Impacts of Climate Change on Seabirds and Waterbirds in the UK and Ireland

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KEY FACTS

What is already happening?

- UK and Ireland seabird and waterbird indices show declines since the 1990s, partly reflecting population responses to changing climatic conditions across species' annual cycles and ranges.
- Declines in breeding seabird numbers have been linked to climate-mediated changes in fish prey species, affecting reproductive success and survival. Strong winds, heavy rain and rough seas can also impact reproductive success and overwinter survival for some species.
- Declines in UK waterbird breeding populations and north-easterly shifts in waterbird winter distributions in Europe are also consistent with a warming climate.

What could happen in the future?

- Climate change is projected to have mixed impacts on the breeding and non-breeding numbers and distributions of seabird and waterbird species in the UK and Ireland. Recent studies highlight the value of protected area networks in supporting resilience of species as they respond to climate change.
- Many UK and Irish seabird populations are at or near the southern limit of their breeding range and/or are highly sensitive to changes in prey availability, limiting their resilience to climate change. Some species may struggle to shift their breeding locations northwards due to low natal and breeding dispersal rates.
- Arctic and sub-Arctic breeding waterbirds that winter in the UK and Ireland are amongst the most vulnerable due to climate change impacts in their high-latitude breeding grounds.
- Direct impacts from changes in severe weather events and sea-level rise may increase for both seabirds and waterbirds in the future.

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SUPPORTING EVIDENCE

Introduction

The coasts and marine waters of the UK and Ireland support internationally important numbers of seabirds and waterbirds throughout the year. Seabirds depend on the marine environment for at least part of their life cycle (BirdLife International, 2023); in the UK and Ireland they include storm-petrels and shearwaters (Procellariiformes), gannets and cormorants (Suliformes), skuas, gulls, terns and auks (Charadriiformes). Waterbirds utilise both freshwater and coastal and marine habitats, and include wildfowl (ducks, geese and swans) (Anseriformes), waders (Charadrii and Scolopaci), rails (Gruiformes), divers (Gaviiformes), grebes (Podicipediformes) and herons (Pelecaniformes) and can also include cormorants, gulls and terns (Rose and Scott, 1997).

Numbers of seabirds in the UK and Ireland are highest in the summer breeding season and decrease later in the year when birds migrate to areas of the north and south Atlantic, the Mediterranean and as far as the Antarctic Ocean. In contrast, while many waterbird species also breed in the UK and Ireland, species diversity and numbers are greatest during the non-breeding seasons, when birds originating from breeding sites in northern Europe, Scandinavia, west- and high Arctic Russia, Iceland, Greenland and Canada winter on UK and Irish coasts or pass through while migrating along the East-Atlantic flyway in spring and autumn. Given these seasonal movements, both seabird and waterbird populations may be subject to multi-scale environmental effects, including changes in climatic conditions, through processes operating in different geographical locations at different periods of their annual life cycle – at their breeding sites, staging sites and wintering areas (Piersma and Lindström, 2004; Maclean *et al.*, 2008; Maclean, 2014). As such, constraints operating on one part of the annual cycle can significantly impact abundance at other stages of that cycle, and in other locations, and thus a holistic approach is needed in considering the drivers of population and distribution change and the processes underlying them.

During the last decades, both seabirds (Dias *et al.*, 2019) and waterbirds (Sutherland *et al.*, 2012) have faced significant threats to their conservation, with alarming changes apparent in the population dynamics of many species (BirdLife International, 2023; Nagy and Langoeden, 2021). While UK and Irish seabird populations expanded in breeding range and size over much of the last century, extensive breeding failures took place from the end of the 20th century and some formerly abundant species began to decline substantially (Grandgeorge *et al.*, 2008; JNCC, 2021; Woodward *et al.*, in press) with climate change considered to be one of the main causes (Mitchell *et al.*, 2020; Burnell *et al.*, 2023). Populations of some of the most-abundant UK and Irish wintering waterbirds also started to decline at the same time (Kennedy *et al.*, 2022; Austin *et al.*, 2023), some of these trends consistent with north-easterly shifts in the winter distributions of species across Europe (Burton *et al.*, 2020).

UK and Ireland Birds of Conservation Concern reviews assess the conservation status of bird species, based on population trends and wider aspects of population condition. In the latest reviews (Ireland: Gilbert *et al.* 2021; UK: Stanbury *et al.*, 2021), the status of the vast majority of species using UK and Irish waters is currently assessed as Red or Amber: in the UK, for example, 88% of wader species, 89% of ducks, geese and swans, 63% of grebes and divers and 78% of seabirds (Stanbury *et al.*, 2021); updated assessments for seabirds (apart from Leach's storm petrel *Hydrobates leucorhoa*) were deferred until after the publication of the latest national census – see below – so their assessed status was carried over from the previous review. The pressures leading to such widespread poor conservation status among marine birds are varied and act at different times of the year and in different locations across the biogeographic ranges of individual species. Climate change is clearly one of the most-important of these pressures, with wide ranging, varied impacts on marine birds, aggravating the effects of other pressures.

What is already happening?

Seabirds

Observed changes

The UK and Ireland are home to internationally important populations of 25 breeding species of seabirds. These populations have been periodically subject to census, in 1969–1970, 1985–1986, 1998–2002, and most recently 2015–2021 (Burnell *et al.*, 2023), with annual monitoring of both their abundance and breeding success across the UK and Ireland undertaken through the British Trust for Ornithology (BTO)/Joint Nature Conservation Committee (JNCC) Seabird Monitoring Programme (SMP: https://www.bto.org/smp), in association with the Royal Society for the Protection of Birds (RSPB), and through collaboration with the National Parks and Wildlife Service and BirdWatch Ireland. The majority of seabird species are not monitored outside of the breeding season, although UK populations of wintering gulls, which use terrestrial, coastal and marine habitats, have also been monitored through periodic Winter Gull Roost Surveys (Burton *et al.*, 2013).

The results of monitoring show declines in the breeding populations of many seabird species across the UK and Ireland since the 1990s (JNCC, 2021). According to the latest wild bird population assessment for the UK (Defra, 2023), the breeding seabird index (which measures changes in breeding seabird populations, based on SMP data for 13 species) was 24% lower in 2019 compared to the baseline of 1986 (Figure 1). Over the short-term period between 2013 and 2018, however, the trend was stable. According to the Quality Status Report (QSR) 2023 on Marine Bird Abundance, surface feeding seabirds within the OSPAR regions of the Greater North Sea (across 14 species) and Celtic Seas (12 species) are classified collectively as being in poor status. These losses are particularly acute for the sub-region of the North Coast of Scotland and Northern Isles (within the Greater North Sea). Benthic feeders (one species) are also in poor status for the North Sea (there were insufficient data for the Celtic Seas, however). The threshold for good environmental status was achieved for water column feeders for the Greater North Sea (seven species) and Celtic Seas (six species), contrary to the negative trend for the other two ecological groupings (Dierschke *et al.*, 2023). Similarly, according to QSR 2023 on Marine Bird Breeding Productivity, surface feeders within the Greater North Sea (14 species) and Celtic Seas (12 species) are regarded in poor status for their breeding productivity (Frederiksen *et al.*, 2022). Furthermore, while the threshold for good environmental status was met for water column feeders for the Greater North Sea (six species), these species had poor breeding productivity for the Celtic Seas (five species). The declines in breeding productivity indicate that further reductions in population size are likely to occur.

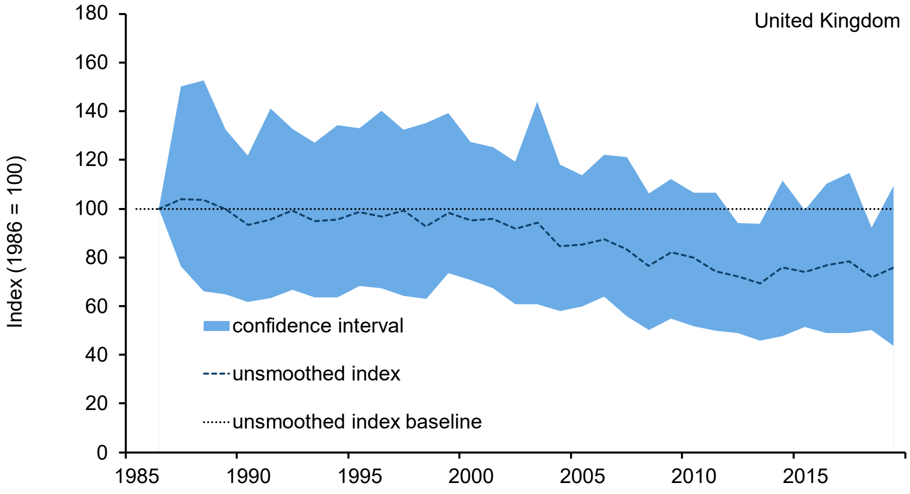


Figure 1a. UK wild bird index for breeding seabirds in the UK, 1986 to 2019 (Defra, 2023).

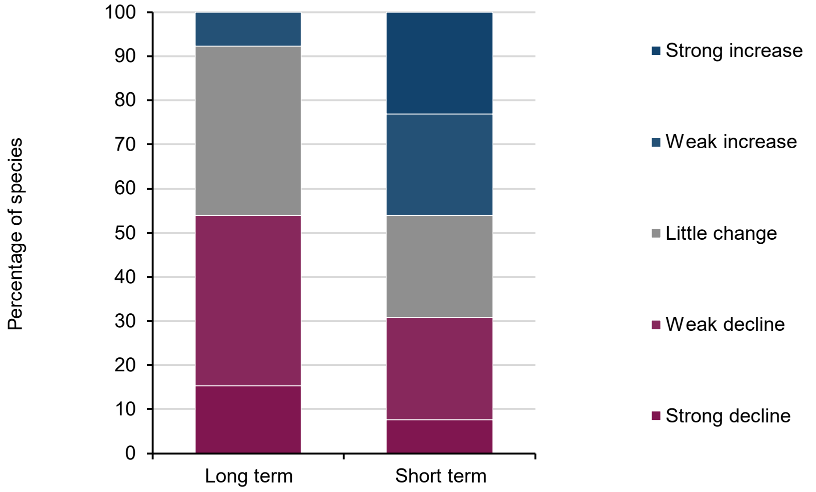


Figure 1b. Long-term and short-term changes in individual species trends for seabirds in the UK, 1986 to 2018 (Defra, 2023).

Most seabird species winter at sea. Our understanding of annual seabird movements was previously limited to data from ringing recoveries which showed that, apart from black guillemot *Cepphus grylle* – which is considered non-migratory, moving only a short distance offshore in winter – UK and Irish breeding seabirds are typically partial migrants, i.e. where populations include some individuals that migrate and some that are resident (Wernham *et al*., 2002). With the recent proliferation of tracking studies, especially those using light-level geolocators, it has been possible to show the scale of annual movements (e.g. many UK breeding black-legged kittiwakes *Rissa tridactyla* winter in the north-west Atlantic between Newfoundland and Greenland: Bogdanova *et al., 2*017) and how different areas may be used in the post-breeding moult and wintering periods (e.g. by razorbill *Alca torda* and common guillemot *Uria aalge*; Buckingham *et al.*, 2022). As such, there is a need to consider how the direct and indirect mechanisms of climate change might differentially affect populations across their annual cycles.

Environmental drivers and processes

A recent review has collated the evidence on the impacts of climate change on seabird populations in the North Atlantic and the mechanisms through which impacts operate (Johnston *et al., 2*021). The majority (80%) of studies identified through this review focused on indirect bottom-up processes affecting seabirds' fish prey (Daunt *et al., 2*017; Mitchell *et al., 2*020). Impacts on populations were recorded through changes in productivity, phenology, abundance and survival (given in order of decreasing numbers of studies). A greater number of studies focused on productivity and phenology as effects of climate on these parameters can be detected over relatively short-time scales, in comparison to abundance and survival for which longer time–series studies are required.

Much of the research has been undertaken in the north-western North Sea, in particular at the Isle of May. Long-term studies here have demonstrated negative effects of temperature on the breeding success and survival of black-legged kittiwakes (e.g. Frederiksen *et al.*, 2004; 2007; Burthe *et al., 2*014) and common guillemots, which are unable to increase breeding effort to buffer demographic rates against poor environmental conditions (Wanless *et al.*, 2023). The strength of the effect varies between North Sea colonies, with limited evidence of temperature effects on black-legged kittiwake breeding success at some localities (Cook *et al., 2*014; Carroll *et al.*, 2017; Eerkes-Medrano *et al.*, 2017). A recent study of multiple colonies along the east coast demonstrated a negative relationship between breeding success and temperature for Atlantic puffin *Fratercula arctica* and common guillemot, but not black-legged kittiwake (Searle *et al., 2*022). This inconsistency suggests that the cascading effects up the food chain are complex. Regnier *et al.* (2019) demonstrated that climate warming affects recruitment of the principal prey of many seabird populations in the UK and Ireland, the lesser sandeel *Ammodytes marinus*, by altering the matching of the timing of key life history events with those of their copepod prey. However, this has proved challenging to demonstrate empirically, with other studies failing to demonstrate a relationship between temperature and sandeel recruitment (Henriksen *et al., 2*021a, Searle *et al., 2*023). Furthermore, temperature alters the timing of emergence of adult (1+ age group) sandeels in the spring (Henriksen *et al., 2*021b). These mechanisms are all potentially important because seabirds feed on both young of the year and 1+ age group sandeels (Howells *et al., 2*017; Wanless *et al., 2*018). In addition, other prey species are becoming more important in the diet of seabirds, in particular sprat *Sprattus sprattus* (Wanless *et al., 2*018), and sprat growth is related to temperature (Lindegren *et al., 2*020). Other studies have demonstrated links between breeding success and additional climate-related oceanographic factors, in particular the timing of onset and strength of stratification (Carroll *et al., 2*015a), which affects the timing of fish availability or abundance of lower trophic levels (Jensen *et al., 2*003; Scott *et al., 2*006). There is also increasing evidence that terrestrial temperature is linked to seabird productivity and abundance (Davies *et al., 2*021; Searle *et al., 2*022), but the mechanisms remain unclear. While the majority of studies investigating the impacts of climate change on seabirds have focused on changes in temperature, studies are hampered by the multiple processes that link temperature and the phenology and abundance of different age classes of forage fish, the limited inference on causality that can be drawn from correlative studies, the lack of consideration of non-linear effects, the limited studies that have considered climate alongside other drivers and the lack of long-term data on aspects of seabird demography, in particular survival rates (Henriksen *et al.*, 2021a; Davies *et al., 2*021; Searle *et al., 2*023).

Species are likely to respond differently to changes in climate according to aspects of their ecology or physiology. For example, effects are linked to the ecological scale over which a species interacts with its environment, with responses of species such as northern fulmar *Fulmarus glacialis*, that have the greatest foraging ranges more closely linked to the North Atlantic Oscillation (NAO) than species such as European shag *Phalacrocorax aristotelis* which has a more restricted foraging range and appears to be more influenced by local conditions such as sea surface temperature (SST) (Johnston *et al., 2*021). There is also evidence that impacts are not consistent in different regions of the UK, with effects of temperature weaker in the western UK (Lauria *et al.*, 2013; Cook *et al.*, 2014; Davies *et al.*, 2021). This weaker link could be due to a greater reliance on species other than sandeels (clupeids and gadids; Swann *et al., 2*008; Chivers *et al., 2*012), but research is limited by the lack of rich, long-term data sets in a number of areas of the UK and Ireland (Johnston *et al., 2*022). However, there is strong, overarching evidence that warming has had a profound impact on marine food webs in coastal UK and Irish waters, linked to northward shifts of thermal boundaries (Beaugrand *et al., 2*008; Reygondeau and Beaugrand, 2011; Frederiksen *et al., 2*013). There is also good evidence that breeding success of a number of seabird species is positively related to sandeel abundance (Frederiksen *et al., 2*007; Daunt *et al.*, 2008; Carroll *et al., 2*017; Eerkes-Medrano *et al.*, 2017; Searle *et al., 2*023), pointing to climate change as an important likely cause of recent seabird declines. However, the variation in responses between species and across regions highlights an urgent need for further research.

A further important mechanism linking climate to seabird demography is the extent of temporal matching between availability of prey and peak energy demands. In the North Sea and elsewhere, a number of seabird species are becoming increasingly vulnerable to trophic mismatch with their prey (Burthe *et al.*, 2012; Keogan *et al.*, 2021; 2022). However, this is not the case in all species – in European shags breeding on the Isle of May, for example, breeding has advanced and become more successful, with no evidence of temporal mismatch (Howells 2019; Keogan *et al.*, 2021).

Seabirds may also be affected by climate directly, through exposure to extreme weather conditions. Extreme climatic events such as strong wind and heavy rainfall can lead to nest and/or egg loss and chick mortality (Aebischer, 1993; Newell *et al.*, 2015). In all seasons, extreme weather and rough seas can impair the ability to forage, leading to poor body condition and lower survival (so-called 'seabird wrecks': Harris *et al.*, 1998; Morley *et al.*, 2016; Fullick *et al.*, 2022). This may partly be due to energy expenditure during flight and foraging, which are higher at greater wind speeds (Daunt *et al.*, 2006; Lewis *et al.*, 2015), or when exposed to such conditions on land (Frederiksen *et al.*, 2008). A potentially important but under-studied question is the effect of winter cyclones on pelagic seabird species such as black-legged kittiwakes and Atlantic puffins (Clairbaux *et al.*, 2021; Reiertsen *et al.*, 2021). Many species experience generally high survival but occasional years of very poor survival, which suggest that extreme conditions at wintering grounds may be an important demographic driver, since most mortality of adults occurs at this time. The European shag regularly experiences wrecks, showing very poor adult survival during sustained periods of strong onshore winds and high rainfall in late winter (Frederiksen *et al.*, 2008; Acker *et al.*, 2021a, b). Studies of direct effects represent <20% of those on effects of climate on seabirds (Johnston *et al.*, 2021). Given that the frequency and severity of severe weather events are predicted to increase in future (IPCC, 2021), they are an important priority for future research. Furthermore, the research focus to date on UK and Irish seabirds has been on the effects of wind and rain. However, seabirds are becoming increasingly vulnerable to extreme heat, as recently demonstrated in high latitude seabirds (Oswald *et al.*, 2008; Choy *et al.*, 2021; Olin *et al.*, 2023). Research in the North Pacific has shown that heat waves may not just have direct effects on seabirds, but affect whole food webs, including primary productivity, zooplankton community composition and consumption rates of forage fish, with knock-on consequences on seabird demography (Piatt *et al.*, 2020).

Waterbirds

Observed changes

The UK's and Ireland's internationally important non-breeding waterbirds are monitored respectively by the BTO/RSPB/JNCC Wetland Bird Survey (WeBS: https://www.bto.org/webs) and Irish Wetland Bird Survey (I-WeBS, funded by the National Parks and Wildlife Service and co-ordinated by BirdWatch Ireland: https://birdwatchireland.ie/our-work/surveys-research/research-surveys/irish-wetland-bird-survey/). The BTO/JNCC/RSPB Breeding Birds Survey (BBS: https://www.bto.org/bbs) and Waterways Breeding Bird Survey (WBBS: https://www.bto.org/wbbs) together provide annual monitoring of some more widely distributed breeding waterbird species in the UK.

The results of these monitoring schemes show that both the breeding populations (Heywood *et al.*, 2023) and wintering numbers (Kennedy *et al.*, 2022; Austin *et al.*, 2023) of many waterbird species across the UK and Ireland have declined in recent decades. The latest wintering waterbird index for the UK (Defra, 2023) (which measures changes in wintering waterbird populations, based on WeBS data) shows that while numbers of waterbirds, waders and wildfowl as a whole were higher in 2019/20 than at the start of the time series in 1975/76, long-term declines since the 1990s have continued over the most-recent five-year (short-term) period (Figure 2). The equivalent index for breeding water and wetland birds in the UK for 1975 to 2021, based on BBS/WBBS data, also shows a shallow decline in populations since the 1990s (Defra, 2023), although is principally representative of terrestrial rather than coastal breeding species and populations. Specific indicators have also been developed to inform the UK Marine Strategy; the associated target for marine bird abundance (that changes in abundance should be within individual target levels in 75% of species monitored) was met for non-breeding waterbirds in the Marine Strategy Framework Directive Greater North Sea sub-region but not in the Celtic Seas sub-region (Mitchell *et al.*, 2018). Updated marine bird distribution indicators showed that no non-breeding waterbird species decreased in occupancy rate by more than 10% at the UK level over the assessment period from 1997/98 to 2015/16, although declines over this threshold were reported for long-tailed duck *Clangula hyemalis* in the Celtic Seas sub-region and black-throated diver *Gavia arctica* in the Greater North Sea sub-region (Woodward *et al.*, in press). Declines in occupancy rate of over 10% were recorded for coastal breeding northern lapwing *Vanellus vanellus* at UK, Greater North Sea and Celtic Seas levels and for coastal breeding Eurasian curlew *Numenius arquata* in the Celtic Seas sub-region. While breeding populations of some coastal breeding waders have declined in the UK, in line with national trends, other coastal breeding waterbird species, such as little egret *Egretta garzetta* have colonised the UK in response to climate change (Pearce-Higgins, 2021).

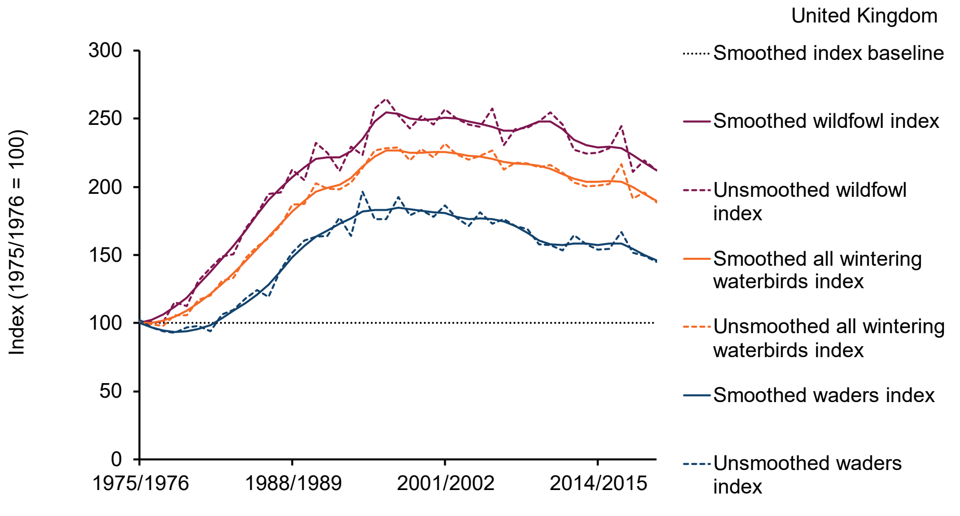


Figure 2a. UK wild bird index for wintering waterbirds in the UK, 1975/76 to 2019/20 (Defra, 2023).

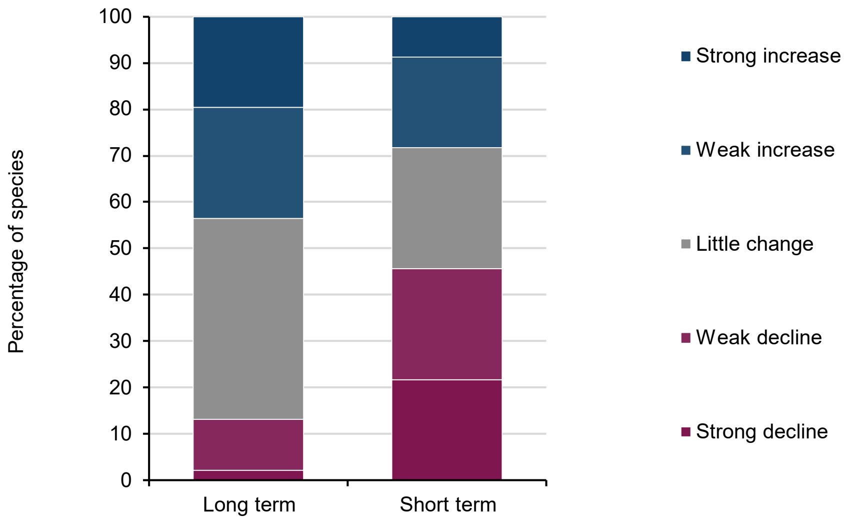


Figure 2b. Long-term and short-term changes in individual species trends for wintering waterbirds in the UK, 1975/1976 to 2018/2019 (Defra, 2023).

Distributions of wintering waterbirds across the UK and Ireland and wider north-west Europe reflect breeding origins, the availability of food resources and climate, with winter temperatures warmer to the south and west. Cold weather movements are an important factor in inter-annual changes in species' abundances at a site-level, with notable influxes of birds into the UK and Ireland during periods of severe cold in continental Europe. However, the decline in the UK wintering waterbird index and the patterns in the indicators for UK Marine Strategy are consistent with evidence described in previous reviews (Austin, 2010; Pearce-Higgins and Holt, 2013; Burton *et al.*, 2020) of changes in species' wintering distributions and longer-term climatic change. In particular, waders (Austin and Rehfisch, 2005; Maclean *et al.*, 2008) and diving ducks (e.g. Marchowski *et al.*, 2020; Pavón-Jordán *et al.*, *2*018) have shown long-term north-eastwards shifts in distributional abundance through this period, reflecting the Arctic or sub-Arctic breeding origins of the majority of species, warming temperatures and an increase in ice-free deep water at the edges of species' wintering ranges. However, the redistributions may also reflect wider overall declines in the abundance of migrants, and thus potentially range contractions, which warrants further investigation.

More-recent research has focused particularly on the importance of protected sites as species respond to changes in climate and, in association with this, effective management. The underlying patterns of species' redistributions reported by these studies have been consistent with previous research, with study questions focused on understanding how patterns of response might vary with site designation and management. Drawing from data collated from across national monitoring schemes through the International Waterbird Census (IWC: https://iwc.wetlands.org/), Pavón-Jordán *et al.* (2020) reported that the abundance of wintering waterbirds in Europe was positively correlated with 'temperature anomaly' – the positive or negative difference in annual winter temperature from the average long-term value – and most strongly towards the north and east of species' distributions, as expected from previous studies highlighting species' north-eastwards shifts in distributional abundance with warming temperatures. Species abundance and trends in abundance were both higher inside Important Bird Areas (IBAs). Gaget *et al.* (2020), also using IWC data, similarly found that wintering waterbird communities using protected sites in the western Palearctic had greater species richness, higher rates of species colonization, lower rates of species loss and lower 'climatic debt' – a measure of how much shifts in range lag in time behind shifts in temperature isoclines – in response to increasing winter temperatures than those communities found outside of protected sites. A subsequent study reported that wintering waterbird communities using European Union Natura 2000 sites designated (as Special Protection Areas (SPAs) under the EU Birds Directive) for waterbirds also responded faster in their abundance to increasing winter temperatures, particularly in sites that also had a management plan (Gaget *et al.*, 2021). These studies are consistent with the results of Wauchope *et al.* (2022) who reported that areas specifically managed for waterbirds or their habitat are more likely to benefit populations, and highlight that as well as supporting greater species' abundances, protected sites may both buffer against losses associated with climate change and also enable more rapid positive responses.

Nevertheless, Gaget *et al.* (2021) also noted that species responses to increasing temperatures were not affected by the length of the designation period, while contrarily, responses were lower at sites funded under the EU LIFE program than at those that had not received funding. A specific study on greater scaup *Aythya marila* also reported a north-eastwards shift in winter distribution across Europe but highlighted that the increasing concentration of the species' population in coastal Poland and Germany (where the species is impacted by bycatch and declining food quality by ineffective implementation of conservation measures) posed a significant threat (Marchowski *et al.*, 2020). Together, these studies highlight the benefits of effective conservation policy in helping waterbird species respond to changes in climate.

An additional signal of climate change has been in the altered phenology of bird migration or breeding. Reviewing previous studies, Lameris *et al.* (2021) highlighted how there had been significant shifts in the timing of departure of many wildfowl and at least one wader species to their Arctic breeding grounds, with earlier departures mostly linked to changes in suitable stopover sites along migratory routes. For example, in response to milder temperatures, Bewick's swans *Cygnus columbianus bewickii*, are both shifting their wintering distributions towards breeding grounds – 'short-stopping' – and spending less time on their winter grounds – 'short-staying' (Nuijten *et al.*, 2020; c.f. Podhrázský *et al.*, 2017). In contrast, Mondain-Monval *et al.* (2021), considering records from the citizen science database 'eBird', reported that the timing of migration of waders on both the Afro-Palearctic (or East Atlantic) and Nearctic flyways had become later in both spring and autumn, with changes in temperatures predicting the timing of autumn migration. It was postulated that migration may be becoming later due to northward breeding range shifts, meaning that a higher proportion of birds travel greater distances and therefore take longer to reach their destinations.

Alternatively, short-stopping may mean that individuals face shorter journeys and are able to delay their migrations.

Environmental drivers and processes

Studies assessing changes in the distributions of waterbirds, such as those described above, have made increasing use of monitoring data collated from across species ranges, but typically considered either just species' breeding or wintering distributions. Recently, however, Nagy *et al.* (2021) modelled the overall distributions of African-Eurasian Waterbird Agreement (AEWA; https://www.unep-aewa.org/) listed waterbird species across their migratory flyways, considering the breeding, passage, wintering, and resident stages of each species, in relation to climatic parameters and wetland extent. For the predominantly migratory species breeding in the Palearctic, their assessment highlighted the importance of annual mean temperature and mean diurnal temperature range in determining distributions across the year, and also that the extent of wetlands was less important in predicting distributions of birds in the breeding season than of dispersive, passage or wintering birds. A recent global assessment of changes in waterbird populations to climate change similarly highlighted that increases of temperature were associated with increases in the abundance of species and populations at higher latitudes, but decreases at lower latitudes (Amano *et al.*, 2020).

The changes seen in waterbird populations and distributions may reflect both demographic and individual responses to changing climatic conditions. Weather effects on breeding Arctic shorebirds are most moderate in the low Arctic of northern Europe and most extreme in the Siberian high Arctic in comparison to other Arctic regions (Meltofte *et al.*, 2007). Decisions to breed and clutch initiation dates are correlated with snowmelt dates and consequently appear to be a function of food availability for laying females. Increasing temperatures may benefit Arctic shorebirds in the short term by increasing both survival and productivity, as warmer weather may be associated with increased invertebrate abundance and reduced energetic demands. However, climate change may also affect these population processes indirectly (Lindström and Agrell, 1999), for example, through changes to predator and prey populations (Gilg *et al.*, 2009; Schmidt *et al.*, 2012; Machín *et al.*, 2019; Rintala *et al.*, 2022), and habitat quality on the breeding grounds (Wauchope *et al.*, 2017). Waterbird breeding success at mid-latitudes, including the UK and Ireland, in contrast, may be negatively impacted by increasing temperatures and associated reductions in rainfall that may reduce prey abundance or availability (Carroll *et al., 2*015b; Kleijn *et al.*, 2010; Pearce-Higgins *et al.*, 2010).

The survival of waterbird species is also particularly related to environmental conditions through the non-breeding seasons. For waders that winter in northern Europe, survival is typically strongly correlated with temperature, with periods of severe winter weather particularly associated with high levels of mortality (Clark, 2004). Similarly, recent increases in goose populations have been linked to the positive effect of temperature on wintering grounds in north-west Europe on adult survival (Layton-Matthews *et al.*, 2020), as well as increased productivity associated with warmer spring and summer weather in Arctic breeding areas and a resulting longer growing season (Descamps *et al.*, 2017). For species that are highly faithful to their breeding and wintering sites, distributional shifts are consequently likely to reflect increased survival and/or juvenile recruitment at the northern or north-eastern edges of winter ranges as temperatures have increased. For Bewick's swans, individuals have been shown to be consistent in their migratory schedules and thus that changes in the phenology of migration are occurring through such generational changes; however, short-stopping in this species is the result of both individual plasticity and generational shifts (Nuijten *et al.*, 2020). In understanding overall impacts on populations, however, Layton-Matthews *et al.* (2020) studying Svalbard barnacle geese *Branta leucopsis* highlighted the need for a holistic approach, considering direct and indirect mechanisms of climate change, and carry-over and density-dependent effects across the annual cycle.

What could happen in the future?

Seabirds

With the largely negative effects of warming temperatures and extreme climate events on the availability and abundance of lower trophic levels including the forage fish that form the main diet of UK and Irish seabirds, there is considerable concern that climate change may threaten the future resilience of these populations.

Carroll *et al.* (2015a) predicted that black-legged kittiwake breeding success would decline by 21–43% between 1961−90 and 2070−99, primarily due to rising SST. Searle *et al.* (2022) extended this analysis to model future climate effects on the breeding success of five seabird species (those where links to climate variables were apparent in an analysis of retrospective patterns) along the east coast of the UK. Of these, four showed a predicted decline (black-legged kittiwake, common guillemot, Atlantic puffin, great black-backed gull *Larus marinus*) and one a predicted increase (northern gannet *Morus bassanus*). Through simulations, however, it was demonstrated that for all five species, there was limited opportunity to increase breeding success by expanding foraging ranges to access more favourable conditions.

It is considerably more challenging to investigate whether future climate change will affect adult survival, the demographic rate that typically makes the most important contribution to population size in most seabirds. This is because of the limited data available on survival to test current relationships, and the large scale over which many species are distributed outside the breeding season, when most adult mortality occurs (Guilford *et al.*, 2009; Bogdanova *et al.*, 2011; Fauchald *et al.*, 2021). However, progress can be made from studies of abundance, which integrates demographic rates such as breeding success and survival. Davies *et al.* (2021) used a range of climatic variables to model spatio-temporal variation in the size of seabird populations within the INTERREG VA Area (comprising western Scotland, Northern Ireland and the border counties of Ireland) in response to future projections of climate change. The models included climate (air temperature, rainfall) and oceanographic variables (SST, Potential Energy Anomaly). The projections were calculated from climate models under Scenario RCP8.5 (equivalent to ~2C global warming by 2050 compared to 1986-2005 levels) using an existing hydrodynamic oceanographic model (Scottish Shelf Model) and data from seabird censuses. Uncertainty in projections was high, but of the 19 species in the analysis, 14 species were projected to decline in abundance in this region, notably Arctic skua *Stercorarius parasiticus* (projected to decline to extinction), Atlantic puffin and European storm petrel *Hydrobates pelagicus* (both by over 80%), and a further six species by more than 50% (northern fulmar, black-legged kittiwake, Sandwich tern *Thalasseus sandvicensis*, little tern *Sternula albifrons*, Arctic tern *Sterna paradisaea* and razorbill). Five species were predicted to increase in the region: black-headed gull *Chroicocephalus ridibundus*, great black-backed gull, lesser black-backed gull *Larus fuscus*, common tern *Sterna hirundo* and European shag. On average, surface feeders showed stronger relationships with oceanographic variables than diving species, supporting the long-standing assertion that they are more sensitive to variation in environmental conditions (Furness and Tasker 2000).

In a related study, Cleasby *et al.* (2021) modelled the future at-sea distributions and abundances of seven seabird species in the INTERREG VA Area region. They combined predicted changes in colony abundance (Davies *et al., 2*021), existing at-sea distribution models and projected values of relevant oceanographic variables. They found that numbers of black-legged kittiwake, common guillemot and razorbill at sea were projected to decline over most of their distribution within this region and, for the latter species, foraging range around colonies was predicted to contract. In contrast, at-sea abundance of European shag was predicted to increase and density around colonies to also increase.

These concerns regarding declines in productivity and abundance are sharpened by the fact that most UK and Irish breeding seabird species are at or near the southern limit of their range in the North-East Atlantic. Accordingly, studies have estimated that habitat suitability will shift northwards (Frederiksen *et al., 2*013). Russell *et al.* (2015) developed climate envelopes based on a composite of winter cold, overall warmth/growing season and available moisture to test the consequences of these changes on seabird breeding distributions. These models predicted that 65% of species would show a decline in their European range. Species breeding at higher latitudes or sensitive to variation in prey availability were particularly vulnerable to declines. In contrast, lower-latitude species had greater capacity to shift northwards, but this range shift was likely to be constrained by low natal dispersal and very low breeding dispersal apparent in most species. Under a best-case scenario of unlimited dispersal, the study predicted that Leach’s storm petrel, great skua *Stercorarius skua* and Arctic skua would come close to extinction in the UK and Ireland by 2100, while the ranges of black-legged kittiwake, Arctic tern and auks would decline significantly.

Future climate warming is also likely to have direct impacts through sea-level rise on ground-nesting seabirds such as terns and gulls breeding in low-lying coastal habitats (Pearce-Higgins *et al.*, 2021). Habitat loss to sea-level rise may be counteracted by managed realignment.

Extreme weather events, e.g. storms and heat waves, may also become more important since most climate models predict an increase in severity and frequency in the future (IPCC, 2021), with potentially profound consequences on the future survival prospects of UK and Irish seabird populations. Although certain species are likely to be particularly susceptible, such as European shag (Frederiksen *et al.*, 2008; Acker *et al.*, 2021a, b), effects may be widespread across species because such events operate at both small scales (e.g. local storm events) and large scales (e.g. winter cyclones). However, a challenge remains in predicting these effects, because of the lack of accurate proxies of extreme weather events that are available as forecasts. A further related question is how individuals and populations respond to increased climate variability. As well as the challenge of conditions at the extremes (e.g. heatwaves vs deep freezes), there may be negative consequences of a less predictable environment on key activities such as foraging and breeding.

More generally, the ability to accurately forecast the effects of warming and extreme climate events will require a good understanding of the processes that link climate to seabird demography, including the interactions with prey populations. This is a particularly important question among UK and Irish seabirds at present because they are showing measurable shifts in diet with a reduction in reliance on sandeels (Howells *et al.*, 2017; Wanless *et al.*, 2018). The relative availability of suitable alternate prey species in UK and Irish waters, and how climate change affects their distribution, phenology, abundance and energetic quality, may be critical to the future status of UK and Irish seabird populations.

Waterbirds

A previous modelling project considering the potential impacts of climate change on 45 species of wintering waterbirds in the UK indicated that while some species were projected to increase significantly in number under a high A1F1 (Fossil Intensive) emissions scenario, 11 species were projected to suffer declines of more than 50% by 2050, and 19 species by 2080 (Johnston *et al.*, 2013). The study particularly considered the impacts of these changes on protected areas, projecting that 10 of 57 UK SPAs would lose all qualifying species by 2050, and 11 SPAs by 2080, but that increases in abundance might result in six and seven new sites respectively, supporting internationally important numbers by these dates, and thus being worthy of designation. Consequently, as coastal sites are often designated for their importance for multiple species, it was concluded that the network would continue to provide protection to non-breeding waterbirds in the future, an important finding in light of the more recent studies that have highlighted the benefits of protected sites to non-breeding waterbirds responding to climate change (Gaget *et al.*, 2020, 2021; Pavón-Jordán *et al.*, 2020).

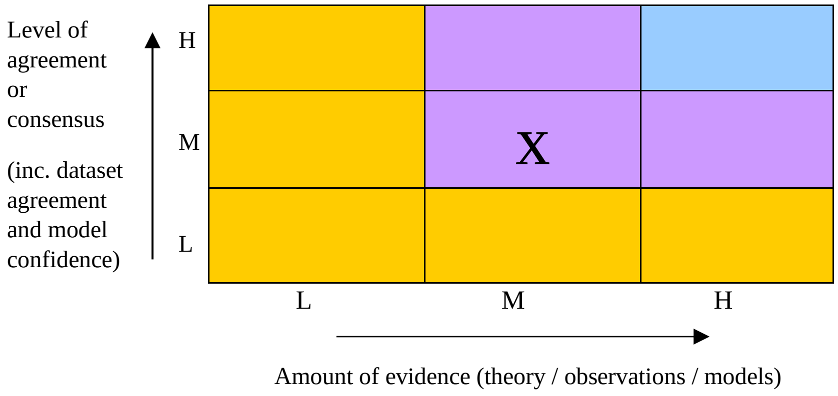
Based on distribution models for AEWA-listed waterbird species across their migratory flyways, Nagy *et al.* (2021) reported that Arctic breeding waders were among those for which the lowest proportions of current breeding ranges were projected to be climatically suitable by 2050 (considering integrated results from two climate models, HadGEM2-ES and IPSL-CM5A-LR, using the Representative Concentration Pathway RCP 6.0). These findings are consistent with previous work by Wauchope *et al.* (2017) who predicted that the climatic suitability of areas used by Arctic breeding waterbirds would decline in size for 66–83% of species by 2080, although with reductions predicted to be less severe in the Eurasian and Canadian Arctic from where the majority of UK and Irish non-breeding waterbirds originate. For most other Palearctic migratory waterbird species, Nagy *et al.* (2021) projects that losses of climatically suitable areas in current passage and wintering ranges would be largely offset by new areas becoming suitable. The study highlighted that the majority of migratory Palearctic waterbirds are widely dispersed in the breeding season and thus with limited proportions of their populations currently supported by ‘Critical Sites’ (i.e. sites that are either important for Globally Threatened Species or support 1% of the bioregional population of any waterbird species). Thus, while protected site networks may provide benefits for species during passage and wintering seasons, it is important to also consider climate change adaptation measures at the landscape scale for breeding populations of Palearctic migrant waterbirds, as is recognised in AEWA guidelines on climate change adaptation for waterbirds (Nagy 2022).

While protected site networks provide benefits for waterbird species responding to climate change, the quality of sites for waterbird species is also changing, and it is thus important that site management across species’ ranges is able to adapt to these changes. Breiner *et al.* (2021) used models based on predictors of the climatic niche of African-Eurasian waterbird species and their habitat, including inundation, to predict changes in those species’ distributions under the HadGEM2-ES and IPSL-CM5A-LR scenarios for 2050. Their study predicted that projected climate change would reduce habitat suitability for waterbirds at 57.5% of existing Critical Sites within the AEWA area. While sites in Africa and the Middle East were reported to be most threatened, the study highlighted that sites in Eastern Europe and West Siberia were expected to be of increasing value for waterbirds, reflecting currently understood shifts in breeding and wintering distributions, while identifying a number of coastal sites in the UK and north-western Europe among those of highest priority for adaption management actions.

Alongside these predictive studies of changes in waterbird populations and distributions in response to changes in climatic and hydrological conditions, there has been continued focus on projected changes in sea levels and the potential consequent changes in coastal ecosystems and the biodiversity that they support. Huismans *et al.* (2022) considered changes in the extent of intertidal areas of the Dutch Wadden Sea, one of the most important areas for waterbirds on the East Atlantic Flyway. Their study highlighted that changes would depend on tidal flat geometry, with the greatest relative area losses in larger basins, of up to 50% by 2100 under the highest sea-level rise scenario considered. Such changes would have considerable impacts on the capacity of coastal sites to support waterbirds (Maclean 2014), highlighting the needs to consider sea-level rise alongside climatic conditions in models predicting future changes to waterbird populations and consequently the importance and effective long-term management of interventions, such as managed realignment (Mander *et al.*, 2021).

CONFIDENCE ASSESSMENT

What is already happening?



Level of agreement or consensus

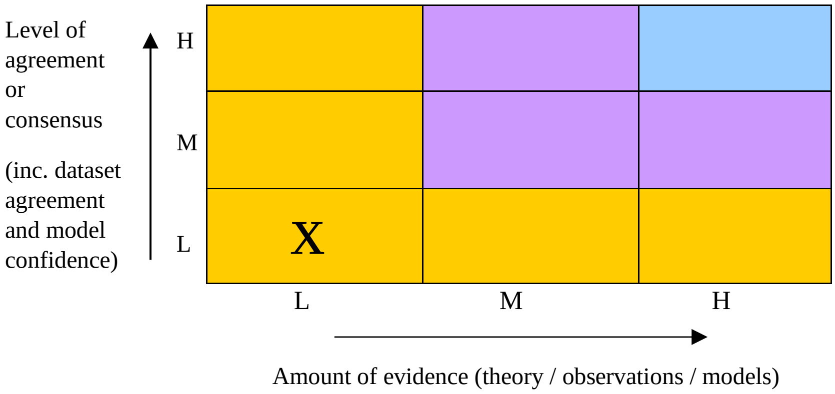
(inc. dataset agreement and model confidence)

	L	M	H
H	🟨	🟪	🟦
M	🟨	🟪 X	🟪
L	🟨	🟨	🟨

Amount of evidence (theory / observations / models)

Since the last MCCIP Report Card, significant reviews have evaluated the evidence on the impacts of climate change on seabird populations in the North Atlantic (Hakkinen *et al.*, 2022; 2023; Johnston *et al.*, 2021; Searle *et al.*, 2022). The evidence for effects on different seabird demographic rates varies in extent, and there is significant variation in responses between species and locations, reflecting complex mechanisms. Furthermore, comparatively few studies have considered the direct effects of extreme weather events. There has also been an increase in the number of papers examining population and distributional responses of Palearctic waterbird species to climate change, across their ranges and annual cycles, with a particular focus on the importance of protected area networks. While, for both groups, there is improved understanding of the environmental drivers behind these changes, there remains a need for improved demographic monitoring to understand the underlying processes. As such, the overall assessment is unchanged.

What could happen in the future?



In association with reviews of the evidence for climate change impacts on seabirds, there have been further studies predicting future changes in populations and their distributions (Cleasby *et al.*, 2021; Davies *et al.*, 2021; Searle *et al.*, 2022). Recent modelling studies of future changes in the populations and distributions of waterbirds have taken a more-holistic approach, predicting responses across species' ranges and annual cycles. These studies corroborate the conclusions of a previous large-scale review of climate impacts on migratory bird populations submitted to CMS (UNEP/CMS/Conf. 8.22) that identified Arctic-breeding waterbirds as amongst the most vulnerable to climate change (Robinson *et al.*, 2009). Nevertheless, the approaches of such predictive studies remain limited and there remains a high degree of uncertainty associated with specific projections for individual species for both groups, given variation in mechanisms across the annual cycle, and also at a country-level. As such, we regard both the extent of evidence and level of consensus across species groups as low.

KEY CHALLENGES AND EMERGING ISSUES

Previous MCCIP Report Cards for seabirds and waterbirds have identified overlapping knowledge gaps which remain relevant and challenging to address. We bring together and expand on these here, based on the current summary, highlighting associated emerging issues.

Increased and improved monitoring and modelling of population responses to climate change

Existing monitoring schemes are invaluable in assessing the status of breeding and non-breeding waterbird and breeding seabird populations in the UK and Ireland (JNCC, 2021; Kennedy *et al.*, 2022; Austin *et al.*, 2023; Defra, 2023). However, there remain challenges in ensuring that trends are robust and in monitoring other aspects of demography (breeding productivity, survival). Seabird abundance and productivity are monitored through the SMP, with integrated demographic monitoring of the abundance, productivity and survival of selected species undertaken at four 'key sites'. Monitoring of survival is also undertaken through the Retrapping Adults for Survival (RAS; https://www.bto.org/ras) scheme, part of the wider Ringing Scheme. The potential for improving and integrating demographic monitoring of UK seabirds is currently being reviewed by the SMP. Similarly, while there is limited direct monitoring of Arctic and sub-Arctic breeding waterbirds, there is significant potential to improve and expand existing volunteer-based monitoring of the abundance, productivity and survival of these populations on temperate non-breeding grounds (Robinson *et al.*, 2005; Guillemain *et al.*, 2013). A significant challenge exists, though, in monitoring these non-breeding populations as distributions shift north and east of areas currently covered by volunteer-based schemes in Europe (Fox *et al.*, 2018).

Integration of data from wider and improved monitoring, through these national schemes, of abundance, breeding productivity and survival in population models, in conjunction with improved mechanistic understanding of processes, is required to better identify the causes of population and distributional change and predict the future impacts of climate change on populations. Where possible, individual-based approaches can also increase the ability to robustly attribute and predict population responses to climate, and to investigate the resilience and evolutionary adaptation of seabird populations to climate change. In understanding overall impacts on populations, we re-iterate the need for a holistic approach, considering direct and indirect mechanisms of climate change, and carry-over and density-dependent effects across the annual cycle.

Improved understanding of interactions between climate and other drivers of population change

Whilst climate change has been flagged globally (Dias *et al.*, 2019) and at a UK and Irish scale (Mitchell *et al.*, 2020; Burnell *et al.*, 2023) as being a major threat for seabirds, other pressures have been identified in informing national seabird conservation strategies (Spencer *et al.*, 2023) or are of emerging concern. In the summer of 2022, Highly Pathogenic Avian Influenza (HPAI) was recorded in a total of 18 seabird species in the UK (https://www.gov.uk/government/publications/avian-influenza-in-wild-birds) causing widespread mortality at a number of seabird colonies (Pearce-Higgins *et al., 2*023). Furthermore, seabirds face pressures from, for example, offshore wind developments, invasive non-indigenous species, reduction in food from fishing, habitat loss, fishery bycatch, pollution, litter, and disturbance (Spencer *et al.*, 2023), which may interact with the effects of climate change. Similarly, waterbirds face pressures from anthropogenic threats including agricultural intensification, conversion of tidal flats and coastal wetlands by human infrastructure developments and eutrophication of coastal systems, as well as infectious diseases (Sutherland *et al.*, 2012), such as HPAI that has also impacted populations of wildfowl species, in particular (Pearce-Higgins *et al.*, 2023).

Improved understanding of the interactions between climate and other environmental and anthropogenic pressures in explaining patterns of population change over time (Figures 1 and 2) is a priority for future research for both species groups (Burthe *et al.*, 2014; Oro, 2014) and would enable improved prediction of future population responses. It is important to know if the impacts from multiple drivers simply have an additive effect or whether they are antagonistic or synergistic; evidence to date suggests that all three types of interaction are common in marine systems (Crain et al., 2008).

Improved understanding of adaptation to climate change

With a growing understanding of the impacts of climate change on both seabird and waterbird populations, there is an urgent need to understand the potential for measures to help seabird and waterbird populations adapt to the impacts of climate change, or to increase their resilience (Hakkinen *et al.*, 2022; 2023). This review has highlighted the value of protected area networks in buffering against impacts as species respond to climatic change. There is also considerable potential for measures such as managed realignment or habitat creation to mitigate the potential losses of the intertidal habitats of waterbirds or of low-lying seabird breeding colonies due to rising sea level. However, the use of such measures to alleviate pressure on seabirds and waterbirds is a significant challenge because of the limitations in manipulating (i.e. engineering or managing) the marine environment.

Given the need to understand how climate change might impact seabird and waterbird populations across their annual cycles, any policies to promote their protection in the context of climate change should require international solutions. Existing focus has been on the overarching value of protected area networks, but improved understanding of specific management practices that benefit adaptation for individual species and reduce the impacts of climate change would be of value to inform future policies (Hakkinen *et al.*, 2022; 2023).

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