Impacts of climate change on seabirds, relevant to the coastal and marine environment around the UK

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EXECUTIVE SUMMARY

- The seabird declines that commenced at the end of the last century have continued during the last two decades.
- Further research into the causes of these declines is required if we are to fully understand the complex mechanisms operating, which are known to vary geographically. Climate change is considered to be one of the main causes of the declines. The principal mechanism is the effect of climate warming on food supply.
- There is growing evidence that short-term weather conditions have an important effect, including extreme weather events. Climate models predict further warming and increased severity and frequency of extreme weather events in UK waters.
- Seabirds face an uncertain future and may decline further in the coming decades, as the interacting effects of new and existing influences will pose additional challenges.

1. WHAT IS ALREADY HAPPENING?

The UK holds internationally important populations of seabirds (Mitchell *et al.*, 2004). After expanding for much of the last century, UK seabirds have shown substantial declines in the last two decades (Grandgeorge *et al.*, 2008; JNCC, 2016). A recent UK Government-led assessment of the state of the UK's seas concluded that breeding seabirds had not achieved 'Good Environmental Status' (GES) as defined by the UK Marine Strategy (Defra, 2019). Over a third of species assessed had experienced declines in breeding abundance of 20–30% or more since the early 1990s (Mitchell *et al.*, 2018a). Furthermore, the proportion of species experiencing widespread and frequent breeding failures has been increasing over the last decade (Mitchell *et al.*, 2018b). These assessments were not confined to UK colonies: similar

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patterns of change have occurred elsewhere in the North-east Atlantic (OSPAR, 2017a; b).

Of the 25 species breeding in the UK, six (24%) are on the UK's 'Red-list' of Birds of Conservation Concern (European shag, Atlantic puffin, black-legged kittiwake, Arctic skua, roseate tern and herring gull) and 18 (72%) are 'Amber-listed' (Eaton *et al.* 2015). Investigating these declines is important because the UK is legally obliged to safeguard seabird populations, and they play an important role in UK recreation and culture. Furthermore, they have the potential to be cost-effective indicators of marine environmental change (Parsons *et al.*, 2008). To develop effective conservation strategies and fulfil the potential of seabirds as indicators requires the mechanisms underpinning population change to be quantified.

A recent assessment concluded that the top three threats to the world's seabirds, in terms of number of species affected and average impact, are: invasive alien species, bycatch in fisheries, and climate change or severe weather (Dias *et al.*, 2019). In the UK, climate change is considered to be one of the primary causes of the declines in seabird populations and for the growing number of red-listed species (Daunt and Mitchell, 2013; Daunt *et al.*, 2017; Eaton *et al.*, 2015; McDonald *et al.*, 2015; OSPAR, *2017*a, b; Mitchell *et al.*, 2018a, b). Previous MCCIP seabird reviews (e.g. Daunt and Mitchell, 2013; Daunt *et al.*, 2017) have described how climate may affect seabird populations via two main processes: indirect effects via changes in food supply, and direct effects such as mortality from extreme weather. Several studies have been published since the last MCCIP seabird review in 2017 (Daunt *et al.*, 2017), which have advanced our understanding of both types of climate change.

Indirect effects of climate via changes in food supply

In the recent assessments of seabird population status in the North-East Atlantic conducted by OSPAR (2017c) and the UK Government and Devolved Administrations (Mitchell *et al.*, 2018a, b; Defra, 2019), species that feed on fish within the water column are faring much better than those that feed at the surface.

Water-column feeders forage at a broad depth range on pelagic and demersal fish and invertebrates (e.g. squid, zooplankton). Water-column feeders include auks, European shag, great cormorant, northern gannet and Manx shearwater, which can also be considered a surface-feeder. Surface-feeders forage within the surface layer (within 1m to 2 m of the surface) on small fish, zooplankton and other invertebrates. Surface-feeders include terns, gulls, skuas, storm-petrels, shearwaters and northern fulmar.

Functional groupings based on foraging behaviour were developed by ICES (2015) and used in marine assessments by the UK Marine Strategy (Mitchell *et al.*, 2018), by OSPAR (2017) by the European Union (see Commission Decision 2017/848/EU).

In the Celtic Seas and Greater North Sea, a higher proportion of surface-feeders failed to meet targets for abundance trends (OSPAR, 2017a; Mitchell, 2018a) and experienced frequent, widespread breeding failures (Mitchell 2018b; OSPAR, 2017b). A similar pattern was found in an assessment of Baltic seabirds and waterbirds (HELCOM, 2018) but not in Norwegian Arctic waters, were surface-feeders and water-column feeders were faring equally poorly (OSPAR, 2017a, b). This supports the widespread assertion that surface-feeding species are more vulnerable to changes in prey abundance (Furness and Tasker, 2000). Previous MCCIP seabird reviews have suggested that climate change affects seabirds indirectly, by driving changes in the availability of small fish that many seabirds rely on for food. They have also highlighted additional impacts on prey availability to seabirds from past and present fisheries. However, it would seem that some species, in particular those that can exploit prey throughout the water column, are buffered to some extent against these effects. Availability of enough prey in the right location and at the right time appears to be crucial, since there is only weak evidence linking absolute prey abundance to breeding success in most species (ICES, 2015).

Previous MCCIP reviews have reported on studies that have related seabird demographic rates (e.g. breeding success, adult survival) to indicators of climate change, such as rising Sea-Surface Temperature (SST). The most-studied species in this context is the back-legged kittiwake. This species is a surface-feeder, specialising on small shoaling fish, particularly sandeels (Wanless *et al.*, 2018). It has shown some of the largest declines in breeding abundance of any seabird in the UK and elsewhere in the North-East Atlantic (JNCC, 2016; Mitchell *et al.*, 2019a; OSPAR 2017).

Studies have shown that the over-winter survival of adult black-legged kittiwakes breeding in eastern Scotland was lower following winters with higher SST, and breeding success one year later was reduced (Frederiksen *et al.*, 2004, 2005, 2007; Frederiksen, 2014). This relationship between breeding success and SST has subsequently been demonstrated at other kittiwake colonies on the British North Sea coast, but the strength of this relationship varies greatly between colonies (Cook *et al.*, 2014a, b). Indeed, recent studies at two north-east coast colonies did not find significant relationships between SST and kittiwake breeding success (Carroll *et al.*, 2017; Eekes-Medrano *et al.*, 2017). There is evidence that breeding success is positively related to sandeel abundance (Daunt *et al.*, 2008; Eerkes-Medrano *et al.*, 2017). In turn, climate affects sandeel recruitment by altering the timing of key life history events in sandeels and their copepod prey (Regnier *et al.*, 2019). The inconsistent patterns observed between kittiwake breeding success and temperature reflects the complex ways in which temperature affects the abundance and timing of sandeels and their prey

(Eerkes-Medrano *et al.*, 2017; MCCIP, 2018; Regnier *et al.*, 2019). Critical new evidence suggests that the proportion of sandeels in the diet of seabirds breeding on the Isle of May National Nature Reserve, south-east Scotland, has declined in both summer and winter over the last three decades, linked to trends in SST (Howells *et al.*, 2017, 2018; Wanless *et al.*, 2018). Warming of waters around much of the UK has led to substantial changes in species composition and abundance at lower trophic levels (Beaugrand *et al.*, 2008; Kirby and Beaugrand 2009; Luczak *et al.*, 2012; Frederiksen *et al.*, 2013). There have been northward shifts of key copepod prey of sandeels, associated with critical thermal boundaries (Beaugrand *et al.* 2008; Reygondeau and Beaugrand 2011). The changes in seabird diet composition may reflect long-term changes in the abundance and quality of their principal and alternative prey resulting from climate change.

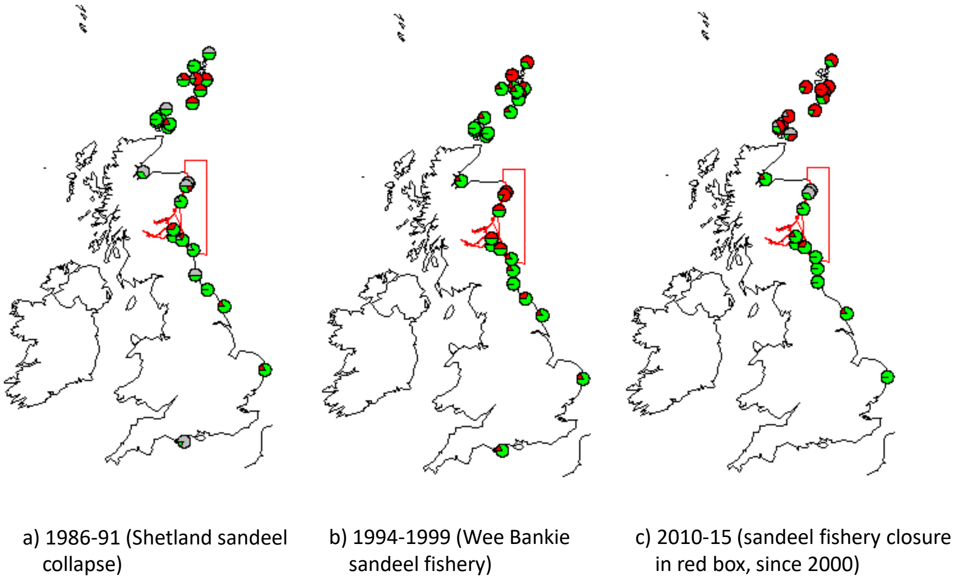
It is important to note that the relationship between SST and breeding success is apparent in other seabirds, including northern fulmar, Atlantic puffin and Arctic tern (Burthe *et al.*, 2014; Cook *et al.*, 2014a). Reed *et al.* (2015) demonstrated that average frequency of skipped breeding in common guillemots was greater in years where SST was higher. The annual survival rates of European shags were also negatively related to temperature (Burthe *et al.*, 2014). Although most studies have focussed on temperature effects, recent evidence has shown that kittiwake breeding success is negatively correlated with another climate-induced process, stratification in the water column (Carroll *et al.*, 2015). Clearly, the processes whereby climate change effects on seabirds are complex and not fully understood (see below).

One important mechanism whereby climate change may affect seabirds is temporal mismatching between availability of prey and peak energy demands in the breeding season. This ‘trophic mismatch’ may have a negative impact on demographic rates of seabirds. In the North Sea, seabirds have not kept pace with changes in the timing of key life-history events of sandeels (Burthe *et al.* 2012). A recent global meta-analysis has demonstrated that seabirds have not adjusted their timing of breeding over time (Keogan *et al.* 2018). This suggests that seabirds may have limited capacity to adjust their timing of breeding to coincide with the peak availability of prey.

The relationship between kittiwake breeding success and SST has recently been used to construct an indicator to determine if kittiwake breeding success is being driven largely by prevailing climatic conditions, or is being impacted by other human pressures (e.g. fishing) or natural factors other than climate warming (e.g. predation, weather; Cook *et al.*, 2014b; Mitchell *et al.*, 2018c). This indicator is informative in understanding regional variation of climate effects on seabirds. The indicator was constructed from breeding success data collected at 22 kittiwake colonies on the North Sea coast of Britain and was assessed annually during 1986–2015 (Mitchell *et al.*, 2018c; see Figure 1). During the late 1980s, the breeding success indicator was in line with SST except in Shetland where it was much lower than expected. This was most likely due to a crash in the Shetland sandeel stock at that time, which was caused by a change in currents and independent of SST (Monaghan *et al.*, 1989; Hamer *et al.*, 1993; Wright and Bailey, 1993). Breeding success at colonies in Shetland subsequently recovered temporarily during the early 1990s. At the same time, breeding success was lower than expected (as predicted by SST) at colonies in eastern mainland Scotland that were adjacent to an area of high sandeel fishing pressure, as previously shown by Frederiksen *et al.* (2004, 2008a). The fishery was closed to fishing from 2000 onwards. Subsequently, breeding success at most colonies on the British mainland remained below what would be expected from prevailing SST. However, since 2009, breeding success at mainland colonies has been in line with SST, except at a colony in eastern England – Bempton Cliffs and Flamborough Head. Carroll *et al.* (2017) found that higher kittiwake breeding success at this colony was associated with higher sandeel spawning stock biomass the preceding winter and lower sandeel fishing mortality two years previously.

In contrast, at all kittiwake colonies in Orkney and Shetland breeding success has been below that expected from SST since 2001. Many kittiwake colonies in Shetland and Orkney have failed to produce any young in numerous years since 2001 and have experienced the steepest declines in breeding numbers in the UK (JNCC, 2016). It is unclear why kittiwake breeding success has been poorer than expected across all colonies in Orkney and Shetland since the early 2000s. It is unlikely to have been due to fishing pressure, since this was low or even absent due to voluntary bans during this period (ICES, 2017). In some years, extreme weather events (e.g. such as heavy rain washing away nests from cliffs) may also have lowered breeding success, but such events are unlikely to have caused such widespread and sustained reductions in breeding success. At some colonies, particularly on Shetland, predation from great skuas is likely to be a major cause of poor breeding success and declines in colony size (Heubeck *et al.*, 1999; Votier *et al.*, 2004).

Interestingly there is no relationship between SST and kittiwake breeding success at kittiwake colonies in the Celtic Seas region, on the west coast of Britain and eastern Ireland (Lauria *et al.*, 2013; Cook *et al.*, 2014b). This could be because kittiwakes in the Celtic Seas are also more reliant on other species of small fish (e.g. sprat, herring) that are differently affected by SST compared to sandeels.


a) 1986-91 (Shetland sandeel collapse)

b) 1994-1999 (Wee Bankie sandeel fishery)

c) 2010-15 (sandeel fishery closure in red box, since 2000)

Figure 1: Kittiwake Breeding Success Indicator (from Mitchell et al. *2018c). The miniature pie charts show the location of kittiwake colonies on the east coast of the UK and the proportion of years (2009–2015) when breeding success was as expected by prevailing climatic conditions (i.e. SST) (green), or was lower than expected (red), or was not measured (grey). The red line denotes limits of the sandeel fishing ban that has been in place since 2000.*

Direct effects – mortality from extreme weather

Seabirds may also be affected by climate directly, in particular during extreme weather (Jenouvrier, 2013). Extreme weather such as high winds and heavy rainfall during the breeding season can chill eggs and kill nestlings and have resulted in widespread breeding failures (Aebischer, 1993; Mallory *et al.*, 2009). Newell *et al.*, (2015) demonstrated severe impacts of a summer storm on breeding performance of four UK seabird species, particularly razorbills.

Extreme weather conditions at sea can impair the ability of some species to forage and find enough food. This can lead to poor body condition, lower survival and can cause substantial ‘wrecks’ (Morley *et al.*, 2016; Louzao *et al.*, 2019). This is at least partly because flight (in flapping flight species) and diving are more costly at higher wind speeds (Kogure *et al.*, 2016). An analysis of European shags on the Isle of May has revealed that very poor adult survival occurs during sustained periods of strong onshore winds and high rainfall in late winter (Frederiksen *et al.*, 2008a). Shag plumage is only partially waterproof, presumably an adaptation to highly efficient underwater foraging, and Frederiksen *et al.* (2008a), speculated that this adaptation may make shags and similar species vulnerable to rough sea conditions during winter.

Most recently, the ‘Beast from the East’ storm in February and March 2018 caused breeding seasons to be markedly delayed at seabird colonies on the east coast of Britain. In addition, the storms that hit the Atlantic coast of Europe in 2013/2014 demonstrated the significant impact that winter storms can have on the over-winter survival of seabirds. The wave action generated during 2013/14 was the most energetic recorded along the Atlantic coast of Europe since at least 1948 (Masselink *et al.*, 2016). A total of 54,982 birds were 'wrecked' along the European coastline, of which 94% were dead, apparently due to starvation, exhaustion and drowning (Morley *et al.*, 2016). The majority of birds found were recorded on the French coastline (80%) and just over half were Atlantic puffins (Morley *et al.*, 2016). The 2013/14 wreck provided an opportunity to test models that predict the cumulative effect of extreme wind events. Louzao *et al.* (2019) identified a threshold response of bird mortality in relation to extreme wind events above which birds experienced consistent increased mortality. This will help local response services to anticipate the occurrence of mass-mortality events under future climatic scenarios.

Such mass mortality events can have long-lasting effects on seabirds, which are generally long-lived and slow to reproduce.

2. WHAT COULD HAPPEN IN THE FUTURE?

IPCC (2018) predicted, under a 1.5°C increase in global temperatures, that UK seas would continue to warm, sea-levels would rise, extreme precipitation and storminess would increase in frequency and magnitude and our oceans would continue to become more acidic as they absorb more CO_2. All these changes will have consequences for seabirds. Most seabird species in the UK are at the southern limit of their range in the North-East Atlantic. As a result, we may see changes in species' ranges in association with climate change, with the potential for associated overall declines in population size.

Frederiksen *et al.* (2013) and Russell *et al.* (2015) predicted that habitat suitability for seabirds will shift northward over the next century, and concluded that northern distributional shifts of seabirds are likely over this period. Russell *et al.* (2015) constructed climate envelopes for each species, which characterised the climate of their range using a composite of measures of (a) winter cold, (b) overall warmth or growing season, and (c) available moisture. The study predicted how the geographical position of the climate envelope and therefore the species range would change under two climate scenarios (A1b and A2 emission scenarios from Solomon *et al.*, 2007), neither of them extreme, which generated very different predicted changes in range. For example, the northern fulmar and great skua were predicted to have 34% and 17% difference in their range reduction under the higher emission scenario (A2) compared to the lower emission scenario (A1b). This illustrates that even small decreases in greenhouse gas emissions could yield benefits for conservation.

Russell *et al.* (2015) predicted that 65% of species breeding in the British Isles would show a decline in their European range, some by as much as 80%. Species that breed at higher latitudes and whose foraging ecology makes them vulnerable to low prey-availability are likely to lose range, due a lack of available land to colonise (Russell *et al.*, 2015). Lower-latitude species could shift their range northwards, but the rate and likelihood of this change is not fully understood. The rate of change is range is expected to be limited due to many species returning to their natal colony to breed (estimated between 38 and 83%, dependent on the species) and have high fidelity to that colony for their life span (> 10 years).

Consequently, range shifts rely on recruitment to a non-natal colony by first time breeders, which is known to vary by species, and thought to be influenced colony-specific factors such as distance from breeding colony, size and age of colony (Coulson and Coulson, 2008; Devlin *et al.*, 2008; Barlow, 2013).

Russell *et al.* (2015) predicted that, under a best case scenario of unlimited dispersal, Leach's storm petrel, great skua and Arctic skua will come close to or completely extinct in the UK by 2100, while the ranges of black-legged kittiwake, Arctic tern and auks are predicted to decline significantly. These studies support the climate envelope modelling of Huntley *et al.* (2007) that predicted that, by the end of the 21st century, the range of some seabird species breeding in the UK would shift northwards and other species may become extinct within the UK.

These predictions seem sensible for species, such as Arctic and great skua, which are confined to breeding in colder parts of the northern hemisphere (Furness, 1988). By contrast, the climate envelope predictions of extinction of Leach's storm-petrel from the UK may be less reliable, since they breed in warmer climes than currently experienced in the UK. Furthermore, the current distribution in the Scottish Continental Shelf is positively correlated with the proximity to deep oceanic water where they feed on plankton concentrated by upwellings and ocean currents (Mitchell, 2004). Thus, future changes in the number and distribution of Leach's storm-petrel breeding in the UK are more likely to result indirectly from climate change via changes in their planktonic food resources, rather than as a direct response to changes in air temperature and humidity or rainfall.

However, it is not clear whether warming will have a similar impact in other regions around the UK where climate effects are weaker, such as in the Irish Sea, Celtic Sea and English Channel (Lauria *et al.*, 2012, 2013). Carroll *et al.* (2015) showed that kittiwake breeding success is predicted to decline by 21–43% between 1961−90 and 2070−99. Regional differences were observed, although with lower probabilities associated, with smaller declines projected for colonies further up the east coast, with the largest proportional decline occurring at Fair Isle. This indicates that larger impacts may not be limited to southern colonies of kittiwakes, which were also recognised by large declines reported in northern Scotland (JNCC, 2016).

In line with recent evidence that seabirds are reducing their reliance on sandeels (Howells *et al.*, 2017, 2018; Wanless *et al.* 2018), emerging prey species may be critical to the future wellbeing of seabirds. However, to be an effective alternative to current prey such as sandeels and sprats, they will have to fulfil important criteria of abundance, availability and quality. This was not the case for the snake pipefish *Entelurus aequoreus* which increased dramatically in UK waters in the mid 2000s, before the population crashed (Kirby *et al.* 2006; Harris *et al.* 2007, 2008). Trophic mismatch may continue to be a concern, depending on the effect of climate change on the timing of key life history events of current and emerging prey.

Furthermore, an outcome of climate change that is of increasing concern is ocean acidification, as more CO_2 is absorbed by our oceans (IPCC, 2018). Increases in pH are already affecting phytoplankton (Riebesell *et al.*, 2013, Richier *et al.* 2014) at the base of the food chain, the consequences of which may be felt right up the food chain to forage fish and associated top predators (Heath *et al.*, 2012). Recent increases in jellyfish, which have been linked to overfishing and climate change, have been observed around the world including in UK waters (Purcell *et al.*, 2007; Brotz *et al.*, 2012). They may impact on seabirds since they are in direct competition with lesser sandeels and other forage fish for planktonic food such as copepods, while also being predators of fish larvae. In summary, if sea temperatures continue to rise as predicted, it is likely that seabirds that feed on small shoaling fish will experience poor breeding seasons and lower survival with increasing frequency in some parts of the UK.

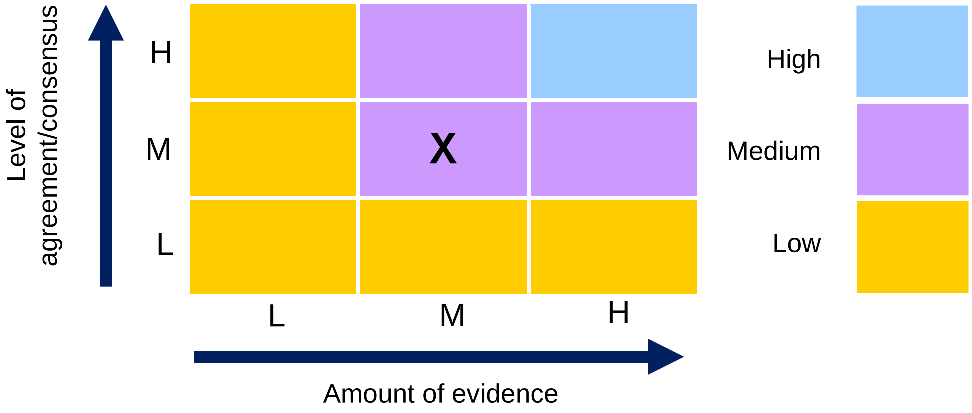
Extreme weather events may also become more important since most climate models predict an increase in their frequency in the future (Solomon, 2007; Rahmstorf and Coumou, 2011). These impacts are likely to have demographic consequences for populations under future predicted changes in storminess (Lewis *et al.*, 2015; Louzao *et al.*, 2019). As mentioned above, European shags are particularly susceptible to stormy weather, but their rapid population growth under favourable conditions allows recovery from periodic large-scale weather-related mortality. However, Frederiksen *et al.* (2008) predicted that an increase in annual variation in survival/mortality rates, as expected from more frequent stormy weather, would lead to reduced population growth rate and increasing probability of extinction.

Future climate change is also likely to have direct impacts on breeding seabirds through sea-level rise, particularly in the southern North Sea where ground-nesting seabirds such as terns, and in particular the little tern, tend to nest just above the high-water mark. Habitat loss to sea-level rise may be mitigated by nesting habitat creation further up the shore.

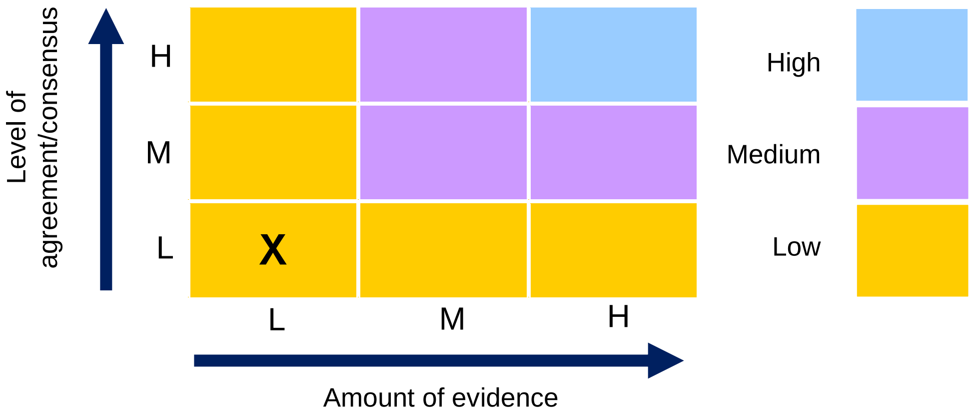
Other drivers of seabird populations are also expected to interact with climate change in complex ways. The previously demonstrated additive effect of fisheries and sea temperatures (Frederiksen *et al.*, 2004b; 2007; 2014) have recently been shown in a colony in eastern England (Carroll *et al.*, 2017). But such effects are unlikely to be maintained at higher sea-surface temperatures, where climate effects are predicted to override fishery effects. Predation by invasive native and non-native mammals at colonies has a profound impact on seabirds (Mitchell and Ratcliffe, 2007; Dias *et al.*, 2019), but it is unclear what the interaction with climate change might be. Evidence is emerging of the importance of parasites on seabirds (Duneau *et al.*, 2008; Reed *et al.*, 2008; Hicks *et al.*, 2019). There is widespread concern that climate change may interact with disease, since increasing temperatures can alter host susceptibility, pathogen survival and disease transmission rates (Lafferty, 2009). This is a particular concern in species like seabirds whose high site-fidelity limits their capacity to escape disease outbreaks. Furthermore, the effects of pollutants, which can have a deleterious impact on seabirds (Thompson and Hamer, 2000), may be exacerbated by environmental conditions and disease (Bustnes *et al.*, 2015). Climate induced changes in prey availability may alter exposure or transmission rates of parasites and pollutants. Clearly, important interactions between climate and other drivers is likely to occur in future but it is challenging to predict whether they with be additive, synergistic or antagonistic (Crain *et al.*, 2008). Accordingly, the current evidence suggests that UK seabirds face an uncertain future because of predicted future climate change and potential interactions with other drivers.

3. CONFIDENCE ASSESSMENT

What is already happening?



What could happen in the future?



The level of confidence on what is currently happening remains at ‘Moderate’, as in previous MCCIP report cards. There is broad consensus on the current effects of climate change on UK seabird populations, but there is a lack of precise, mechanistic understanding of how climate affects seabirds and the interplay between climate and other factors. Evidence is also mostly limited to effects on seabirds during the breeding season. However, we know much less about how climate affects seabirds outside the breeding season when they are distributed across large areas of sea and ocean.

Furthermore, confidence remains ‘Low’ on what will happen in the future. Predictive studies are becoming more common, but results show high uncertainty and are dependent on the choice of climate scenario. Furthermore, model projections on frequency or severity of extreme storm events remain limited, impairing our ability to predict future changes in seabird populations affected by weather.

4. KEY CHALLENGES AND EMERGING ISSUES

Previous MCCIP report cards have identified three main knowledge gaps (a) the effects of climate on the small shoaling fish (notably sandeels) that are the principal prey of seabirds; (b) the interaction between climate and other anthropogenic drivers such as fisheries, pollutants, disease and marine renewables; and (c) the role of phenotypic plasticity and microevolution in enabling seabird populations to adapt to climate change.

These knowledge gaps are as relevant now as they were a decade ago because they are very challenging to address. The approach of most studies is still to link climate or plankton to seabirds, because of the limited data available on mid-trophic level fish such as sandeels or sprat. However, a growing body of work is emerging on the links between climate and these important fish species (notably sandeels) and their prey (in particular Calanus copepods), which is proving of great benefit to seabird ecologists (van Deurs *et al.*, 2009, 2014; Engelhard *et al.*, 2013; Eerkes-Medrano *et al.*, 2017; Regnier *et al.*, 2019). However, there is a paucity of evidence on climate change impacts seabirds outside the breeding season (see above on 'Confidence'), which makes it difficult to predict how populations will adapt and respond to climate change. A key area of demography that we do not understand well is dispersal and migration and how this might respond or adapt to climate change and how this would impact population dynamics.

The interaction between climate and other drivers remains unknown and should be a focus for future research (Burthe *et al.*, 2014; Oro, 2014). It is important to know if the impacts from multiple drivers simply have an additive effect on seabirds or whether they are antagonistic or synergistic; evidence to date that all three types of interaction are common in marine systems (Crain *et al.*, 2008). Research is emerging on phenotypic plasticity of traits in relation to environmental variation in seabirds, but it remains in its infancy (Grémillet and Charmentier, 2010; Sydeman *et al.*, 2015). A future priority is to test whether micro-evolution can provide a rapid 'evolutionary rescue'. Central to this research area is the need to better quantify the extent to which key climatic drivers, such as temperature and extreme weather, can cause selection). Comparatively few study systems have the potential to do this, but this should not discourage researchers to focus on this important question.

5. EMERGING ISSUES

A potential driver of immediate and future relevance is the impact of marine renewables on seabirds. A huge expansion in marine renewable developments is planned in the coming years to meet ambitious renewable energy targets. Seabirds may be affected by these developments through a range of mechanisms, notably collision and displacement (Grecian *et al.*, 2010). These effects may be additive to climate change, or may interact with climate if, for example, the latter results in seabird range shifts, changing the spatial overlap with fixed developments. Breeding birds may be particularly vulnerable because, as central place foragers, they are constrained to obtain food within a certain distance from the breeding colony (Masden *et al.*, 2010b; Langton *et al.*, 2011), and developments are proposed in areas that lie within breeding seabird foraging ranges (Harris *et al.*, 2012). Cumulative and combined effects must also be considered when quantifying interactions between marine renewables and climate (Masden *et al.*, 2010a).

Seabirds may also face additional threats that may interact with climate change (Burthe *et al.*, 2014; Oro, 2014). There are concerns about leaching of legacy contaminants (e.g. metals, persistent organic compounds, biocides) and emerging contaminants (e.g. pharmaceuticals, personal care products, transformation products and micro and nano-polymers) into the marine environment (Brand *et al.*, 2018) that may detrimentally affect seabirds (Goutte *et al.*, 2014; Bustnes *et al.*, 2015). There is growing concern with the increase in plastics in the marine environment, which seabirds are known to ingest, but the ramifications are unclear (Wilcox *et al.*, 2015; O'Hanlon *et al.*, 2017).

Furthermore, positive management measures designed to allow commercial fish stocks to recover may have adverse impacts on seabird populations (Bicknell *et al.*, 2013). The current implementation of EC Landing Obligations will lead to an eventual halt to discarding fish from vessels and remove an important food source for some species (ICES, 2016). In addition, Reilly *et al.* (2014) suggested that haddock and whiting could outcompete kittiwakes for sandeels in the North Sea, and, if management succeeds in recovering stocks of these two fish species, the resulting competition could have an important effect on the availability of sandeels to kittiwakes that could potentially exceed the effect the industrial sandeel fishery had in the past (Frederiksen *et al.*, 2004).

It will be critically important to consider these multiple drivers simultaneously, not in isolation, because the complex way in which they interact with climate may play a key role in determining the long-term well-being of the UK's seabirds.

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