine Bowgen*'s work focuses on Welsh bird populations and their conservation. *Nathalie Pettorelli* is an applied ecologist interested in climate change mitigation and adaptation.

*Corresponding author. Email: Nathalie.Pettorelli@ioz.ac.uk. Telephone: 0044 020 7449 6498.

Abstract

1- An increasing number of species are facing unprecedented levels of threat to their long-term survival due to the direct and indirect impacts of climate change. Key opportunities for science to inform wildlife management are linked to increasing our understanding of how changes in climatic conditions will impact species, as well as whether, and how, managers may facilitate species' ability to adapt to change. However, information on species' climate change vulnerability and the effectiveness of potential conservation actions are not yet strategically collected or collated; this disconnect between threat level, ecological research and conservation practice is reducing opportunities to guide decision-making, ultimately hindering conservation outcomes.

2- To demonstrate this point, we explore how existing knowledge can be brought together in a pressure-state-response framework that connects climate change ecology, conservation evidence assessments and management. Seabirds in Western Europe are used as a case study, as they are well-researched and vulnerable to climate change. Using a combination of literature reviews and surveys, we identify the main threats posed to seabirds in the region by climate change, as well as existing conservation actions that could be applied to lessen the impacts of each of these threats.

3- Our results show that 29% of the types of actions considered for reducing the impacts of climate change on seabirds are either associated with conflicting evidence or lack sufficient information to make robust conclusions about their effectiveness: actions aiming at restoring or creating habitat, encouraging relocation, treating or preventing disease, and reducing inter-species competition all have limited or mixed evidence to support their use. Moreover, several threats identified by conservation practitioners as being of high priority to address, such as changes in prey abundance and eutrophication, have few or no viable identified actions to reduce their impact on seabirds.

4- We suggest that existing knowledge on species vulnerability to climate change and evidence of conservation action effectiveness should be more commonly brought together in tailored pressure-state-response frameworks. Such an approach provides an easily transferable platform for identifying missing information and areas where connections between research and management need to be tightened to improve conservation outcomes.

Keywords: climate change; seabirds; conservation evidence; management interventions; pressure-state-response framework.

Background

Anthropogenic climate change poses a major threat to biodiversity, ecosystem services, and human well-being. It is endangering the long-term survival of many species (Urban, 2015) and has already led to a wide-scale redistribution of biodiversity (Pecl et al., 2017), local to regional extirpations (Garciá Molinos et al., 2016) and, in some cases, contributed to the global extinction of an entire species (Waller et al., 2017). Moreover, climate change is a complex, multi-faceted phenomenon which can directly and indirectly impact species in a multitude of ways, both positively and negatively. For example, climate change can directly impact species through changes in environmental conditions that exceed their physiological tolerances (Ainsworth et al., 2016). It can also impact species indirectly, by altering food quality, quantity or availability and causing the collapse of a food chain that a species is part of (Jones et al., 2018, 2019), or by facilitating range shifts or population persistence of potential predators (McClelland et al., 2018; Smith et al., 2017), disease vectors or pathogens (Hofmeister & Van Hemert, 2018). Many of the threats to wildlife from the current climate breakdown cannot be averted or stopped; but impacts to populations could be prevented or reduced, as long as threats can be ascertained and prioritised, and effective solutions identified and implemented.

Identifying the best action (if any) in response to observed population declines associated with changing climatic conditions is however challenging. First, unveiling the various mechanistic pathways by which changes in climatic conditions may impact a given population or species, and subsequently assessing whether each of these potential pathways may threaten the viability of one or more populations, is a complex process. Carrying out such an assessment requires a solid understanding of the species' ecology and a comprehensive overview of recent changes in environmental conditions. Second, choosing what actions to consider in response to an identified threat requires knowing what the options are, and how they compare in terms of effectiveness. Interestingly, these two steps to decision-making are rarely discussed in tandem, as research on climate change adaptation and on the effectiveness of conservation actions are widely disconnected (Butt et al., 2020). Without good connections between these two steps, good communication and a translational ecology approach (Enquist et al., 2017), we are at risk of deploying insufficient or ineffective solutions to a given threat at a certain location and for a particular species, leading to wasted efforts and funding.

To illustrate this disconnection and its potential implications for species conservation, we focus on seabirds in Western Europe, and develop a pressure-state-response (PSR) approach (OECD et al. 1994) to identify the threats seabirds face from climate change in the region, the relative seriousness of these threats, and the potential conservation actions that could be considered to address them (Supplementary Information). Seabirds are an interesting study case for several reasons. First, they are thought to be particularly vulnerable to climate change (Dias et al., 2019) and in many cases are already suffering from the impacts of climate change (Mitchell et al., 2020). Second, seabirds are a well-studied group (Dias et al., 2019) with various conservation actions having been trialled for these species (see below). Finally, as seabirds have large distribution ranges, and often depend on multiple jurisdictions throughout their annual cycles, previous conservation strategies have necessarily been international, which has resulted in a strong network of researchers and practitioners that underpins data collection and policy engagement (Beal et al., 2021).

To carry out this assessment, we combined information from the published literature, conservation databases and first-hand knowledge from conservation practitioners. We used this collated information to 1) create a ranked list of climate change threats; 2) build a list of potential conservation actions for each of these climate change threats; and 3) identify gaps in knowledge about threats and how to alleviate them. The benefits of considering such a PSR framework that connects climate change ecology and evidence of intervention effectiveness, such as the one presented here, are discussed.

Seabirds in Western Europe

We broadly focused our research on seabirds in the northeast Atlantic region as defined by the Oslo/Paris convention (OSPAR; https://www.ospar.org/about). OSPAR is the mechanism by which 15 Governments (Belgium, Denmark, Finland, France, Germany, Iceland, Ireland, Luxembourg, The Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and United Kingdom) and the European Union cooperate to protect the marine environment of the northeast Atlantic. Our study area includes countries that surround the Baltic Sea, including Finland and the Baltic states: this adjustment was made in response to known distributions of significant fish stocks, as well as information on areas known to be important breeding and/or wintering grounds for species otherwise common in Western Europe (Fig. 1).

Using the most recent data released by BirdLife International, we compiled information on the distribution of all seabird species to identify both breeding and non-breeding species that spend a significant portion of the year within the study area. Species listed as vagrants, marginal or that only enter our study area as part of migratory passage were excluded. Seventy-five seabird species have distributions that fall within our chosen area of interest; most (N=61) of them breed in this area. One species is known to be Critically Endangered (the Balearic shearwater *Puffinus mauretanicus*) and another is classified as Endangered (Zino’s petrel *Pterodroma madeira*); neither breed in our area of interest. Another five species are classified as Near Threatened while eight species are classified as Vulnerable; the majority of these 13 species breed in our study area. All other species are classified as Least Concern but several of them are known to have experienced regional declines recently (BirdLife International & Handbook of the Birds of the World, 2020).

We contacted major seabird conservation organisations in sixteen countries: Belgium, Denmark, Estonia, Finland, France, Germany, Iceland, Ireland, Latvia, Lithuania, Netherlands, Norway, Portugal, Spain, Sweden, UK. We emailed staff from Birdlife International and associated branches, the Royal Society for the Protection of Birds, the British Trust for Ornithology, the Norwegian Institute for Nature Research, Naturschutzbund Deutschland, Birdwatch Ireland, Vogelbescherming Nederland, Natuurpunt, Ligue pour la Protection des Oiseaux, Dansk Ornitologisk Forening, AZTI, Consejo Superior de Investigaciones Científicas, Sociedade Portuguesa para o Estudo das Aves, Sociedad Española de Ornitología, Norwegian Ornithological Society, Muséum National d'Histoire Naturelle, l'Office Français pour la Biodiversité and Luonnonvarakeskus. Altogether, we contacted more than 180 practitioners involved with seabird conservation in Western Europe. We invited each practitioner to participate in two anonymous surveys. The first survey asked participants to contribute to a list of climate change threats and conservation actions that could be carried out in response. The second asked participants to rate the severity of each threat and provide information on the extent to which each action was being considered by their organization. At both stages, practitioners were asked to share insights on current gaps in knowledge that may hinder seabird conservation. The questions from each survey are expanded upon in further detail below. Our surveys were only sent to practitioners based in our region of interest and they were asked to assess threats as they applied to Europe and their study sites. Moreover, practitioners were asked to consider breeding and non-breeding sites relevant to seabird conservation, but only when these occurred in Europe or their study sites: as such, climate change threats impacting migratory species with parts of their range outside Western Europe were not captured by our surveys. In total we received 45 and 35 responses, for survey 1 and 2 respectively, from 13 countries.

Pressure and state: routes to climate change vulnerability

As a first step, we compiled information on described pathways by which climate change may directly or indirectly impact the state of seabird populations globally; we primarily based this compilation on two comprehensive reviews on the impacts of climate change on seabirds (Dias et al., 2019; Sydeman et al., 2015). This enabled us to identify a number of direct and indirect pathways, which relate to changes in energetic costs, nest destruction, prey availability, habitat availability and quality (e.g., change in vegetation cover, increased bioavailability of contaminants such as methylmercury), predation and competition pressure (including predation by, and competition with, invasive species), occurrence of infectious and non-infectious disease (e.g., algal bloom toxicosis) and human activities (e.g., increased competition with fishing fleets). For the purpose of this study, we did not include pathways related to the expansion of the renewable energy sector (e.g., increased number of windfarms) and associated potential impacts on seabirds.

We then asked practitioners to review our compiled list of threats and either remove threats that did not apply to the study area or add additional threats that were not listed (survey 1, launched on the 14th April 2021 for one month; this survey was available in English, French, German, Norwegian, Spanish, Swedish and Finnish). We followed up on this request by asking practitioners to review the consolidated list of threats (survey 2, launched on the 2nd June 2021 for one and a half months) and gathered any additional feedback. No additional threats were identified in survey 2. Table 1 details the final list of threats currently at the forefront of practitioners' minds in the region. The direct and indirect threats identified broadly map onto the threat categories used by the IUCN as being related to climate change and severe weather (namely, habitat shifting and alteration, droughts, temperature extremes, storms and flooding, and other impacts; IUCN, 2021).

In survey 2, practitioners were also asked to detail how concerned they were about each threat on a 1-5 scale, ranging from "not a concern" (1) to "very serious threat" (5). We compiled responses and ranked all threats by the percentage of respondents that gave a score of 4 ("serious threat") or 5 ("very serious threat"; Table 1). This showed that reduced prey availability, increased threat from human activity and reduced habitat availability were major concerns for most practitioners surveyed.

Response: options for reducing the impacts of climate change on seabird populations

To collate information on potential conservation actions that may increase population resistance or resilience to the threats identified, we (1) compiled an initial list of possible actions based on the published literature, and (2) asked practitioners to review our compiled list of actions and either remove or add actions that they themselves use or are aware of being used (survey 1). We included actions to tackle both direct and indirect threats from climate change. As for threats, we did not aim for this list of actions to be comprehensive, but to reflect actions being used by seabird conservation practitioners. To ascertain the effectiveness of these various actions, we used the latest available data from Conservation Evidence (https://www.conservationevidence.com/), an initiative collating evidence on the effectiveness of conservation actions globally (Sutherland et al., 2020; Williams et al., 2013).

Very few studies report conservation action effectiveness for seabirds in the context of climate change; because of this, our assessment of effectiveness includes (1) studies published for birds other than seabirds, and (2) studies that may or may not have deployed this particular action in response to climate change. We acknowledge that information from sources other than Conservation Evidence could be used to assess the effectiveness of conservation actions; however, we do not believe such choice would alter the general conclusions presented in this contribution.

The identified 31 conservation actions (Supplementary Information) were grouped into 14 broad types, ranging from habitat restoration and translocations to predator control and eradication, and competitor removal. According to the information compiled by Conservation Evidence, 10 of these 14 potential types of actions are known to be beneficial to some seabird species, while the remaining 4 types of actions either have mixed evidence (i.e., vaccination or treatment against diseases and parasites) or lack sufficient evidence (i.e., manipulation of existing habitats to encourage natural colonisation; habitat restoration and creation; competitor removal) to make robust conclusions about their effectiveness (Fig. 2). For actions related to the treatment and prevention of diseases and parasites, as well as to providing artificial nesting sites, making new sites more attractive for nesting birds, controlling habitat-altering species, protecting nests with barriers and enclosures, managing avian predators and increasing legal protection, the assessment was partly or solely based on non-seabird species.

Learning outcomes and ways forward

Various studies have attempted to predict how seabirds may be affected by climate change in the coming decades, using this information in some cases to call for a reduction in greenhouse gas emissions and the creation of new marine protected areas (e.g., Clairbaux et al., 2021). Yet, when it comes to identifying or prioritising local management actions that should be considered to reduce the impacts of climate change for a given seabird population, guidance remains rare. Below we detail the main knowledge gaps our work identified as needing to be addressed to lessen the impacts of climate change on seabird populations.

Not all climate change threats are equally researched

Several threats listed in Table 1 have received little attention in the context of climate change; a good example of this relates to the changes in risks posed by diseases to seabirds, which 45% of practitioners surveyed thought was a serious threat to seabird populations. It has been suggested that climate change can induce changes in the distribution ranges and population dynamics of disease vectors, as well as changes in disease epidemiology, and that such changes might contribute to declines in wild bird populations (Fuller et al., 2012). Yet existing knowledge of seabird disease ecology is limited (Uhart et al., 2018). In addition, existing reviews of threats to seabirds acknowledge the potential role of disease, including the possible increase in parasite load (Uhart et al., 2018) and change in the frequency and severity of toxic algal blooms (Gibble & Hoover, 2018), but an overview of the specific conservation actions that could reduce such threats is mostly lacking (but see Bourret et al., 2018 for an example on albatross and avian cholera). For example, practitioners across Western Europe ranked the increased risk of nest destruction and disease as equally concerning, but while Conservation Evidence lists 27 studies that look at providing robust artificial nesting sites it only lists two studies focusing on a single species that have trialled disease treatment in a wild seabird population. Another glaring knowledge gap relates to how threats are researched with respect to seabirds' life cycle: 27% of the practitioners surveyed rated the potential impacts of climate change on their migration routes as serious or very serious, yet, to our knowledge, few studies (such as Clairbaux et al., 2019) have explored how serious this threat may be for various seabird species and there are currently no conservation actions listed on Conservation Evidence that could alleviate such impacts.

Downscaling climate change threat assessments to the population level

The relative importance of climate change related threats to a given species is often spatially variable, with some threats (such as reduced prey availability or change in predation pressure) being more problematic in specific parts of the species' range. Threats to populations do not act in isolation (Dias et al., 2019), and interactions between various threats can differ in direction and strength across the range of species. During our surveys, we found that practitioners from various parts of Europe were concerned by different threats, although concern about some specific threats (in this case prey availability, changes in habitat suitability and human-related impacts) were widely shared across Europe, from Finland to Portugal. Downscaling threat assessments or applying threat assessments based on one area to another is extremely challenging and not always adequate. Similarly, it is difficult to gather comprehensive information on where specific threats (and interactions between threats) are particularly problematic for species, but this information is critical to help practitioners prioritise action on the ground. Recent reviews of global threats to seabirds represent important progress on this front, but these assessments remain too broad for most conservation organisations to act upon. A downscaling of these assessments to the scale of taxonomic families, species or regions relevant to conservation is therefore an important next step to prioritise action.

Not all climate change threats have viable conservation actions

The most concerning impacts of climate change to practitioners were reduced prey availability, increased threat from human activities and reduced habitat availability (Table 1). For each of these there are potential conservation actions that have been trialled in several seabird species. However, for these actions, the evidence for intervention effectiveness is based on studies where climate change was never the primary threat to be addressed; for most groups of species, including seabirds but also mammals, amphibians and others, the practical evidence for reducing the impacts of climate change threats remains extremely scarce (Sutherland et al., 2020). In addition, even when potential solutions have been suggested and trialled in seabirds, there are still major caveats. Some actions, such as providing supplementary food, are very labour intensive, unlikely to be practical for most populations, and could cause serious disturbance. For seabirds, few known effective conservation action options are available to tackle indirect threats that are shaped in many cases by long and complex causative pathways operating at large spatial scales. Examples of such indirect threats include climate change resulting in increased localised rainfall, itself accelerating nutrient flow from agricultural lands into wetlands and coastal areas, leading to eutrophication and reduced food availability for seabirds. Another example relates to climate change leading to a greater frequency of toxic algal blooms, which may, depending on their timing and location, result in increased exposure and mass starvation of seabirds. The above examples were mentioned by practitioners as pathways they were particularly concerned about with regards to the populations they managed, and that currently had few viable solutions.

Improving evidence-based assessments of effectiveness

Table 1 shows that, for most actions listed, few studies are available to draw conclusions on their effectiveness. Potential changes in effectiveness of conservation actions between various areas within a species range and different species are thus mostly unknown. Most conservation actions have moreover only been trialled in a few species, and given the diverse ecology of seabird species, it cannot be assumed that action effectiveness is easily transferable. While we currently have tools to model or monitor the impact of some concrete actions for certain species, agreeing on indicators that are easily transferable across most or all seabird species and habitats remains a challenge.

Unintended consequences

Interactions between conservation actions can have a drastic effect on the overall effectiveness of management intervention (Larrosa et al., 2016; Sutherland et al., 2020), something that was highlighted by several individuals surveyed. While a given action may reduce the impact of a targeted threat, subsequent unintended consequences may counteract any positive gain from it (e.g., Prior et al., 2018). Initiatives such as Conservation Evidence collect published information on unintended consequences, which is then used to moderate effectiveness assessment levels. However, in many cases these unintended consequences are not captured, explored and reported in the same studies or for groups other than the target (i.e., a conservation action for birds might have unintended harmful impacts for reptiles but sufficiently robust monitoring might not extend to that group). There is a need to develop a more holistic, consistent and systematic approach to the assessment of possible unintended consequences of conservation actions, so that this information can be factored into future effectiveness assessments.

Conclusions

The challenges posed by the rapid changes in climatic conditions we are experiencing require efficient coordination between science, management, policy and advocacy, so that key questions are given research priority and effective conservation actions can be deployed in areas where they are most needed. Without a joined-up approach between conservation research and action, there is a risk that (1) research does not provide useful information for practitioners; and (2) practitioners do not make conservation decisions that are supported by evidence, either because such evidence is not readily available or because it does not exist; leading to scarce conservation funding being wasted.

Using seabirds as an example, we suggest that existing knowledge should be more often brought together in a fully realised pressure-state-response framework that connects climate change ecology and evidence of intervention effectiveness (OECD et al., 1994). Our approach identified several threats for which there are limited local management options to prevent or reduce their impacts on seabirds, and several conservation actions which are currently not well supported by scientific evidence. This is despite the fact that seabirds in Western Europe are a well-researched group of animals that receives high conservation attention. The presented framework provides an easily transferable platform for identifying missing information and areas where connections between research and management need to be tightened to improve conservation outcomes. Combining research on climate change threats and management interventions in such a coherent way can facilitate coordination and synthesis of insights between multiple disciplines (e.g., ecology, veterinary sciences, geography, meteorology) and stakeholders (e.g., policy makers, wildlife managers), while enabling scientists to prioritise research for the most pressing threats. In the face of rapidly changing environmental conditions, we believe the adoption of frameworks such as ours could help align efforts to prioritise and implement evidence-based climate change adaptation practices to safeguard a future for the species most at risk.

Acknowledgements: We are grateful to all the members of the seabird conservation community who took time to answer our surveys. We would also like to thank Mark Bolton, Graeme Buchanan and two anonymous reviewers for their comments on previous drafts of this manuscript. This work has been funded by Stichting Ave Fenix Europa. NP is funded by Research England. SOP and WJS are funded by Arcadia, The David and Claudia Harding Foundation and MAVA.

Authors' contributions: HH**,** NP, SP and WJS conceived the ideas and designed methodology; HH collected and analysed the data; HH and NP led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

References

Ainsworth, T. D., Heron, S. F., Ortiz, J. C., Mumby, P. J., Grech, A., Ogawa, D., Eakin, C. M., & Leggat, W. (2016). Climate change disables coral bleaching protection on the Great Barrier Reef. *Science*, *352*(6283), 338–342. https://doi.org/10.1126/science.aac7125

Beal, M., Dias, M. P., Phillips, R. A., Oppel, S., Hazin, C., Pearmain, E. J., Adams, J., Anderson, D. J., Antolos, M., Arata, J. A., Arcos, J. M., Arnould, J. P. Y., Awkerman, J., Bell, E., Bell, M., Carey, M., Carle, R., Clay, T. A., Cleeland, J., … Catry, P. (2021). Global political responsibility for the conservation of albatrosses and large petrels. *Science Advances*, *7*(10), eabd7225. https://doi.org/10.1126/sciadv.abd7225

BirdLife International, & Handbook of the Birds of the World. (2020). *Bird species distribution maps of the world* (2020.1). http://datazone.birdlife.org/species/requestdis

Bourret, V., Gamble, A., Tornos, J., Jaeger, A., Delord, K., Barbraud, C., Tortosa, P., Kada, S., Thiebot, J.-B., Thibault, E., Gantelet, H., Weimerskirch, H., Garnier, R., & Boulinier, T. (2018). Vaccination protects endangered albatross chicks against avian cholera. *Conservation Letters*, *11*(4), e12443. https://doi.org/10.1111/conl.12443

Butt, N., Rosner-Katz, H., Binley, A. D., Davis, S., Pon, J., Radu, T., & Bennett, J. (2020). Threats, Costs, and Probability of Success: Informing Conservation Choices. *Frontiers in Ecology and Evolution*, *0*, 223. https://doi.org/10.3389/FEVO.2020.00223

Clairbaux, M., Cheung, W. W. L., Mathewson, P., Porter, W., Courbin, N., Fort, J., Strøm, H., Moe, B., Fauchald, P., Descamps, S., Helgason, H., Bråthen, V. S., Merkel, B., Anker-Nilssen, T., Bringsvor, I. S., Chastel, O., Christensen-Dalsgaard, S., Danielsen, J., Daunt, F., … Grémillet, D. (2021). Meeting Paris agreement objectives will temper seabird winter distribution shifts in the North Atlantic Ocean. *Global Change Biology*, *27*(7), 1457–1469. https://doi.org/10.1111/gcb.15497

Clairbaux, M., Fort, J., Mathewson, P., Porter, W., Strøm, H., & Grémillet, D. (2019). Climate change could overturn bird migration: Transarctic flights and high-latitude residency in a sea ice free Arctic. *Scientific Reports 2019 9:1*, *9*(1), 1–13. https://doi.org/10.1038/s41598-019-54228-5

Dias, M. P., Martin, R., Pearmain, E. J., Burfield, I. J., Small, C., Phillips, R. A., Yates, O., Lascelles, B., Borboroglu, P. G., & Croxall, J. P. (2019). Threats to seabirds: A global assessment. *Biological Conservation*, *237*, 525–537. https://doi.org/10.1016/j.biocon.2019.06.033

Enquist, C. A. F., Jackson, S. T., Garfin, G. M., Davis, F. W., Gerber, L. R., Littell, J. A., Tank, J. L., Terando, A. J., Wall, T. U., Halpern, B., Hiers, J. K., Morelli, T. L., McNie, E., Stephenson, N. L., Williamson, M. A., Woodhouse, C. A., Yung, L., Brunson, M. W., Hall, K. R., … Shaw, M. R. (2017). Foundations of translational ecology. *Frontiers in Ecology and the Environment*, *15*(10), 541–550. https://doi.org/10.1002/FEE.1733

Fuller, T., Bensch, S., Müller, I., Novembre, J., Pérez-Tris, J., Ricklefs, R. E., Smith, T. B., & Waldenström, J. (2012). The ecology of emerging infectious diseases in migratory birds: An assessment of the role of climate change and priorities for future research. *EcoHealth*, *9*(1), 80–88. https://doi.org/10.1007/s10393-012-0750-1

Garciá Molinos, J., Halpern, B. S., Schoeman, D. S., Brown, C. J., Kiessling, W., Moore, P. J., Pandolfi, J. M., Poloczanska, E. S., Richardson, A. J., & Burrows, M. T. (2016). Climate velocity and the future global redistribution of marine biodiversity. *Nature Climate Change*, *6*(1), 83–88. https://doi.org/10.1038/nclimate2769

Gibble, C. M., & Hoover, B. A. (2018). Interactions between Seabirds and Harmful Algal Blooms. In Sandra E. Shumway, JoAnn M. Burkholder, & Steve L. Morton (Eds.), *Harmful Algal Blooms* (pp. 223–242). Wiley. https://doi.org/10.1002/9781118994672.ch6

Hofmeister, E., & Van Hemert, C. (2018). The Effects of Climate Change on Disease Spread in Wildlife. In *Fowler's Zoo and Wild Animal Medicine Current Therapy, Volume 9* (pp. 247–254). Elsevier. https://doi.org/10.1016/b978-0-323-55228-8.00036-9

IUCN. (2021). *Threats Classification Scheme*. https://www.iucnredlist.org/resources/threat-classification-scheme

Jones, T., Divine, L. M., Renner, H., Knowles, S., Lefebvre, K. A., Burgess, H. K., Wright, C., & Parrish, J. K. (2019). Unusual mortality of Tufted puffins (Fratercula cirrhata) in the eastern Bering Sea. *PLOS ONE*, *14*(5), e0216532. https://doi.org/10.1371/journal.pone.0216532

Jones, T., Parrish, J. K., Peterson, W. T., Bjorkstedt, E. P., Bond, N. A., Ballance, L. T., Bowes, V., Hipfner, J. M., Burgess, H. K., Dolliver, J. E., Lindquist, K., Lindsey, J., Nevins, H. M., Robertson, R. R., Roletto, J., Wilson, L., Joyce, T., & Harvey, J. (2018). Massive Mortality of a Planktivorous Seabird in Response to a Marine Heatwave. *Geophysical Research Letters*, *45*(7), 3193–3202. https://doi.org/10.1002/2017GL076164

Larrosa, C., Carrasco, L. R., & Milner-Gulland, E. J. (2016). Unintended Feedbacks: Challenges and Opportunities for Improving Conservation Effectiveness. *Conservation Letters*, *9*(5), 316–326. https://doi.org/10.1111/conl.12240

McClelland, G. T. W., Altwegg, R., Aarde, R. J., Ferreira, S., Burger, A. E., & Chown, S. L. (2018). Climate change leads to increasing population density and impacts of a key island invader. *Ecological Applications*, *28*(1), 212–224. https://doi.org/10.1002/eap.1642

Mitchell, I., Daunt, F., Frederiksen, M., & Wade, K. (2020). Impacts of climate change on seabirds, relevant to the coastal and marine environment around the UK. In *MCCIP science review 2020* (pp. 382–399). Lowestoft, Marine Climate Change Impacts Partnership. https://doi.org/https://doi.org/10.14465/2020.arc17.sbi

OECD, Organization of Economic Cooperation and Development, & OECD Staff. (1994). *Environmental indicators: OECD core set*.

Pecl, G. T., Araújo, M. B., Bell, J. D., Blanchard, J., Bonebrake, T. C., Chen, I.-C., Clark, T. D., Colwell, R. K., Danielsen, F., Evengård, B., Falconi, L., Ferrier, S., Frusher, S., Garcia, R. A., Griffis, R. B., Hobday, A. J., Janion-Scheepers, C., Jarzyna, M. A., Jennings, S., … Williams, S. E. (2017). Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Science*, *355*(6332), eaai9214. https://doi.org/10.1126/science.aai9214

Prior, K. M., Adams, D. C., Klepzig, K. D., & Hulcr, J. (2018). When does invasive species removal lead to ecological recovery? Implications for management success. *Biological Invasions*, *20*(2), 267–283. https://doi.org/10.1007/s10530-017-1542-x

Smith, K. E., Aronson, R. B., Steffel, B. V., Amsler, M. O., Thatje, S., Singh, H., Anderson, J., Brothers, C. J., Brown, A., Ellis, D. S., Havenhand, J. N., James, W. R., Moksnes, P.-O., Randolph, A. W., Sayre-McCord, T., & McClintock, J. B. (2017). Climate change and the threat of novel marine predators in Antarctica. *Ecosphere*, *8*(11), e02017. https://doi.org/10.1002/ecs2.2017

Sutherland, W. J., Dicks, L. V, Petrovan, S. O., & Smith, R. K. (2020). *What Works in Conservation 2020* (W. J. Sutherland, L. V. Dicks, S. O. Petrovan, & R. K. Smith, Eds.). Open Book Publishers. https://doi.org/10.11647/obp.0191

Sydeman, W. J., Poloczanska, E., Reed, T. E., & Thompson, S. A. (2015). Climate change and marine vertebrates. *Science*, *350*(6262), 772–777. https://doi.org/10.1126/science.aac9874

Uhart, M. M., Gallo, L., & Quintana, F. (2018). Review of diseases (pathogen isolation, direct recovery and antibodies) in albatrosses and large petrels worldwide. *Bird Conservation International*, *28*(2), 169–196. https://doi.org/10.1017/S0959270916000629

Urban, M. C. (2015). Accelerating extinction risk from climate change. *Science*, *348*(6234), 571–573. https://doi.org/10.1126/SCIENCE.AAA4984

Waller, N. L., Gynther, I. C., Freeman, A. B., Lavery, T. H., Leung, L. K.-P., Waller, N. L., Gynther, I. C., Freeman, A. B., Lavery, T. H., & Leung, L. K.-P. (2017). The Bramble Cay melomys Melomys rubicola (Rodentia: Muridae): a first mammalian extinction caused by human-induced climate change? *Wildlife Research*, *44*(1), 9–21. https://doi.org/10.1071/WR16157

Williams, D. R., Pople, R. G., Showier, D. A., Dicks, L. v., Child, M. F., Zu Ermgassen, E. K., & Sutherland, W. J. (2013). *Bird Conservation: Global evidence for the effects of interventions (Vol. 2)*. Pelagic Publishing.

Table 1: Ranked climate change threats to seabirds in Western Europe and possible local management solutions. For each threat, practitioners (N=35) were asked how much of a threat they perceived it posed to the seabird population they managed. Vote percentage indicates the percentage of conservationists who thought the threat was “serious” or “very serious”. For each threat we identified several theoretically possible types of actions that could be used to alleviate or prevent the threat; some of these actions may however not be practically feasible at a sufficiently large scale. For each action we indicate how many studies have assessed their effectiveness for seabirds, as detailed in Conservation Evidence (CE).

Threat	**Vote percentage**	**Suggested actions**	**# seabird studies in CE**
Reduced prey availability	79%	Provide supplementary food	13
		Translocate the population to a more suitable area	5
		Make new sites more attractive to encourage birds to colonise them	16
		Artificially incubate eggs or hand-rear chicks in captivity	5
Increased threats from human activities	64%	Increase legal protection	2
Reduced habitat availability	64%	Restore or create habitat	7
		Control or remove habitat-altering species	4
		Provide artificial nesting sites	27
		Translocate the population to a more suitable area	5
		Make new sites more attractive to encourage birds to colonise them	16
		Alter current site to encourage birds to move away	1

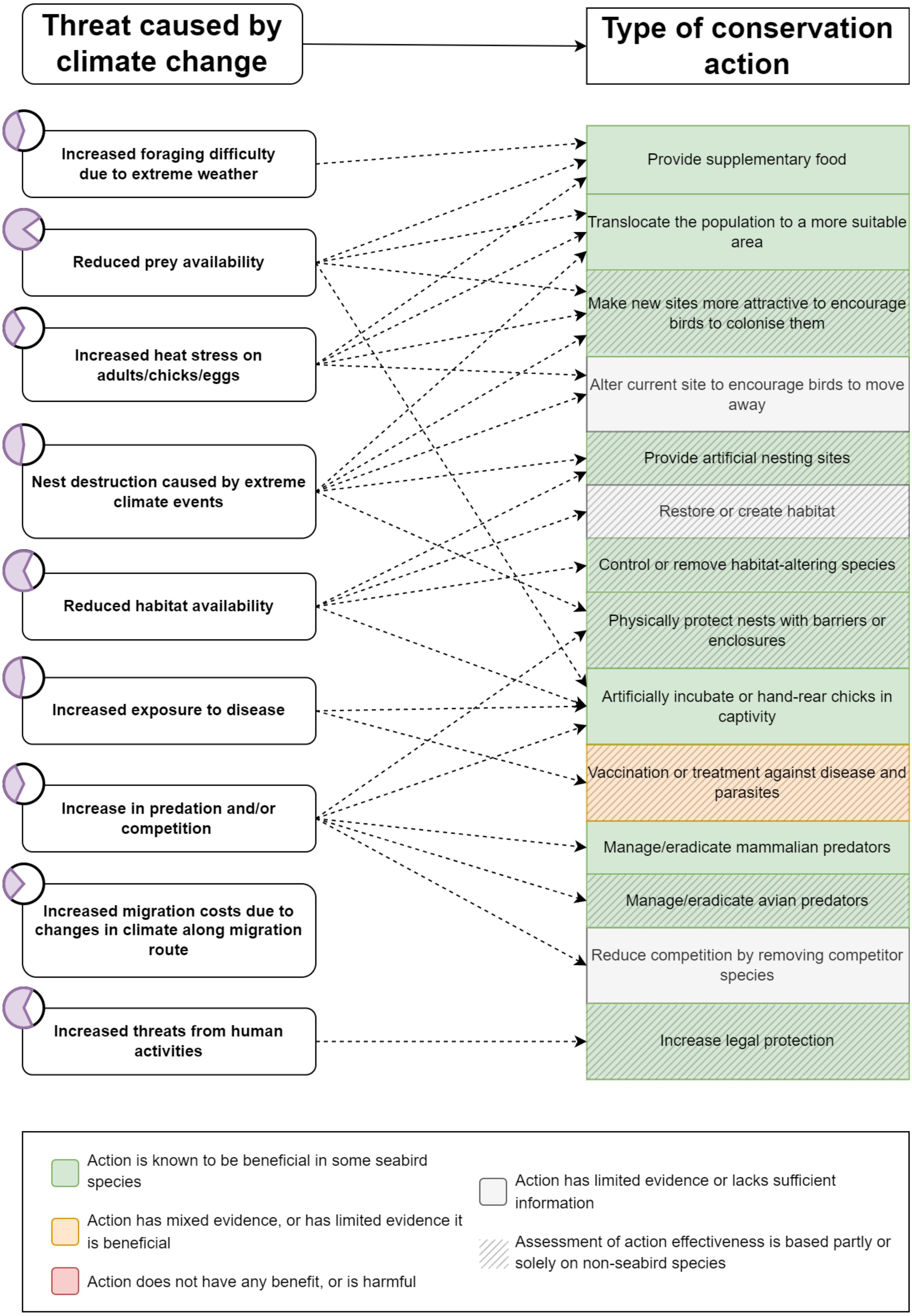
Nest destruction caused by extreme climate events	45%	Provide artificial nesting sites	27
Increased exposure to disease	45%	Vaccination or treatment against disease and parasites	2
Increased foraging difficulty due to extreme weather	39%	Provide supplementary food	13
Increased predation and/or competition	36%	Manage/eradicate mammalian predators	22
		Manage/eradicate avian predators	8
		Reduce competition by removing competitor species	7
		Physically protect nests with barriers or enclosures	9
		Artificially incubate eggs or hand-rear chicks in captivity	5
Increased heat stress on adults/chicks/eggs	33%	Translocate the population to a more suitable area	5
		Make new sites more attractive to encourage birds to colonise them	16
		Alter current site to encourage birds to move away	1
Increased migration costs due to changes in climate along migration route	27%	None available	NA

FIGURES

Figure 1: Study area. We broadly focused our research on the northeast Atlantic region as defined by Oslo/Paris convention (OSPAR). We also considered seabird populations in countries that surround the Baltic Sea, such as Finland and the Baltic states: this adjustment was made in response to known distributions of significant fish stocks, as well as information on areas known to be important breeding and/or wintering grounds for species otherwise common in Western Europe.

Figure 2: Summary of types of conservation actions (i.e., interventions) listed in Conservation Evidence that can be considered to reduce the impacts of climate change on birds. Each type of conservation action is a summary of several related actions (see Supplementary Material for the comprehensive list). For each type of conservation action, the output of the effectiveness assessment carried out by the Conservation Evidence team is summarised. The percentage of practitioners having identified each threat as serious or very serious to seabird populations in Europe is provided in pie charts (in purple).

Figure 1.



513

514 Figure 2