UN
environment
programme

Convention on the Conservation of Migratory Species of Wild Animals

CMS

6th Meeting of the Sessional Committee of the CMS Scientific Council (ScC-SC6)

Bonn, Germany, 18 – 21 July 2023

UNEP/CMS/ScC-SC6/Inf.12.4.1a

IMPACTS OF CLIMATE CHANGE ON MIGRATORY SPECIES

(Submitted by the Joint Nature Conservation Committee of the United Kingdom of Great Britain and Northern Ireland)

Summary:

The United Kingdom of Great Britain and Northern Ireland, through a contract to the British Trust for Ornithology funded by the Department of Environment, Food and Rural Affairs via the Joint Nature Conservation Committee, has undertaken a review of climate change and migratory species. The review is provided to the 6th meeting of the Sessional Committee of the Scientific Council meeting as a draft subject to final editing.

The report of this work is provided in a series of four INF documents:
Inf.12.4.1a: Impacts of climate change on migratory species
Inf.12.4.1b: Conservation of Migratory Species and the use of Indicators for Monitoring Climate Change Impacts
Inf.12.4.1c: Migratory Species and Their Role in Ecosystems
Inf.12.4.1d: Case Studies

Parties are invited to read the Inf documents in parallel with Document 30.4.1.

Part 1 - Impacts of climate change on migratory species

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1 Summary

Background

Over the last several decades, anthropogenic emissions (primarily of CO_2) have rapidly increased global temperatures and altered climate patterns (IPCC 2023). Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred, affecting both average conditions and annual variability, in particular the frequency of extreme events. Climate change has already caused substantial damage, and increasingly irreversible losses, to most species groups in terrestrial, freshwater and marine ecosystems.

Migratory species are vulnerable to a wider range of threats, both climate and non-climate related, as they move between countries and ecosystems on a seasonal basis, potentially exposing them to the impacts of climate change at multiple locations along their annual cycle, and their potential interactions and divergence in timing of cues at these locations.

The Convention on Conservation of Migratory Species of Wild Animals (CMS, also known as the Bonn Convention, where it was signed in 1979) is the global international agreement of the United Nations which addresses the conservation and sustainable use of migratory animals and their habitats. Over the past 40 years, CMS Parties have identified over six hundred species that merit protection under the Convention as they migrate across Range State boundaries and so require cooperative actions between Range States. The Convention recognises the need to consider climate change and this report aims to critically review the evidence of the impact of climate change on migratory species, with regards to both the size of those impacts at a population level, and the relevance of this evidence for international conservation strategies and also the strength of evidence for each. This will help to (a) prioritise international conservation actions and (b) identify key knowledge gaps.

We carried out a review of literature on the impacts of climate change on each class of species within CMS Appendix I and Appendix II from 2005 - present to identify new research since the previous review of climate change impacts on migratory species (Robinson *et al.* 2005, McNamara *et al.* 2010). This previous report identified pole-ward shifts in the distribution of species likely to particularly detrimentally affect Arctic and montane species, and changes in the timing of life history events. A range of climate change threats on migratory species were identified, research gaps identified and potential conservation responses listed. As previously there was generally more information available for birds than

other groups, although relative knowledge and understanding of impacts in marine ecosystems appears to have increased substantially.

1.1 Seabirds

Seabirds are a taxonomically diverse group of species that are linked by their use, to a greater or lesser extent, of marine habitats. Most are long-lived, breed colonially and spend long periods away from land. Increases in sea surface temperature generally induce reductions in food availability which are having widespread negative effects on survival, breeding success and population abundance. Linked to this, reductions in sea ice extent are reducing the area of suitable habitat for polar-dwelling species, and these may be replaced by more temperate species. The breeding habitat of those utilising low-lying coastal areas is threatened by both sea-level rise and a predicted increase in the frequency and severity of storms. There are already observed changes in distribution, but also changes in the timing of breeding (creating the potential for temporal mismatches between peak food requirement and prey availability) and, possibly, changes in migration routes. Furthermore, extreme events (such as intense storms) are having large impacts on individual colonies, which may be particularly problematic for those with restricted distributions.

1.2 Waterbirds

Waterbirds fall into three main groups: waterfowl (ducks, geese and swans), wading birds (herons and allies) and shorebirds which rely on freshwater and/or coastal wetlands at some point in their life-cycle. The effects of increased temperatures, at least for temperate species, have been broadly positive, although summer drought and drying out wetland habitats, especially at lower latitudes, will reduce the area of suitable habitat available and prey availability, with consequent negative population effects. Coastal habitats, on which many of these species rely, are particularly vulnerable to sea level rise, both through a reduction in area (especially where ‘hard’ sea-defences, such as sea-walls, are employed) and a predicted increase in the frequency and severity of storms. We are already seeing large-scale distributional shifts (in both breeding and no-breeding distributions) in many temperate species which are projected to continue into the future, although the mechanisms by which this happens appear to vary between groups, affecting the speed with which species can adapt.

1.3 Raptors

Historically, raptors have been persecuted in many parts of the world, and many populations have suffered from the effects of toxic chemicals (pesticides, antibiotics) that have entered the environment, although some populations are now recovering. Major habitat change has also reduced many populations, e.g. in steppe habitats of central Asia. These long-term threats may mask species’ responses to climate change. Evidence based largely on changes in productivity and survival in response to annual variation in conditions suggest that raptors are affected to a greater extent by changes in precipitation than temperature. Such impacts can be either negative by limiting foraging potential, or positive, by enhancing prey abundance through a cascade through the food-chain.

1.4 Afro-Palaearctic Passerines

Numerically, passerine birds that migrate between Eurasia and Africa in their billions each year are one of the biggest groups to be affected by changing climates. Such impacts are well documented, with both changes in range and migration routes/timing, particularly in response to widespread increases in temperature. The population consequences of these, though, are less well characterised, being confounded by simultaneous widespread changes in habitat area and suitability. The potential impacts of mismatches between the timing of breeding and peak prey abundance are perhaps less severe than first thought, but depend on the capacity of species to adapt their migration schedules, which varies. Populations of many species fluctuate with respect to rainfall on the non-breeding grounds which affects overwinter survival and hence annual population change. Changes to the timing and quantity of rainfall along these species' migratory routes could have large population-level impacts but research into this is limited.

1.5 South American Grassland Birds

The effects of climate change on South American migratory grassland birds have not yet received much focus in the literature, though it is recognised as an important subject to address moving forwards. It is likely that changes in precipitation patterns will impact food availability and habitat structure, and that species will become vulnerable to heat stress, particularly during extreme events. As grasslands are often used as agricultural and grazing habitats, which independently puts pressure on the habitat available for the bird population, the responses of farming to climate change will further influence how birds and agriculture interact in these regions.

1.6 Terrestrial Mammals

Terrestrial mammals are a diverse group of species, including primates, bears, elephants, carnivores, and ungulates. Migration is generally seasonally driven by food availability, often linked to rainfall patterns. Declines in rainfall across some areas, for example over much of the Sahel region and northern Africa, will lower primary productivity, reducing food availability for herbivores, thus also reducing food available for carnivores, indicating the inter-linked nature of climate-induced changes. Population trends vary between species and regions, but declines are most common, and for many species habitat loss due to human activities is the biggest threat, which may be compounded by human responses to climate warming.

There is evidence that migratory terrestrial mammals have some capacity to adapt to current and future climate change through behavioural changes, changes in migratory patterns and pole-wards range changes. However, such adaptation may be short-term and adaptability will be limited where movement is prevented by human infrastructure, such as fences and roads, and suitable habitat in more favourable climates is not available. Interventions to create and maintain protected habitats and corridors will be vital for the survival of many migratory terrestrial mammals.

1.7 Bats

Research on how bats are being affected by climate change is low compared to other taxa and generally insufficient to comprehensively determine the impacts. Research that has examined the consequences of climate change for migratory bats has highlighted a range of impacts, resulting particularly from changes in temperature and precipitation and extreme weather events, all of which can alter population size. Extreme weather events, particularly heat waves in the tropics, negatively impact survival and breeding success, with multiple mass die-off events being reported, particularly in flying foxes.

In response to the changing climate, range expansions/shifts have been observed in some species and are projected through predictive modelling for many more, with some evidence of phenological shifts which respond more to wind and precipitation than temperature. A major cause of mortality in bats is the installation of wind turbines as a renewable energy source as a means of mitigating greenhouse gas emissions; specific location choices and farm designs have the potential to reduce ongoing fatality rates.

1.8 Marine Mammals

The impact of climate change on marine mammals is particularly complex as there are likely to be long-term fundamental changes to ocean currents and circulation. There has been much work on marine ecosystems in recent years, but their capacity to adapt is poorly understood, making future population-level impacts very difficult to predict. The most important impact of climate change for most marine mammal species is likely to be on food availability, which in most cases will reduce. Temperature increases, loss of sea ice, increasing ocean acidification and increases in oceanic weather systems events such as the El Niño/La Niña climate system are generally predicted to reduce food availability, particularly krill abundance. Other climate change factors include the increased risk of disease and toxic algal blooms, responsible for an increase in mass mortality events, and an increase in the frequency of coastal storms and sea level rise.

Changes in food availability will lead to changes in the range, phenology and abundance of marine mammals. Arctic species such as the Polar Bear, Narwhal and Beluga Whales may be particularly vulnerable as their habitat is lost and they face increasing competition from other species moving pole-wards. Most studies predict declines in baleen whales although this is not consistently predicted. In particular marine mammal declines are predicted in mid- and low latitudes while there may be increases in some areas. Other particularly vulnerable species include freshwater and coastal species.

1.9 Marine Reptiles

Marine turtles and Salt-water Crocodiles are particularly threatened by the loss of nesting habitat due to sea level rise and increasing storm frequency and intensity. Coastal developments on alternative beaches, particularly at the pole-ward edges of their shifting ranges, is a key threat to their ability to adapt to sea level rises and temperature increases. The human response to storm surges and sea level rise will also determine whether beach profiles shift inland naturally, likely maintaining suitable nesting habitat, or are lost. Temperature increases have had a significant impact on turtle and crocodile sex ratios, although currently this is likely to be beneficial to population trends.

1.10 Migratory Fish

Most migratory fish species have undergone extreme population declines over the past 50 years. The main drivers of these declines are habitat loss, disruption of migration through damming, and overfishing, but climate change is increasingly becoming a major threat. The impacts of climate change on migratory fish are complex and under-researched but it are likely to be detrimental to most species. Increasing temperatures and reduced river flow due to the increasing temperatures, and in some areas reduced rainfall, will lead to spawning habitat loss and may also impact survival rates and could lead to extinctions. Poleward range shifts may be possible for some species, but many are strongly tied to natal spawning grounds, which will reduce their ability to shift ranges. Human interventions such as translocation, artificial stocking, habitat restoration and the removal of dams, or installation of bypasses, may be necessary for many species to survive increasingly warm temperatures.

1.11 Sharks, rays and skates

Since 1970, the global abundance of oceanic sharks and rays has declined by 71%, largely due to overfishing, bycatch and coastal habitat loss, mainly from fishing activities such as trawling. The impacts of climate change on sharks and rays are complex, due to various physiological, behavioural and ecological changes. For most species, research on the impacts of climate change is scarce, but in general, sharks and rays are thought to be vulnerable to climate change due to low reproduction rates. Species that are dependent on coastal and inshore nursery habitats or coral reef habitats are probably at the highest risk from climate change. Increases in sea surface temperatures are changing food availability, but also metabolic rates. Increased ocean acidification reduces the growth of zooplankton, on which some species feed, and reduces olfactory function in sharks and rays, reducing their ability to hunt. Pole-ward range shifts are already moderately well documented and changes in migration phenology are predicted, although there is little research to examine this. Increases in temperature and sea level are likely to reduce the amount of suitable habitat available, while an increased frequency and severity of storms particularly affects species with inshore nurseries.

1.12 Insects

There are many migratory species of insects, but only one species is listed on the CMS Appendices, the Monarch Butterfly. It occurs in North and Central America and has been a major focus of research, with increases in temperature and the frequency of extreme events having an impact on local population sizes. However, with a multi-generational migratory cycle, long-term impacts of climate change are hard to discern.

2. Contents

3 Introduction

3.1 Impacts of climate change on biodiversity

Biodiversity is declining globally at unprecedented rates, and climate change is one of the major drivers of this, as the result of a wide range of changes in the physical environment (IPBES 2019). There are well-documented increases in global temperatures, but also increases in the frequency of extreme weather events, global sea-levels and ocean acidification and decreases in snow/ice-cover. While there is global action to limit greenhouse gas emissions that drive these changes, they are projected to increase for at least the remainder of the century, even if emissions are reduced (IPCC 2023). There is already compelling evidence that animals and plants have been affected by climate change over the last few decades, with impacts on their genetic evolution, physiology, morphology, behaviour, phenology, abundance and distribution, cascading to alter communities and ecosystems (Scheffers *et al*. 2016). Many of the impacts on species' populations and communities result from mechanisms operating through altered species interactions (Ockendon *et al.* 2014). The impacts of climate change vary globally, with impacts mediated through changes in precipitation more important in the tropics than at higher latitudes, where temperature is the main driver of change (Pearce-Higgins *et al.* 2015b).

Animal migration is the persistent, directional movements from one destination to another, without stopping to make use of intervening resources, although it is important to note that migration is rarely 'point-to-point', but is often followed by substantial post-migratory movement, which may itself be climate-driven through variations in resource availability (Teitelbaum *et al.* 2023). The CMS regards a species (or population) as migratory where a significant proportion of its members cyclically and predictably cross one or more national jurisdictional boundaries, which includes species where individuals make shorter, but regular, movements within their overall range.

Each year billions of individual animals undertake seasonal movements that, in aggregate, span the globe (Bauer & Hoye 2014). Migratory wildlife is subject to a wide range of environmental influences, due to the large distances travelled, and rely on a wide range of natural resources making them particularly likely to be affected by climate change at some point in their life cycles (Learmonth *et al.* 2006; Robinson *et al.* 2009; Winkler *et al.* 2014). Migrants require not only suitable habitats at each end of their migration route but also suitable conditions and habitats *en route*. Wind speed and direction or ocean currents may be important for the successful completion of a migratory journey, and the presence of high-quality stop-over sites for resting or foraging is also of key importance. Throughout their migrations, animals must gather information, integrate environmental and internal state data, and make decisions about the timing and orientation of migratory movements, which can be increasingly difficult in rapidly changing environments. This raises the possibility of major mismatches between behaviour and environmental conditions, especially when cues in one area may be increasingly decoupled from changes in other areas. The complexities of uncertain migratory connectivity, and the difficulty in undertaking assessments of population processes throughout the full lifecycle of migratory species, make understanding the impacts of climate change and assessing climate change vulnerability in migratory species particularly challenging (Small-Lorenz *et al.* 2013).

Previously identified threats from climate change include: loss of habitat, from both increased temperatures melting sea ice and permafrost and lower rainfall reducing wetland areas; increased frequency of extreme weather events, both localised (storms) and regional (e.g. through the El Niño Southern Oscillation); sea-level rise; increased acidification of oceans; and changes in ocean circulation patterns. More pervasive, and harder to predict, are wide scale changes in ecosystem functioning, particularly changes in the spatial and temporal distribution of prey, but also the composition of biological communities. Direct effects include changing hatchling sex ratios in those species with temperature-based sex determination (e.g. turtles) and phenological shifts in the timing of life-cycle events (including migration itself). Existing anthropogenic threats, such as human take (deliberate or bycatch), existence of physical barriers (sea-walls, river dams or fences), and habitat loss will exacerbate the challenges faced by migratory species under changing climate regimes. Some of these will act synergistically with climate change impacts, for example, increased water abstraction in areas with reduced rainfall, or expanding renewable energy developments. These will further reduce resilience to cope with, and ability to adapt to climate change (Robinson *et al.* 2005; McNamara *et al.* 2010).

The impacts of climate change on migratory wildlife may usefully be classified into two general categories. Firstly, climate change may affect the species' biology directly, through changes to the abiotic environment. These may affect either the species physiology (e.g. increased heat stress or changes in wind patterns affecting migratory journeys), or its habitat (e.g. drying out of aquatic habitats, rising sea-levels encroaching on coastal habitats). Secondly, overlain on these, are less-direct biotic impacts as a result of altered species interactions, for example, changes in the spatial or temporal distribution of prey or competitors. The impact of many of these indirect effects is difficult to predict. There is a further dimension to the indirect effects, which derives from how society responds to climate change. Such adaptations are likely to be multifaceted, encompassing a wide range of objectives, from mitigating emissions to maintaining food security, which, in turn, may have major impacts on biodiversity (Morecroft *et al.* 2019). Such complexities mean converting scientific knowledge into policy and conservation action has been slow, even where such knowledge is relatively good (Trathan *et al.* 2020).

3.2 CMS and climate change

In a global context, conservation of migratory species is led by the Convention on the Conservation of Migratory Species of Wild Animals (1979) (CMS, also known as the Bonn Convention), which provides a global platform for the conservation and sustainable use of migratory animals and their habitats. Over the past 40 years, CMS Parties have identified several hundred species that merit protection under the Convention as they migrate across Range State boundaries, including many birds, land mammals and bats, as well as a range of marine vertebrates, and one invertebrate. The Convention has two Appendices: Appendix I lists migratory species that have been assessed as being in danger of extinction throughout all or a significant portion of their range, whilst Appendix II lists migratory species that have an unfavourable conservation status and that require international agreements for their conservation and management. Species that have a conservation status which would significantly benefit from an international agreement, can also be included in Appendix II. The Convention works alongside a number of daughter instruments targeted at particular groups, for example, the Agreement on the Conservation of African-Eurasian Migratory Waterbirds or the Memorandum of Understanding concerning Conservation Measures for Marine Turtles of the Atlantic Coast of Africa, and species, for example, the Memorandum of Understanding concerning Conservation, Restoration and Sustainable Use of the Saiga Antelope. Depending on the way they were negotiated and are formulated, Agreements and MoUs may be legally or non-legally binding.

The topic of climate change was introduced to CMS in 1997 (CoP Recommendation 5.5) and has been the topic of subsequent CoPs, most recently as Resolution 12.21 which calls on

Range States to address the effects of climate change, despite the remaining uncertainty surrounding the full scale of the impacts of climate change on migratory species and to assess what steps are necessary to help migratory species cope with climate change. In advance of CMS CoP14, the Sessional Committee of the CMS Scientific Council will consider climate change at its meeting in July 2023. To inform these discussions there is a need to critically review the evidence of the impact of climate change on migratory species, with regards to both the size of those impacts at a population level, and hence relevance for international conservation strategies, as well as the strength of evidence for each in order that (a) international conservation actions may be prioritised and (b) knowledge gaps identified.

In this report, we aim to review the evidence of the impact of climate change on migratory species, focusing primarily on those species listed in Appendices I and II of the CMS, but drawing on studies of non-listed and non-migratory species, where relevant.

4 Methods

To identify relevant references on the impacts of climate change on migratory species, we undertook a rapid review of the primary literature as set out below, as well as using existing reviews. We carried out a review of the literature on the impacts of climate change on each class of species (birds, mammals, reptiles, bony fish, sharks and rays, and insects) within CMS Appendix I and Appendix II species from 2005 - present to identify new research since the previous review of climate change impacts on migratory species (Robinson *et al.* 2005). We divided large classes (e.g. Aves) into smaller subgroups, generally based on their taxonomy at ordinal level, but aggregating smaller groups where they had similar ecological characteristics, and so were likely to respond similarly to climate changes. For each group, we carried out a search in ‘Web of Science’ (WoS) and given timescales, reviewed at least the first 50 papers for each search listed below, unless there were fewer than 50 available. We then carried out the same search in Google Scholar for larger groups, identifying any relevant papers that did not appear in the WoS search from the first 30 papers. We assessed the remaining papers from the WoS search (based on the title alone) to identify any additional key papers examining climate change impacts on the group.

The standard search we carried out was:

(Population* OR Demograph* OR Reproduct* OR Decline* OR Abundance OR Breeding OR Survival OR Mortality OR Fecundity OR Density) AND (Climate* OR Global warming OR Sea-level rise OR Global environmental change) AND (migrat*) AND [group name(s)]

The group names we included were as follows:

Aves: (duck OR goose OR swan), (albatross OR petrel OR shearwater OR procellariiformes), (accipiter OR eagle OR aviceda OR buzzard OR falco OR kite OR circus OR osprey), (owl), (“microcarbo pygmaeus” OR “phalacrocorax nigrogularis” OR “fregata andrewsi”), (diver OR loon), (flamingo) AND (lesser OR greater), (“podiceps auritus” OR“podiceps grisegena”), (gull OR tern), (egret OR heron OR bittern OR ibis OR pelican), (sporophila OR seedeater OR tyrant OR bobolink), (warbler), (“Afro-palearctic migrant”), (muscicapidae OR sylviidae OR turdidae OR motacillidae), (bustard), (“spheniscus demersus” OR “spheniscus humboldti”), (corncrake OR crake OR crane OR flufftail), (stork), (vulture OR condor), (wader OR shorebird), (wader OR shorebird OR Charadriidae OR Scolopacidae OR Laridae OR Haematopodidae OR Burhinidae OR Ibidorhynchidae OR

Recurvirostridae OR Pluvianellidae OR Dromadidae OR Glareolidae OR Laridae OR Alcidae).

Mammalia: Terrestrial mammals: (ungulate OR gazelle OR antelope), (gorilla OR chimpanzee), ("Ursus arctos isabellinus"), (Elephant) NOT (Seal), ("Lycaon pictus" OR "Acinonyx jubatus" OR "Panthera onca" OR "Panthera pardus" OR "Panthera leo" OR "Uncia uncia"); Bats: (bats); Marine mammals: (marine) AND (mammal OR cetacea* OR carnivor* OR seal OR lion OR manatee OR dugong), (Lontra), ("Ursus maritimus").

Reptilia: (marine) AND (turtle); "Crocodylus porosus"; "Gavialis gangeticus"; "Podocnemis expansa"

Actinopterygii: (sturgeon OR actinopterygii OR shovelnose);

Chondrichthyes: (shark OR ray OR chondrichthyes OR sawfish)

Insecta: ("Danaus plexippus")

We also drew on more recent reviews including Robinson *et al*. (2009, and associated papers), Pearce-Higgins & Green (2014), Ockendon *et al.* (2014), Pearce-Higgins *et al.* (2015b) and Robinson *et al.* (2015) to identify additional references, more general patterns and responses of migratory species to climate change.

Accounts for each group follow a standard format. First, we provide a brief overview of the migratory patterns and conservation status, before going on to discuss reported climate change impacts and then documented adaptations and responses to changing climatic conditions. Each subsection deals with a specific aspect and begins with a summary statement (*in italics*) of the key patterns and an indication of our level of confidence in this (**in bold**). We then provide details from the primary literature and reviews identified to support these statements. In general, we chose to present the topics for which there is better evidence first within each group.

Following Mastrandrea *et al.* (2010), we used a combination of the amount of evidence and the degree of agreement in that evidence to provide a three-level assessment of confidence associated with individual statements. Statements supported by many peer-reviewed papers (c. 5 or more) with a high degree of consistency were regarded as being associated with HIGH CONFIDENCE. Statements supported by a small number of papers, or more than one or two contradictory studies were given a MEDIUM CONFIDENCE. Statements supported by only one or two studies, with high uncertainty expressed in the studies, or with a very mixed evidence base were regarded with a LOW CONFIDENCE.

5 Aves: Seabirds

5.1 Overview of migration patterns & distributions

Seabirds are defined by their extensive use of marine habitats and cover a range of taxonomic groups, including the Procellariiformes (albatrosses, petrels and shearwaters), Sphenisciformes (penguins) and some members of the Charadriiformes (gulls and auks). Most seabird species are long-lived, maturing late and exhibiting low fecundity (the largest lay a single egg and may not breed every year). As a result, their breeding populations are most sensitive to changes in survival (Sæther & Bakke 2000). All are migratory to some extent. They typically breed colonially in (often remote) coastal locations or islands before migrating out to sea for the non-breeding months. Despite advances in tracking technology, which have provided some insight into their movements in the last couple of decades, there is still much we don’t know about their movements and migration, especially before they reach breeding age (Strøm *et al.* 2021).

Albatrosses (all species) and petrels (14 species) form the core of the seabird species listed by CMS and are the subject of a specific multilateral Agreement (ACAP, Cooper *et al.* 2006). Three key threats that seabirds are facing are the presence of invasive species, especially those that predate nests, in breeding colonies, bycatch from fisheries and climate change (Lascelles *et al.* 2014; Dias *et al.* 2019). As a result of long-term studies there are good demographic models of some Antarctic seabird populations, enabling some confidence in projected climate change impacts (e.g. Barbraud *et al.* 2011, Trathan *et al.* 2020).

5.2 Climate change impacts

5.2.1 Sea-surface temperature

Many seabird species show generally negative associations with sea-surface temperature with well-demonstrated effects on survival, breeding success and population abundance. **(HIGH CONFIDENCE)**

Temperate shallow, coastal seas are characterised by a spring flush of diatoms that drives a cascade of increasing zooplankton and small fish biomass. In such systems, seabird productivity is often negatively associated with sea-surface temperature, due to the negative impacts of warming on food availability. Global change is acting to ‘speed up’ such ecological processes, and change their timing (Johnston *et al.* 2022). For example, warmer temperatures can lead to changes in the timing and abundance of plankton blooms, reducing food availability for small fish (Scott *et al.* 2006; Burthe *et al.* 2012). Cold-water copepods are replaced with warm-water species that emerge later in the year reducing the flush of plankton for fish (Beaugrand *et al.* 2002, 2003). The net result is a reduction in the size and abundance of juvenile fish, such as Sandeels, around seabird colonies, and the abundance and size of 1-class fish (those of a size that indicates they hatched in the previous year) that are also important for many seabird species. This has been well-demonstrated around the North Sea (e.g. Wanless *et al.* 2004; Frederiksen *et al.* 2004, 2006), Baltic Sea (Österblom *et al.* 2006), and the east Pacific (Gjerdrum *et al.* 2003; Hedd *et al.* 2006).

Away from shallow coastal seas, different processes may operate. Although seabird populations in more open waters may be less sensitive to temperature-mediated trophic cascades (Johnston *et al.* 2022), variations in temperature and the strength of different oceanic currents may still have strong impacts on the abundance of fish prey close to breeding colonies, and therefore on their breeding success (Durant *et al.* 2003, 2005; Davoren & Montevecchi 2003; Diamond & Devlin 2003).

In response to these pressures, adults can show considerable flexibility in their foraging behaviour to try and minimise impacts on their populations, for example in Southern Rockhopper Penguins (Pütz *et al.* 2018) and Little Auks (Jakubus *et al.* 2020).

In Little Penguins, the land-based climate during the moult period has the greatest effect on adult survival (Ganendran *et al.* 2016), while higher sea surface temperatures decrease breeding success (Johnson & Colombelli-Négrel 2021). Additionally, reductions in prey abundance and foraging range during periods of prolonged drought in El Niño years have caused reduced breeding success (Preston *et al.* 2010; Kowalczyk *et al.* 2015).

Extreme temperatures can reduce breeding success by causing nest desertion, as seen in Adélie and African Penguins (Chapman *et al.* 2011; Traisnel & Pichegru 2018).

Increasing sea-surface temperature negatively affects survival in Bulwer's Petrel, which is predicted to decrease under all projected climate change scenarios (Cruz-Flores *et al.* 2022). The study also highlighted that they found stronger impacts on populations in tropical than subtropical or temperate regions.

5.2.2 Sea-ice extent

Reductions in sea-ice extent reduce the area of high-quality foraging habitats for seabirds. **(HIGH CONFIDENCE)**

Species that rely on prey whose distribution is tied to sea-ice show reduced breeding success in warmer years. For example, the productivity of southern populations of Brünnich’s Guillemots is reduced by the impact of warming upon Arctic Cod abundance (Gaston *et al.* 2005). Cold years also favour planktivorous Crested and Parakeet Auklets (Kitaysky & Golubova 2000).

In the Southern Ocean, the extent of sea-ice is positively related to the productivity and survival of many seabird species as krill are closely tied to sea ice extent, including in Adélie and Emperor Penguins (Jenouvrier *et al.* 2005, 2006; Ducklow *et al.* 2007), Southern Fulmars (Jenouvrier *et al.* 2003) and Snow Petrels (Barbraud & Weimerskirch 2001). The productivity of the Light-mantled Sooty Albatross (Inchausti *et al.* 2003) and Snow Petrels (Barbraud & Weimerskirch 2001) which feed in the Antarctic is negatively correlated with warming. Lower sea ice concentrations during summer in Antarctica increased the foraging efficiency of Adélie Penguins, though extreme events can disrupt the response (Lescroël *et al.* 2014).

Increases in mortality in Emperor Penguins were observed in relation to reductions in sea ice extent; this effect was more pronounced in males than females reflecting differences between the sexes in foraging areas. Increases in breeding success associated with shorter distances between the breeding colony and open water in warmer years did not offset the negative impact of warming on survival, so overall the population has declined (Barbraud & Weimerskirch 2001) and is likely to continue to do so (Trathan *et al.* 2020).

5.2.3 Timing of spring peaks in prey abundance

Seabirds may be vulnerable to mismatch with the timing of spring peaks in prey abundance, as a result of the timing of those peaks being strongly temperature-dependent. Temperature-related reductions in prey abundance can also limit the ability of seabirds to shift their timing of breeding. **(MEDIUM CONFIDENCE)**

On average, the timing of breeding of seabird species around the world has not shifted in response to warming or through time, potentially making them vulnerable to changes in the timing of oceanographic processes (Keogan *et al.* 2018). Where the cues which influence the timing of breeding and the timing of peak resource availability differ, then mismatch can occur. This can occur when the flow of coastal currents influences the timing and availability of small fish, but the timing of bird breeding is related to temperature, or when temperature-related reductions in prey populations delay the timing of seabird breeding despite advances in the timing of peak prey availability (Pearce-Higgins & Green 2014). These impacts can be compounded by negative impacts of climate change on prey abundance, but there is a general lack of studies climate-mediated trophic asynchrony may pose to populations worldwide (Samplonius *et al.* 2021).

5.2.4 Changes in oceanic currents

Large-scale changes in oceanic currents can greatly alter food availability, especially for central-place foragers like seabirds that have to return to a specific location, the breeding colony. **(HIGH CONFIDENCE)**

There are marked effects on seabird populations concerning variation in the strength and direction of the El Niño Southern Oscillation (ENSO). El Niño years (negative values of the Southern Oscillation Index) are associated with warmer temperatures and reduced productivity in tropical seabird species, due to reductions in the extent of cold water upwellings, reducing nutrient circulation, plankton production and fish productivity. This has been shown to impact Galápagos Penguin (Boersma 1998) and Blue-footed Booby (Oro *et al.* 2010; Ancona *et al.* 2012) in the Pacific, and Roseate Tern productivity in the Indian Ocean (Ramos *et al.* 2006; Monticelli *et al.* 2007).

Elsewhere, high sea-surface temperature (associated with reduced food availability) during breeding and positive episodes of the Southern Oscillation (La Niña) during the non-breeding season, negatively impact survival in Cory's Shearwater. These population effects of climate were greater than that of longline fisheries (Ramos *et al.* 2012).

The intensity of winds in the Southern Ocean are increasing which alters the depth of layers within the ocean; this can impact prey availability and foraging behaviour/efficiency as seen in Little Penguins (Ropert-Coudert *et al.* 2009; Saraux *et al.* 2016).

5.2.5 Frequency of stormy weather

Increased frequency of stormy weather can impact on the survival and breeding success of some species, depending on the timing, with potential consequences for population size. **(HIGH CONFIDENCE)**

Phalacrocoracidae species, such as Shag, have poor weather-proofing and hence can suffer high mortality following stormy or wet conditions (Harris *et al.* 1994; Frederiksen *et al.* 2008).

Arctic-breeding species are vulnerable to extreme weather events, and it is speculated that climate change may increase the frequency of these, as well as expand the range of stressors that might induce mass mortality in breeding seabirds (Mallory *et al.* 2009)

When storms occur during the breeding season, they can result in the loss of low-lying coastal nests in species such as of gulls and terns (e.g. Weston & Fraser 2020), or of low-lying exposed cliff nests in others (Newell *et al.* 2015). Similarly, outside of the breeding season, severe storms can cause mass mortality events, known as ‘wrecks’ (Camphuysen *et al.* 1999).

Increased intensity of the ENSO has enhanced local storm activity, increasing mortality in Manx Shearwaters. Mortality in Atlantic Yellow-nosed Albatrosses and Magellanic Penguins also increased with storm activity, regardless of ENSO (Tavares *et al.* 2020). Climate change may also increase the turbidity of the water, which can reduce foraging efficiency in seabirds e.g. Manx Shearwater (Darby *et al.* 2022).

5.2.6 Rising sea-levels

Many seabirds are cliff-nesters, but for those nesting in low-lying areas, such as albatrosses and penguins, rising sea-levels threaten to inundate nest sites, especially where there are natural or anthropogenic barriers to movement inland (Trathan et al. 2015). **(LOW CONFIDENCE)**

5.3 Adaptations and Responses

5.3.1 Timing of migration and breeding

The timing of migration or breeding can be sensitive to temperature and large-scale atmospheric systems, though responses vary within and between species. **(MEDIUM CONFIDENCE)**

Advances in arrival dates and breeding are documented in a range of species e.g. Ring-billed Gull, Pacific Loon, and Glaucous Gull, and correlate with temperature increases (Giroux *et al.* 2016; Solovyeva *et al.* 2022), however, this is not true for all species (Solovyeva *et al.* 2022).

In Common Terns, the changes in arrival timing relative to North Atlantic and Southern Oscillation indices differ between age-classes and have shown no long-term trends in recent decades (Szostek *et al.* 2015). The timing of arrival at a European stopover site differs for Great and Sooty Shearwaters, but for both species coincides with favourable flying conditions (Louzao *et al.* 2015).

Local conditions appear to be the main driver of breeding phenology for many seabird species (Keogan *et al.* 2022), particularly temperature, although negative impacts of warming on resource availability can also delay breeding (reviewed by Pearce-Higgins & Green 2014). Resident seabird species appear better able to adjust the timing of breeding in response to climatic variation than migratory, as seen among species breeding on the Houtman Abrolhos Islands in the eastern Indian Ocean (Surman *et al.* 2012).

5.3.2 Distribution

The response of seabird distribution ranges to climate change varies among species; shifts or expansions that have been observed are most often pole-wards. **(HIGH CONFIDENCE)**

Modelling suggests that increases in sea surface temperature have driven the pole-ward range expansions in Balearic Shearwater likely associated with similar shifts in prey (Wynn *et al.* 2007), while there have been southward range expansions in Gentoo and Adélie Penguins, tracking the retraction of sea ice (Lynch *et al.* 2012; La Rue *et al.* 2013).

Not all species appear to be responding to changing climate conditions through a change in their distribution, for example, the migration habits of Herring Gulls that breed in Newfoundland seem to be well-established and no northward shift has been observed (Robertson 2016).

In some species, distribution shifts have been attributed to changes in productivity, for example, warmer temperatures are increasing productivity in Brünnich’s Guillemots at the pole-ward range-margins due to reductions in sea-ice, but causing reductions in the southern range-margins (Gaston *et al.* 2005). In other species, similar patterns are seen in survival, for example, survival in eastern Atlantic populations of Atlantic Puffin is positively related to temperature in the north of its range, but negatively in the south (Grosbois *et al.* 2009).

Seabirds are amongst the most vulnerable species to climate change in the UK, where many are towards their southern range margin. Temperature-related reductions in abundance anticipated are widely anticipated, and are symptomatic of anticipated pole-ward shifts of these species (Johnston *et al.* 2013; Pearce-Higgins 2021).

5.3.3 Migration routes

Some species may have adaptive responses to variations in climate that allow them to alter migratory routes or destinations. **(LOW CONFIDENCE)**

In Cory's Shearwater, whilst some individuals show high site fidelity, others are capable of shifting their winter locations between years which is expected to be advantageous under changing and fluctuating environmental conditions (Dias *et al.* 2011).

6 Aves: Waterbirds

6.1 Overview of migration patterns & distributions

Waterbirds are one of the most studied groups when it comes to understanding the impacts of climate change. They are globally distributed and fall into three main taxonomic orders, Anseriformes (also known as waterfowl – ducks, geese and swans), Pelecaniformes (herons, ibises and pelicans, often referred to as “wading birds”) and Charadriiformes (gulls, terns and shorebirds/waders - hereafter termed shorebirds to avoid confusion with other wading birds), along with a small number of representatives from other groups. Almost all species inhabit freshwater and/or coastal wetlands at some point in their life-cycle, either breeding or non-breeding, and there is a wide range of migratory strategies. Indeed, many of the shorebird species are among the world’s longest distance migrating species and as such have been considered ‘sentinels’ of global change (Piersma & Lindström 2004).

Most waterbirds, at least of those breeding in the northern hemisphere, migrate along one of eight ‘flyways’, defined by the Ramsar Convention on Wetlands as “composed of many overlapping migration systems of individual waterbird populations and species, each of which has different habitat preferences and migration strategies”. Three of these flyways are in the Americas (along the Pacific coast, inland along the Mississippi catchment to Central and South America, and along the Atlantic coast), three connecting Eurasia with Africa (along the East Atlantic, western Asia to northern Africa, and central Asia to southern Africa), and, further East, the central Asian and East Asian-Australasian flyways (Davidson & Stroud 2018).

Temperate wetland and boreal, upland habitats are among those most altered by climate change, and as a result, waterbirds are among the species most threatened by climate change and for which climate change impacts (both negative and positive) have been well documented.

6.2 Climate change impacts

6.2.1 Increased temperatures

The effect of increased temperatures on breeding success and survival varies between species, but generally has a short-term neutral or positive effect, at least for species breeding at higher latitudes **(HIGH CONFIDENCE)***, although extreme temperatures (both hot and cold) are detrimental* **(MEDIUM CONFIDENCE)***.*

Temperature and the timing of snowmelt did not affect breeding success for 12 out of 17 studied species of Arctic-breeding shorebirds (Weiser *et al.* 2018a). But for those affected, earlier snowmelt/warmer temperatures generally increased clutch size; taken together this suggests that, in the short-term, climate change will neutrally/positively affect breeding in Arctic-breeding shorebirds. Adult survival of six shorebirds was not explained by the timing of snowmelt or temperature at the breeding grounds, suggesting these species seem robust to conditions at the Arctic sites and conditions at stopover and wintering sites are more likely driving changes in survival (Weiser *et al.* 2018b).

Duck species breeding success was found to be higher in warmer and drier springs in the American prairies (Drever *et al.* 2004; Drever & Clark 2007).

Svalbard Barnacle Geese have shown increased egg production and hatching success with advancing snowmelt and increasing summer temperatures, although these conditions have also correlated with an increase in the abundance of Arctic Foxes and a consequent overall decrease in fledging success (Layton-Matthews *et al.* 2020). Increased temperatures in their UK wintering grounds are also associated with an increase in annual survival rates.

During the breeding season, temperature positively affected breeding success in Slavonian Grebes from estimates made across Scotland (Ewing *et al.* 2013), but not within a single population that was the focus of another study (Brooks *et al.* 2012), and climate change doesn’t seem to be directly driving the declining population trends (Ewing *et al.* 2013). On the other hand, the condition, and hence first-year survival, of Lesser Snow Goose goslings are lower in warmer than average years (Aubry *et al.* 2013).

Temperature has been shown to have a positive effect on growth rate in some populations of Arctic and sub-Arctic breeding shorebirds; this was strongest in the populations that generally breed in the coolest locations and there is evidence that timing of breeding relative to the peak in arthropod abundance influences growth rate (Lameris *et al.* 2022).

Fluctuations in abundance and variation in adult survival rates of a range of wetland bird species are positively correlated with winter temperature, including shorebirds (Yalden & Pearce-Higgins 1997; Cook *et al.* 2021), herons (Pearce-Higgins 2017), and waterfowl (Gunnarsson *et al.* 2012), leading to overall positive relationships between abundance and winter temperature (Johnston *et al.* 2013).

Extreme cold weather is, unsurprisingly, detrimental to wading bird populations, with increased mortality having been demonstrated in Greater Flamingo (Deville *et al.* 2014), Bittern (Cormont *et al.* 2014) and coastal winter species like the Redshank in the UK (Clark 2009). It is worth noting that such extreme events can precipitate a decline from which the population cannot recover, for example UK breeding populations of Northern Lapwing decreased as the result of a series of cold winters, but have not recovered due to insufficient reproductive capacity, despite the proximate cause of the decline no longer being present (Robinson *et al.* 2014).

Finally, the effects of increased temperature can be quite indirect. For example, warmer temperatures in Arctic Canada have meant an increase in the amount of woody vegetation (as a result of faster temperature-mediated growth), reducing the area of suitable breeding habitat for Whimbrel (Ballantyne & Nol 2015). However, in Iceland, warmer temperatures are increasing the area of suitable habitat for several species, such as the Black-tailed Godwit (Gunnarsson *et al.* 2006).

6.2.2 Altered patterns of precipitation

Increased precipitation can have a positive effect on breeding success, and drought a negative impact, at least on temperate breeding waterbirds. Where precipitation is projected *to fall, especially in the summer months, overall effects are likely to be negative.* **(HIGH CONFIDENCE)**.

Breeding success was halved in dry years compared to wet for Purple Herons in Portugal due to higher rates of predation (Carneiro *et al.* 2016).

In the longer-term, hotter, drier summers can have negative impacts on shorebirds (e.g. Pearce-Higgins *et al.* 2010), and species associated with wetland habitats, either through impacting habitat availability, or indirectly through impacts on prey abundance, particularly invertebrates (Carroll *et al.* 2015b; Pearce-Higgins & Morris 2022).

Breeding success was highly influenced by rainfall for White Storks in Spain, with much higher success in wetter years (Cuadrado *et al.* 2016). Survival (Nevoux *et al.* 2008) and population size (Sæther *et al.* 2006) are positively affected by the level of rainfall in the Sahel, however in recent decades, as there has been more precipitation, the strength of this environmental effect has faded.

Egg production was positively influenced by precipitation at a Norwegian stopover site during spring migration for Barnacle Geese in Svalbard (Layton-Matthews *et al.* 2020). Similarly, warmer and wetter conditions during spring and autumn migration increase survival in Greenland Barnacle Geese (Doyle *et al.* 2020).

The survival and changes in abundance of migratory waterbirds that winter in the Sahel are positively correlated with the extent of wet-season rainfall (May – October) which recharges wetland habitats during the subsequent winter, likely impacting food resource availability (Zwarts *et al.* 2012). Similarly, migratory herons benefit from wetter conditions on the African wintering grounds (e.g. Fasola *et al.* 2010; Marion *et al.* 2006; Nevoux *et al.* 2008; Sæther *et al.* 2006).

For Dalmatian and Great White pelicans in the Black Sea/Mediterranean flyway, water level fluctuations in inland wetlands are a widespread problem (Catsadorakis *et al.* 2015) and in later breeding species (e.g. White-headed Duck), the earlier drying of wetlands can have negative effects (Özgencil & Uslu 2021).

An increase in precipitation during autumn migration, and on the breeding grounds whilst breeding, reduced recruitment in Whooping Cranes. Similarly, fewer days below freezing during the winter months on the breeding grounds also reduced recruitment, thought to be the result of a positive relationship between winter days below freezing and pond depth during the following summer (Butler *et al.* 2017).

6.2.3 Sea-level rise

Sea-level rise is predicted to cause habitat loss, particularly at stopover sites along the migratory routes and wintering grounds. **(HIGH CONFIDENCE)**

The extent of habitat loss varies between species but has been predicted for a wide range of wading birds (Wikramanayake *et al.* 2020; Iwamura *et al.* 2013; Convertino *et al.* 2011; Mustin *et al.* 2007; Galbraith *et al.* 2014; Iwamura *et al.* 2014; Ma *et al.* 2014; Aiello-Lammens *et al.* 2011) and migratory waterfowl (Moon *et al.* 2021; Clausen & Clausen 2014; Livolsi *et al.* 2021). As an example, earlier arriving Semipalmated Sandpipers at a migration stopover site in Nova Scotia experienced higher tides which resulted in higher energy expenditure and a longer stopover duration. The authors suggest that sea-level rise is therefore likely to increase the energetic costs of stopovers as extreme tidal amplitudes increase in frequency (Mann *et al.* 2017). Loss of habitat in individual estuaries can have disproportional population impacts through reductions in network connectivity, since such sites tend to form key stopover areas for long-distance migratory shorebirds. For example, in the East Asian-Australian Flyway, 23-40% loss of habitat as a result of inundation can reduce bird population flows by over 70% (Iwamura *et al.* 2013).

Anthropogenic barriers to landward expansions of coastal habitats, such as sea walls, exacerbate the effects of sea-level rise on available habitat (Moon *et al.* 2021; Ma *et al.* 2014).

6.3 Adaptations and Responses

6.3.1 Distribution and range shifts

Pole-ward/elevational range shifts have been observed and are predicted to intensify throughout a wide range of wetland and coastal bird species. **(HIGH CONFIDENCE)**

As water is crucial for providing food and protecting from predation for dabbling and diving ducks, temperature is a key driver of their winter distribution (Schummer *et al.* 2010). Wintering European waterbird abundances and distributions are already shifting in response to warming (Johnston *et al.* 2013), with particular shifts northwards and eastwards towards the breeding grounds (Maclean *et al.* 2008; Lehikoinen *et al.* 2013; Pavón-Jordán *et al.* 2020).

Similarly, long-term shifts in European wintering duck populations have mostly been in northward and eastward directions or into regions previously considered too cold (Musil *et al.* 2011; Ekroos *et al.* 2012; Guillemain *et al.* 2013). Waterfowl with distributions that already occupy the northern edge of the continent are expected to experience range contractions (Guillemain *et al.* 2013).

Climate change appears to be affecting the range of several endangered wading bird species, which will need to be accounted for when formulating conservation management plans targeted at currently small populations. Black-Necked Crane on the Qinghai-Tibetan plateau are expected to experience an expanding range, of varying degrees depending on the climate scenario, with movements particularly to the northwest and higher elevation (Li *et al.* 2022). Similarly, the distribution of the Red-crowned Crane is predicted to shift pole-ward, moving away from almost all of its current breeding range in the next century; this shift will change the country containing the greatest proportion of the population from China to Russia (Liu *et al.* 2020).The wintering range of the Black-faced spoonbill is predicted to increase in area in addition to shifting pole-wards (Hu *et al.* 2010).

Climate change is projected to reduce the suitability of 58% of critical sites for waterbirds within Africa-Eurasia, with those in Africa and the Middle East, where protection is least effective, most threatened (Breiner *et al.* 2022). The most vulnerable species are dispersive species within the Afro-tropical realm and Arctic breeding shorebirds (Nagy *et al.* 2021). Projected improvements in passage and wintering conditions are likely to support the northwards and eastwards expansion of non-breeding ranges across Eurasia, particularly into Eastern Europe, Scandinavia, Russia and Kazakhstan (Nagy *et al.* 2021; Breiner *et al.* 2022).

6.3.2 Changes in migratory route

Whilst species vary in their capacity to alter migratory routes, shorebirds seem highly site faithful, with changes only coming about as young birds learn new routes. For other species adult birds appear able to occupy new wintering areas. **(LOW CONFIDENCE)**

The establishment of new wintering sites with more favourable conditions and closer to the breeding grounds has occurred in Whooping Cranes, a behavioural change enabled by older birds, highlighting the importance of age structure within populations for allowing adaptive responses to change (Teitelbaum *et al.* 2016), and Pink-footed Goose, in response to warming temperatures, enabled by cultural transmission within and between species (Madsen *et al.* 2023).

In contrast, for Icelandic Black-tailed Godwits, adults remain highly site faithful and new areas (which have tended to be closer to the breeding grounds) have been settled by young birds (Gunnarsson *et al.* 2005). Similarly, body condition and juvenile survival in Lesser Snow Geese are higher in newly colonised areas (Aubry *et al.* 2013).

6.3.3 Timing of migration and breeding

The timing of migration and breeding is most often advancing in response to warmer temperatures, with generally positive impacts on breeding success. **(HIGH CONFIDENCE)**

Changes in the timing of arrival tend to be much better documented than the timing of departures, although it should be noted that such work often concentrates on the arrival of the earliest individuals, rather than the median across the population, which may show different patterns, for example being confounded by population trend (Miller-Rushing *et al.* 2008). Later departure (Stirnemann *et al.* 2012, Orellana-Macías *et al.* 2020) and earlier arrival (Vähätalo *et al.* 2004) at the breeding grounds have been documented for European waterfowl in response to the decreasing harshness of winter. Similarly, White Storks arrive earlier in western Poland when March is warmer (Tobolka *et al.* 2015).

In a study of Danish breeding shorebird species, there were phenological responses to the North Atlantic Oscillation, temperature and precipitation and the authors conclude that spring arrival can respond to climate in short-, medium- and long-distance migrants, but not all long-distance species are advancing the start of their respective breeding seasons (Meltofte *et al.* 2018).

The initiation of breeding in six Nearctic wading bird species was correlated with the timing of snowmelt and the time of snowmelt affected the extent of phenological mismatch between the breeding birds and their invertebrate prey, suggesting wading birds may be vulnerable to negative consequences of mismatch under climate change (Kwon *et al.* 2019).

The timing of spring migration is not related to the climatic conditions at the breeding grounds for American White Pelican (King *et al.* 2017). Great White Pelicans have not advanced their average timing of breeding, but have advanced the endpoint, thereby reducing the duration of their breeding season (Doxa *et al.* 2012).

7 Aves: Raptors

7.1 Overview of migration patterns & distributions

Taxonomically, raptors fall into three orders: Cathartiformes (New World vultures) Accipitriformes (hawks, eagles and Old World vultures) and Falconiformes (falcons), all species in these orders are listed on the Appendices of the CMS (with the exception of the anomalous Secretary Bird). Many are considered as part of the Memorandum of Understanding on the Conservation of Migratory Birds of Prey in Africa and Eurasia, which also includes 12 species of migratory owl. Raptors range from relatively sedentary to highly migratory. The larger species (vultures, eagles, some hawks) in particular, use thermal updrafts to assist their migration and as a result migration routes can become quite narrow, especially where sea crossings are involved (for example, most raptors cross the Mediterranean at either its eastern (Bosporus) or western (Gibraltar) extremity, resulting in large concentrations of birds.

Raptors face a wide range of threats, including agricultural practices (e.g. Sánchez Zapata *et al.* 2003), hunting and the prevalence of toxic chemicals, but climate change has largely not been seen as a widespread conservation issue to date (McClure *et al.* 2018), with the most widely documented effects being on distribution and timing of migration (Martínez-Ruiz *et al.* 2023). Although some have undergone large-scale population recoveries in recent years, a substantial number are threatened with extinction.

7.2 Climate change impacts

7.2.1 Altered patterns of precipitation

Changes in precipitation can affect breeding success, although the direction of the effect varies depending on the general climate and habitat the birds breed in. *Tropical breeding raptors tend to show positive effects of rainfall on their populations through impacts on prey abundance* **(MEDIUM CONFIDENCE)**, *whilst at higher-latitudes, more negative responses to precipitation are likely due to chilling and reduced foraging opportunities* **(MEDIUM CONFIDENCE)**.

A wide range of species show negative impacts of heavy rain when the semi-precocial chicks are young, although these effects are particularly apparent at northern latitudes (Pearce-Higgins & Green 2014). There is a combined impact of chilling of chicks and reduced foraging opportunities in wet weather that, alongside heavy rainfall, has a negative impact on raptor breeding success in the tropics – for example, monsoon conditions (Senapathi *et al.* 2011).

In contrast, breeding in Wedge-tailed Eagles in Australia is positively affected by rainfall in arid habitats, whilst rainfall has no effect in mesic regions. The productivity of nests is also substantially lower in the arid zone which may put the population at risk with the increasing frequency of extreme weather events (Cherriman *et al.* 2022).

Tropical breeding raptors tend to show positive effects of rainfall on their populations, although these are primarily associated with lagged impacts during the following year rather than direct impacts (Pearce-Higgins & Green 2014). Rainfall has a positive impact on vegetation growth and the abundance of prey species, as shown for larger raptors in the Kalahari (Krüger *et al.* 2002), Aplomado Falcon in Mexico (Macias-Duarte *et al.* 2004) and kestrels in the Mediterranean (e.g. Fargallo *et al.* 2009). In such dryland systems, El-Niño heavy rainfall events can stimulate rapid vegetation growth and rodent population increases, leading to a flush of food for owls and raptors, which then contribute to a decline in rodent populations alongside a return to dry conditions (Lima *et al.* 2001).

Higher rainfall in the Sahel (the wintering grounds), particularly when paired with high breeding success, had a positive effect on adult survival in Montagu's Harrier, which is expected to imply higher prey availability over winter (Millon *et al.* 2019). Similarly, there was a positive correlation between adult survival and rainfall in the Sahel for Eurasian Scops Owls that breed in France (Barbraud *et al.* 2022).

7.2.2 Increased temperatures

The effects of temperature change appear relatively weak, with no strong impact of temperature upon breeding success. **(LOW CONFIDENCE)**

Increased spring temperatures are associated with an increase in breeding success in Switzerland’s Red Kite population (Nägeli *et al.* 2021).

Higher temperatures were associated with decreased hunting frequency but were not found to affect hunting success in Snowy Owls. The authors suggest this may imply they are better able to meet their metabolic demands with warmer temperatures; snow depth did not affect hunting frequency or success (Winter & Shields 2021).

Lower adult survival was associated with cooler and drier years for Little Owls in the Netherlands (Le Gouar *et al.* 2011).

Survival was higher in years with earlier snowmelt, milder winters and warmer breeding seasons for Peregrine Falcons breeding in Alaska (Bruggeman *et al.* 2015).

7.3 Adaptations and Responses

7.3.1 Timing of migration and breeding

The timing of migration and onset of breeding responds to temperature and precipitation, though responses vary among species. **(MEDIUM CONFIDENCE)**

Arctic Peregrine Falcons arrive back in Alaska faster in years with earlier snowmelt/milder winters (Bruggeman *et al.* 2015).

Golden Eagles in north-eastern North America have been found to delay spring migration and advance autumn migration in response to warmer temperatures, reducing the duration of time spent on the breeding grounds and contrasting with the most common results regarding shifts in the timing of migration (Maynard *et al.* 2022).

The timing of autumn migration is being delayed as temperatures increase, leading to the potential for longer breeding seasons, in both Europe (Jaffré *et al.* 2013) and North America (Buskirk 2012).

7.3.2 Distribution and range shifts

Changes in temperature and precipitation are expected to influence species distribution ranges, with some current evidence of range losses. **(MEDIUM CONFIDENCE)**

Increasing summer temperatures and precipitation are thought to drive the absence of Red Kites in regions of Spain (Seoane *et al.* 2003), though climatic parameters only weakly affect their distribution in Germany at the core of their range. The effects of shifting climatic conditions across Europe on reproduction may influence population declines at the south of their range (Mattsson *et al.* 2022).

It is predicted that there will be substantial range contractions on both the breeding and wintering grounds for the Oriental Honey Buzzard, which will increase the distance required for migration under all climate change scenarios (Condro *et al.* 2022).

For vulture species in the Gangetic-Thar-Deccan region of India, environmental factors such as land use and direct anthropogenic impacts are estimated to have the greatest influence on current distribution, but climatic variables such as temperature and precipitation are predicted to be the greatest determinant as climate change progresses (Jha & Jha 2021).

8 Aves: Afro-Palaearctic migratory passerines

8.1 Overview of migration patterns & distributions

Every year, in the order of 2 billion birds migrate between Europe and Africa in a huge transfer of ecosystem resources (Hahn *et al.* 2009). About three-quarters of these individuals are from 16 species and 95% are passerines, particularly from the Muscicapidae/Sylviidae group of families, with eight individual families listed in their entirety on the Appendices of the CMS (Cisticolidae, Acrocephalidae, Locustellidae, Phylloscopidae, Sylviidae, Turdidae, Muscicapidae and Motacillidae). These species exhibit a range of migratory schedules, both between and within species, with some individuals being relatively sedentary, while others migrate long distances. Leap-frog migration is common, with northern breeding populations migrating to more southerly locations for the boreal winter than southern breeding populations.

Threats to these species come mainly from habitat loss and alteration, and despite widespread population responses to climate change (Pearce-Higgins & Crick 2019), just 15 out of 103 studies have found demographic parameters to be directly affected by climatic variables, suggesting limited evidence for the impact of climate change compared to that of anthropogenic habitat/land-use changes (Vickery *et al.* 2014, 2023). Climate change appears a more important driver of change on the breeding grounds of short-distance migrants, but land-cover change on the wintering grounds for long-distance migrants (Howard *et al.* 2020).

8.2 Climate change impacts

8.2.1 Alteration in patterns of precipitation

Annual variation in the survival and abundance of long-distance migratory passerines, especially those that spend the boreal winter in African drylands (such as the Sahel), tends to be most strongly linked (positively) to variation in rainfall there. **(HIGH CONFIDENCE)**

Long-term changes in the abundance of migrants that winter in the Sahel match long-term rainfall trends, whilst annual fluctuations also correlate with rainfall levels (Newson *et al.* 2009; Pearce-Higgins & Green 2014). This is driven by rainfall during the wet season (May - October) influencing the carrying-capacity of the region during the subsequent winter (Baillie & Peach 1992), either by determining the extent and duration of wetland habitats for wetland associated species such as Sedge Warblers and Sand Martins (Zwarts *et al.* 2012), or by stimulating vegetation growth, increasing the abundance of fruit and invertebrate prey (Schaub *et al.* 2005). There is some evidence that these conditions can carry-over to impact the timing of breeding (and in some species clutch-size), although the magnitude of these effects is relatively small (Ockendon *et al.* 2014).

The overwinter survival rates of Nearctic migrants fluctuate in response to rainfall in the Caribbean (Sillett *et al.* 2000; Mazerolle *et al.* 2005), although the evidence for such effects is from fewer species than for Afro-Palaearctic migrants. There is also evidence for carry-over effects of overwintering conditions in the tropics impacting on the timing of arrival back to the breeding grounds (Studds & Mara 2005), and subsequent return rates of female American Redstarts (Studds & Mara 2007).

Heavy rainfall during critical periods may negatively impact migrant survival rates, as shown for Barn Swallows (Møller 1989) and Alpine Swifts (Robinson *et al.* 2020). Such effects may be most likely to occur close to or during migration periods (Stokke *et al.* 2005). Weather conditions on migration may also carry-over to impact the timing of breeding (Finch *et al.* 2014).

8.2.2 Increases in temperature

Increased temperatures generally promote an abundance of insect prey, which are the primary source of food in the breeding season (less so in the, boreal, winter months), and often results in higher breeding success, if temperatures are not too extreme. **(MEDIUM CONFIDENCE)**

Food availability on the breeding grounds is a key driver of breeding success, and is often linked to temperature through its effect on insect development. This means that the abundance of invertebrate prey can strongly impact the breeding success of migratory passerines. Given the strong links between the weather and invertebrate populations, climate change has the potential to impact migratory bird productivity through impacts on their invertebrate prey (Pearce-Higgins & Morris 2022). For example, the abundance of aerial insects is positively correlated with the survival of Barn Swallow chicks (Martay *et al.* 2023), and the productivity of Black-throated Blue Warblers is linked to the effects of weather on caterpillar abundance (Sillett *et al.* 2000). Long-term declines in the abundance of key invertebrate groups, such as moths, partly driven by climate change (Fox 2013; Martay *et al.* 2017), may therefore have contributed to declining long-distance migrant populations across Europe.

High temperatures have also been directly linked to negative impacts on birds. High temperatures reduce Barn Swallow chick growth (Facey *et al.* 2020), while the risk of overheating reduced chick provisioning rates at high temperatures for an American migratory passerine, the Tree Swallow (Tapper *et al.* 2020). High temperatures are linked to increased mortality in Great Reed Warblers, though their reproduction has been benefiting from improved rearing conditions (Schaefer *et al.* 2006).

8.2.3 Timing of spring peaks in prey abundance

Increased temperatures in the spring can lead to earlier insect emergence, and hence asynchrony with the timing of breeding **(LOW CONFIDENCE)**

The spring caterpillar peak in temperate deciduous woodlands provides a pronounced pulse of food availability in spring, utilised by a range of passerines, both migratory and resident, whilst rearing offspring. Some evidence suggests asynchronous timing of spring arrival or breeding in birds relative to this caterpillar peak is detrimental to breeding success (Both *et al.* 2006) and asynchrony increases with temperature (Burgess *et al.* 2018; Franks *et al.* 2018). However, while there is a substantial amount of evidence for temporal asynchrony in the timing of breeding with respect to the prey base, evidence for population impacts is generally lacking and even in the two best-studied species, one of which is the migratory Pied Flycatcher, only some populations seem affected (Franks *et al.* 2018; Samplonius *et al.* 2021; Nater *et al.* 2023). The ability to adapt to such changes may also depend on the cues that trigger migration - if these are uncorrelated with conditions in the breeding range, departure times may not change reducing the flexibility of populations to respond (Davies *et al.* 2023).

8.3 Adaptations and Responses

8.3.1 Timing of migration and breeding

Temperature, in particular, positively influences the timing of breeding and spring arrival, although these effects can be modified by more local weather conditions en route. **(HIGH CONFIDENCE)**

Earlier arrival, and breeding, of migratory passerines in Europe is one of the most well-documented impacts of climate change (Pearce-Higgins & Green 2014; Haest *et al.* 2020), although not all species are doing so (Davies *et al.* 2023).

As migratory birds often breed later than their resident competitors, they are thought to be at higher risk of the detrimental effects of being mistimed. However, robust evidence of widespread demographic effects is lacking, despite vast amounts of research among a small number of resident (Great Tit) and migratory (Pied Flycatcher) species (Samplonius *et al.* 2021).

8.3.2 Distribution and range shifts

Migratory passerines are shifting/expected to shift pole-ward in both their breeding and wintering grounds, though the Sahara presents a barrier for those north of the Equator in their African wintering grounds. **(MEDIUM CONFIDENCE)**

In northern Europe, the range edges of resident bird species have shifted further north than the range edges of long-distance migrants (Hällfors *et al.* 2023). As an example, Reed Warblers, which breed primarily in reedbeds, and whose productivity is related to the rate of growth of reeds (which is often constrained by lower than optimum temperatures), are expanding their range northwards as temperatures increase (Eglington *et al.* 2015). Six species, none of which breeds primarily in reedbeds, in this study showed no change.

It has been predicted that 37 of the 64 long-distance Afro-Palearctic migratory passerines studied will experience a winter range reduction by 2100; those wintering in the southern hemisphere will shift pole-ward, while those north of the Equator will shift east due to being limited to the north by the Sahara (Barbet-Massin *et al.* 2009).

Documented changes in migratory routes are few and are likely, initially at least, to involve only part of the population (as has been seen in shorebirds and waterfowl), which may be difficult to detect. However, new range areas can be established as (boreal winter) temperatures have increased (Dufour *et al.* 2021).

9 Aves: South American grassland birds

9.1 Overview of migration patterns & distributions

There are 288 grassland bird species in South America as a whole, 16% of which are migratory- including those that migrate to North America (Chesser,1994; Vickery *et al.* 1999). However, the proportion of migratory species (30%) within the temperate grasslands of south-eastern South America is higher (Azpiroz *et al.* 2012; Jahn *et al.* 2017). Of these species which migrate within South America, six are classified as ‘Globally Threatened’ and a further six as ‘Near Threatened’. A range of migration strategies are observed, with species migrating either between temperate and tropical ecosystems, or solely within tropical ecosystems and some movements are more nomadic, tracking the availability of grass seeds (e.g. Pearce-Higgins 1996). Research on these species directly is limited, so we refer to species in other ecosystems to make inferences.

9.2 Climate change impacts

9.2.1 Alteration in patterns of precipitation

Tropical systems tend to be rainfall, rather than temperature-limited, and therefore the strongest climate change impacts on tropical migratory passerines are likely to be through changes in precipitation patterns, which are mixed, depending on location **(LOW CONFIDENCE)**

In semi-arid systems, rainfall has a positive impact on the breeding success of a range of North American sparrows (Rotenberry & Wiens 1991; Chase *et al.* 2005), likely mediated through the effects on vegetation growth and invertebrate abundance. In wet years, a greater number of nests are produced, increasing the length of the breeding season (Chase *et al.* 2005; Dean *et al.* 2009). There is a similar relationship for Little Bustard in Spain (Delgado *et al.* 2009).

In similar ecosystems in Africa, studies of the granivorous Red-billed Quelea support the importance of precipitation in driving grassland bird populations. Rainfall stimulates new grass growth and rapid increases in invertebrate (caterpillar and Orthoptera nymphs) abundance, leading the birds to breed. As soon as the young fledge, the adults move along an advancing rain-front to breed again. Six weeks after the rainfall ceases across the species’ range and the birds have stopped breeding, they nomadically track grass seed availability and move ahead of the next rain front which causes the remaining seeds to germinate and the whole cycle starts again (Ward 1971, Cheke *et al.* 2007).

9.2.2 Increased temperatures

There is growing evidence that extreme heat can have negative impacts on tropical species through sudden and catastrophic mortality. This does not appear to result from drought, but from physiological responses to heat stress. **(LOW CONFIDENCE)**

Recent heat waves have led to significant mortality in desert species such as Budgerigars, Zebra Finches and Carnaby’s Black Cockatoos (Albright *et al.* 2017; Saunders *et al.* 2011; Low 2011; McKenchie *et al.* 2012).

Studies from similar habitats in Africa indicate that high temperatures mean individuals spend more time keeping cool, reducing foraging opportunities and impacting breeding success in a range of bird species (van de Ven *et al.* 2020; Bourne *et al.* 2020; Bladon *et al.* 2019). It is possible that this could also be an issue for South American passerines depending on the magnitude of future warming, but we are not aware of any research on this.

Even where the risks of mass mortality are low, chronic, sub-lethal impacts of rising temperatures are projected to cause population declines (e.g. Kalahari; Conradie *et al.* 2019).

10 Mammalia: Terrestrial mammals

10.1 Overview of migration patterns & distributions

There are three ape species (Eastern and Western Gorillas and Chimpanzee), which are ‘technical’ migrants, crossing range state boundaries but only by moving relatively short distances), one bear species (Gobi Bear), three elephant species, six carnivores and 32 ungulates (14 African, 16 Asian and two South American species) listed on the CMS Appendices. Importantly, there are a number of widespread migratory terrestrial mammals that occupy temperate and boreal habitats which are not listed in the CMS appendices, such as Caribou, Elk and Bison. Literature for the impacts of climate change of these species have not been reviewed unless the impacts were more general to other similar species that are on the CMS appendices. For most terrestrial mammals, migration is driven by availability of food or water, often linked to rainfall which affects primary productivity (e.g. ungulates: Kauffman *et al.* 2021; African Elephants: Owen-Smith 2014).

Habitat loss due to increasing human activities is probably the biggest threat to most migratory terrestrial mammals with a second major threat being the increasing barriers that prevent ungulates from migrating to follow seasonal food resources, such as increases in human infrastructure, fences and loss of habitat corridors. Illegal hunting is also an important threat for some species.

10.2 Climate change impacts

10.2.1 Alteration in patterns of precipitation

Changes in rainfall patterns are likely to have a significant impact on many terrestrial mammal populations, particularly in the tropics given strong links between rainfall, primary productivity and food resources. **(HIGH CONFIDENCE)**

Across Africa there are rainfall declines predicted over much of the Sahel region, northern Africa and western equatorial Africa, but increases over parts of eastern and southern Africa (Martínez-Freiría *et al.* 2016; Bush *et al.* 2020), and similarly for the Middle East (Lelieveld *et al.* 2012). Declines in rainfall are likely to cause declines in many terrestrial mammal populations due to the link between rainfall and primary productivity and thus food availability for herbivores (e.g. ungulates: Bastille-Rousseau *et al.* 2016; Mukhopadhyay *et al.* 2019; Giraffe: Owen-Smith *et al.* 2005; Ogutu *et al.* 2008; Duncan *et al.* 2012; Martínez-Freiría *et al.* 2016; Grevy’s Zebra: Kigen *et al.* 2013; Goitered Gazelle: Kaky *et al.* 2023; elephants: Boult *et al.* 2019; Dejene *et al.* 2021). These impacts will be strongest at low latitudes (Pearce-Higgins *et al.* 2015b).

In turn this has the potential for impacts on carnivore populations that prey on such species (Lion: Celesia *et al.* 2010; Leopard: Rodriguez-Recio *et al.* 2022; Sanderson *et al.* 2022; Zeng *et al.* 2022).

Conversely, for some species, declines in rainfall are positive or have little impact. Wild Dog pup survival declines in wet periods (Buettner *et al.* 2007) and Gorillas are more stressed in months with high rainfall (Eckardt *et al.* 2019).

Rainfall patterns also impact some Great Ape populations, with areas of high annual rainfall and high seasonal variation in rainfall generally supporting high ape populations (Carvalho *et* *al.* 2021). However, the impacts are minor compared to the impact of human disturbance and temperature (Ginath Yuh *et al.* 2020; Carvalho *et al.* 2021).

10.2.2 Increased Temperatures

Rising temperatures can cause heat stress impacting productivity and are generally linked to population declines **(HIGH CONFIDENCE)**, *but may benefit some populations in cold environments by reducing the risk of higher mortality linked to severe cold* **(LOW CONFIDENCE)**

Terrestrial mammal species are generally adapted to a species-specific temperature range (Zhou *et al.* 2022; e.g. Goitered Gazelle: Kaky *et al.* 2023; Grevy's Zebra: Kigen *et al.* 2013; Asian Elephant: Kanagaraj *et al.* 2019; African Elephant: Mpakairi *et al.* 2020; Dejene *et al.* 2021; Chimpanzee: Wessling *et al.* 2020). Temperature increases are predicted globally, which can increase terrestrial mammal stress (Gorilla: Eckardt *et al.* 2019), reduce reproductive success (Wild Dog: Woodroffe *et al.* 2017; McNutt *et al.* 2019; Abrahms *et al.* 2022) and decrease populations (e.g. Giraffe: Martínez-Freiría *et al.* 2016; Huemel: Riquelme *et al.* 2020; Great Apes: Carvalho *et al.* 2021; ungulates: Luo *et al.* 2015).

This can be due to difficulties thermoregulating (African Elephant: Dunkin *et al.* 2013; Pontzer *et al.* 2020; ungulates: Semenzato *et al.* 2021; Wild Dog: Woodroffe *et al.* 2017; Rabaiotti *et al.* 2019) and because of the impacts on the availability of food plant species (e.g. Gobi Bear: Qin *et al.* 2020). Behavioural adaptations can mitigate some temperature increase, such as foraging earlier and later in the day and with altitudinal shifts (e.g. ungulates: Semenzato *et al.* 2021).

Higher temperatures can improve hunting success for some carnivores as prey species struggle to thermoregulate when being hunted (Wild Dog: Creel *et al.* 2016).

There are some instances where warming climates could benefit terrestrial mammals. For example, in colder regions across Asia, very severe winters can reduce fecundity and cause mass mortality events for species such as the Saiga Antelope (Coulson *et al.* 2000) and Przewalski's Horse (Kaczensky *et al.* 2011). Any lessening in the frequency of extreme winters may be beneficial. However, while average temperatures will increase, an increase in extreme weather events is also predicted, so it is uncertain whether winter mortality will increase or decrease.

10.2.3 Extreme weather events

Where droughts are projected to increase in severity and frequency, they are likely to negatively impact populations of migratory mammals. Heavy rain and flooding can cause localised impacts, but generally appear to have weak population impacts. **(MEDIUM CONFIDENCE)**

Floods may increase in frequency and severity in some areas and can increase mortality as habitat is lost to the flood (Lion cub mortality: Kotze *et al.* 2021) while some carnivore populations are relatively resilient to floods (Jaguar: Burrage *et al.* 2020).

Rainfall declines around the Sahara and the Middle East are likely to lead to increased mortality and local carnivore extinctions (Leopards: Khorozyan *et al.* 2015; Lions: Cooper *et al.* 2021), although some carnivore populations are fairly resilient to droughts (Jaguar: Burrage *et al.* 2020; Lions: Ferreira *et al.* 2021).

Increased levels of drought have been implicated in a rise in the prevalence of mass mortality events. For example, over 300 African Elephants have recently died in Botswana as a result of biotoxins produced by cyanobacteria in drinking water, triggered by extremes of hot, dry weather (Wang *et al.* 2021).

Droughts have also been linked to increases in parasite loads in African Elephants and lions, as more individuals rely on limited water resources (Munson *et al.* 2008; Obanda *et al.* 2011; Titcomb *et al.* 2021) and an increased prevalence of infectious diseases in Asian Elephants (Mumby *et al.* 2013).

Droughts are also linked to increasing human-wildlife conflicts, for example for African and Asian Elephants, which can lead to increased mortality (Mariki *et al.* 2015; Mukeka *et al.* 2019; Ramesh *et al.* 2022).

10.2.4 Habitat loss

The combined changes in rainfall and temperatures are predicted to cause habitat loss in many species, generally due to reductions in food availability. For some species, particularly those with ranges that are heavily restricted by human activities and land-use, direct climate change impacts on distribution may be hard to discern. **(MEDIUM CONFIDENCE)**

Climate change is predicted to cause severe habitat loss for ungulates on the Tibetan Plateau (Luo *et al.* 2015), Iranian Leopards (Sanei *et al.* 2011; Ebrahimi *et al.* 2017; Ashrafzadeh *et al.* 2019), many Great Ape populations (Lehmann *et al.* 2010; Junker *et al.* 2012; Sesink Clee *et al.* 2015). Brown bears, the species that Gobi Bears are a subspecies of, are also predicted to lose habitat due to climate change (Su *et al.* 2018; Penteriani *et al.* 2019; Dar *et al.* 2021; Ara *et al.* 2022).

Lion ranges are predicted to be relatively stable, but losses are predicted for southern Africa and West Africa (Peterson *et al.* 2014).

In some countries, suitable Asian Elephant habitat is predicted to decline by the end of the century or earlier due to climate change (Alamgir *et al.* 2015; Li *et al.* 2019). However, other studies have predicted climate change to have a minimal impact on Asian Elephants (Kanagaraj *et al.* 2019; Yang *et al.* 2022b).

The effect of climate change on habitat suitability for African Elephants is less clear. One study predicted only small effects, with a slight improvement in climatic suitability in southern and eastern Africa and reduction in western Africa and northern portions of central Africa (Zacarias & Loyola 2018). Another study predicted a 40% temperature-driven habitat loss in an area in southeast Africa (Mpakairi *et al.* 2020).

More generally, where habitat is lost due to climate change, interactions between mammals, humans and livestock are likely to increase which increases diseases in migratory mammals (e.g. Great Apes: Patz *et al.* 2000; Wild Dog: Rabaiotti *et al.* 2021).

10.3 Adaptations and Responses

10.3.1 Distribution and range shifts

Pole-wards *range shifts have been observed and predicted. However, the ability of terrestrial mammals to shift their ranges in response to climate change is often unknown and may be restricted by lack of suitable habitat within areas of suitable climate and barriers that prevent range shifts* **(MEDIUM CONFIDENCE)**

Some species have already shifted their ranges pole-wards or to increasing altitudes (Bai *et al.* 2022), while pole-wards range shifts are predicted for others (e.g. Chimpanzee: Wessling *et al.* 2020; Asian Elephants: Kitratporn & Takeuchi 2022). However, the ability of species to shift their ranges in response to climate change is often unknown; for example, Gobi Bears plant food species are predicted to shift range, but the ability of Gobi Bears to follow that shift is unknown (Qin *et al.* 2020). Any range shifts are likely to increase Human-wildlife conflicts (Asian Elephants: Kitratporn & Takeuchi 2022) and may be prevented by a lack of corridors or suitable habitat. For many migratory terrestrial mammals, maintaining and creating protected areas and corridors between them is vital for conserving these species under a changing climate (e.g. bears: Su *et al.* 2018; Mukherjee *et al.* 2021; Ashrafzadeh *et al.* 2022; Dar *et al.* 2022; Asian Elephant: Li *et al.* 2019; Leopard: Liang *et al.* 2022)

10.3.2 Timing of migration and breeding

Some changes in birthing and migration phenology have been seen in migratory mammals, but cues for when to breed may be maladaptive. **(LOW CONFIDENCE)**

For example, Wild Dogs have delayed parturition by 7 days per decade, but this has led to increased temperatures during denning periods, which reduces pup survival (McNutt *et al.* 2019; Abrahms *et al.* 2022)

11 Mammalia: Migratory bats

11.1 Overview of migration patterns & distributions

Bats are the second largest group of mammals, with over 1400 species described, but the biology of most is poorly known. There are at least 87 species of migratory bats (Krauel & McMracken 2013), of which 58 species are listed within the CMS appendices. There is some long-distance migration (<500km) to hibernacula in European species (Hutterer *et al.* 2005), however long-distance migrants from temperate regions more often travel to winter in milder climates where food is available (Fleming & Eby 2003). Short-distance migration (100-500 km) also occurs within temperate regions as bats move to and from hibernacula sites where they overwinter (Rodrigues & Palmeirim 2008). In tropical and subtropical regions, migration movements are generally in response to the availability of ephemeral food resources (Fleming & Eby 2003).

11.2 Climate change impacts

11.2.1 Increased temperatures

Changes in temperature are likely to affect foraging efficiency and flight behaviour with uncertain consequences for populations **(LOW CONFIDENCE)***. Warming may also affect the abundance of key invertebrate prey in different and contrasting ways, with variable impacts on bat populations, depending on diet, taxa and climate change context* **(LOW CONFIDENCE)***.*

The impacts of temperature increases on bats is currently best described for changes in hibernation behaviour, but impacts on overall population status are not well understood. In the UK, increasing temperatures and decreasing precipitation in spring have had a positive effect on the population size of Greater Horseshoe Bat (Froidevaux *et al.* 2017). It is also suggested that populations of both Greater and Lesser Horseshoe Bats in the UK have recovered over the past 20 years due to milder winters (Battersby 2005; Schofield 2008). Analyses of the impacts of climate changes on UK bat populations more generally suggested the potential for some negative impacts on some species, but noted these were inconclusive and inconsistent (Martay *et al.* 2017).

An overall increase in body size in female Bechstein's Bats with increased temperatures has advanced the onset of reproduction and increased mortality risk, causing a change in the generation time (Mundinger *et al.* 2022).

More frequent winter bat activity with increased temperatures may result in the potential disappearance of a hibernation period over the next 60-80 years on the Mediterranean coast (Mas *et al.* 2022). The study highlights the importance of conserving wetlands as one of the few available winter foraging habitats.

Temperature changes may alter foraging efficiency and flight behaviour in different ways among species. Temperature impacts the distance at which insects can be detected using echolocation, with differing effects depending on the frequency of the call; this suggests that global warming may alter foraging efficiency in different ways for species with different echolocation frequencies (Luo *et al.* 2014).

Heat dissipation and evaporative water loss in migratory and high-altitude flying bats are likely to increase with increasing temperatures and decreasing humidity. Drinking frequency increases with temperature/decreases with humidity (Adams & Hayes 2008), as such changes in temperature/humidity are predicted to increase the frequency at which high-altitude flying bats return to the ground to drink or alter the aerial layers in which they can forage (Voigt *et al.* 2018).

Warmer temperatures and summer drought conditions may reduce the abundance of aerial insects, with potential consequences for the availability of aerial insects, which are the primary food source for bats. The impacts of climate change on insect migrations are likely to indirectly affect migratory insectivorous bats, though the consequences are currently unknown (Voigt *et al.* 2018). More generally, large-scale declines in the biomass of aerial insects have been reported in Europe (e.g. Hallman *et al.* 2017), although the causes and even the extent of the decline are debated. Declines in moth populations in the UK may partly be attributed to warming (Martay *et al.* 2017), although trends in other aerial insects appear mixed (Martay *et al.* 2023). There is good evidence that summer drought will reduce the abundance of aerial insects with aquatic life-stages such as many Diptera (Pearce-Higgins 2010, Pearce-Higgins & Morris 2022). However, the impacts of any changes in insect populations on bats are highly uncertain based on current knowledge.

11.2.2 Reduced water availability

Reduced water availability and drought can reduce breeding success, migration and competitive dynamics amongst species. **(LOW CONFIDENCE)**

Breeding success decreases when water availability is low during lactation (Adams 2010; Adams & Hayes 2008). The effect of reduced surface water availability on breeding success as climate change progresses is predicted to negatively impact population size (Hayes and Adams 2017).

Changes in water availability paired with changes in heat dissipation/evaporative loss are likely to have negative consequences for migratory bats as they require water along the migratory route (Popa-Lisseanu & Voigt 2009).

Reductions in the sizes of water sources are likely to negatively impact less manoeuvrable bat species as they are less able to drink efficiently (Hall *et al.* 2016); this is expected to provide a competitive advantage to more agile species.

11.2.3 Extreme weather events

The response of bat populations to extreme events is usually negative, either in terms of range contraction or population reduction. **(MEDIUM CONFIDENCE)**

Extreme heat weather events can reduce survival and breeding success, particularly in flying foxes (*Pteropus* spp), though responses differ among species. Heatwaves and drought in India cause mass die-offs in Indian Flying Fox (Dey *et al.* 2015). Extreme heat (42°C) has also caused mortality of wild flying foxes in Australia.In 2002, over 3,500 individuals were killed in one day, and over 30,000 individual bats have been reported dead across 19 events from 1994 to 2007 (Welbergen *et al.* 2008). More recent mortalities have been even larger (e.g. https://www.animalecologylab.org/flying-foxes--extreme-heat.html). Variation in the vulnerability of different *Pteropus* spp. may be linked to the thickness and depth of their fur (Ratnayake *et al.* 2020).

High temperatures may also impact other bat species. Breeding success of Soprano Pipistrelle in the Mediterranean is reduced when available maternity roosts overheat due to extreme temperatures (Lourenço & Palmeirim 2004).

Cold-related mortality can also impact bats, and would be expected to reduce in a warming climate. During an extreme winter in Germany, two bat species, Daubenton's and f Bechstein’s Bats, experienced a substantial population crash (Reusch *et al.* 2019; Fleischer *et al.* 2017), whilst another, Natterer's bat, only showed a small decline (Reusch *et al.* 2019).

11.2.4 Human responses to climate change

Wind turbines pose a substantial threat to many bat species and have been shown to be a major cause of mortality. **(HIGH CONFIDENCE)**

The families Molossidae, Rhinolophidae and Vespertilionidae (representatives of all of which are listed on CMS Appendix II) have been identified as being among the most vulnerable to wind-farm collisions (Zimmerling & Francis 2016; Thaxter *et al.* 2017), often with levels of mortality exceeding those of birds. Migratory species and those which roost in trees appear to be particularly vulnerable in North America (Cryan *et al.* 2014; Zimmerling & Francis 2016), but non-migratory species in South Africa (Aronson 2022). Mortalities may vary with age (Kruszynski *et al.* 2022).

Evidence suggests that the use of particular wind farm designs, turbine sizes and capacity, and locations may be able to reduce the risk of large-scale mortality (Thaxter *et al.* 2017; MacGregor & Lemaître 2020), as well as curtailing turbines during sensitive periods (Squires *et al.* 2021) or at lower wind speeds (Arnett *et al.* 2010).

11.3 Adaptations and Responses

11.3.1 Distribution and range shifts

Range expansions and shifts towards higher latitudes have been observed in a few species and are predicted for many more. **(MEDIUM CONFIDENCE)**

The distribution range of bat species is often heavily influenced by temperature, though precipitation can also have some impact (Ancillotto *et al.* 2016; Lundy *et al.* 2010). Range expansions and shifts towards higher latitudes have been observed in a few species, e.g. Kuhl's Pipistrelle (Sachanowicz *et al.* 2006; Ancillotto *et al.* 2016), Savi's Pipistrelle (Ancillotto *et al.* 2018), Nathusius' Pipistrelle (Lundy *et al.* 2010) and Brazilian Free-tailed Bat (McCracken *et al.* 2018) and are predicted for many more (Rebelo *et al.* 2010), although accurate knowledge of distributions is missing for many species. However, the disappearance of a species from regions within their historic distribution receives more support to date through predictive modelling rather than observed records (Arumoogum *et al.* 2019; Razgour *et al.* 2021; Festa *et al.* 2023).

The latitudinal shift of hibernacula in Noctule Bats is suggested to be the result of generational shifts to new locations, driven mostly by first-year males (Kravchenko *et al.* 2020).

Range shifts may have important consequences for trophic interactions with both bottom-up and top-down impacts; for example, Greater Long-nosed Bats are an important pollinator of agave plants which are in turn a food source for the bats, however, the distribution overlap between them is predicted to reduce by 75% in the next 50 years (Gómez-Ruiz & Lacher 2019).

Increasing spring temperatures can variably affect the migratory behaviour and distribution of different species. For example, the thermal response of *Myotis* bats' downhill migration in the Rocky mountains (following hibernation) varies among species; in some cold-adapted species, increased temperature correlates with reduced downhill migration (Adams 2018), indicating a temperature-driven shift in distribution.

11.3.2 Timing of Migration

The results of studies to date suggest the timing of migration in bats is more affected by weather conditions, such as precipitation and wind, than temperature. **(LOW CONFIDENCE)**

Some bat species are able to change the timing of migration in response to wind conditions and precipitation, though not all species show a response to environmental conditions. For example, the timing of spring migration has advanced by 16 days over 22 years in Brazilian free-tailed bats; this shift is predominantly driven by the wind conditions at stopover areas during the migration period and not by temperature. The autumn migration was also unaffected by temperature and driven more by precipitation levels (Haest *et al.* 2021; Stepanian & Wainwright 2018).

Photoperiod was the best predictor of migration timing for Natal Long-fingered Bats in South Africa, compared to a range of environmental variables, which may make them vulnerable to phenological mismatch as climate change progresses (Pretorius *et al.* 2020).

12 Mammalia: Marine mammals

12.1 Overview of migration patterns & distributions

Most marine mammals are highly pelagic (i.e. in open ocean), although the pinnipeds (seals, sea lions and walruses) retain a link to land, meaning that most occur extensively in areas beyond national jurisdiction (Lascelles *et al.* 2014). They are distributed throughout the world's oceans and most are highly migratory, leading to large transfers of biomass between latitudes. They are highly dependent on patterns of marine productivity and their abundance is highest where marine primary productivity is high, e.g. around deepwater and coastal upwelling zones. Most are carnivorous, with species taking a range of prey, from amphipods, to large fish and other marine mammals; sirenians are herbivorous.

15% of marine mammals are currently classified as threatened (i.e. classified by the IUCN as Endangered or Vulnerable). They face a wide range of threats, including fishing, pollution and disturbance from human activities (which includes adaptation to climate change through marine renewables developments). Thirteen percent (65 of 480) of “Level 1” threats (as defined by IUCN) to marine mammals are assigned to climate change or severe weather events (Lascelles *et al.* 2014).

There are 130 marine mammals, of which 90 are listed on the Appendices of CMS. Marine mammals can be split into several broad groups:

- Pinnipeds, the seals, sea lions and walruses (6 CMS species)
- Baleen whales such as Bow, Blue, Grey, Fin, Northern Right, Southern Right and Humpback Whales, of which 13 are CMS species. Most baleen whales undertake long seasonal migrations between tropical calving grounds in winter and high latitude (north or south) feeding grounds in summer (Learmonth *et al.* 2006).
- Toothed whales, including dolphins (32 CMS species), porpoises (7 CMS species) and other whales (25 CMS species). Dolphins and porpoises generally undertake shorter migrations between their summer and winter ranges, while Arctic species, such as Narwhal and Beluga migrate seasonally to follow food resources and access breeding areas.
- Sirenians, encompassing the three manatee species and the Dugong, are all CMS listed species, and are mostly coastal species that undertake shorter distance migrations
- Polar bears are largely land or ice-based, but are largely reliant on marine species as prey, hence their inclusion as marine mammals. Their migration is seasonal, following the sea-ice.
- Otters, of which the two CMS species are coastal species that seasonally follow food resources. There is very little research on climate change impacts for migratory otters.

12.2 Climate change impacts

12.2.1 Increased temperatures

Temperature increases are likely to have a major impact on marine mammal populations indirectly via changes to food availability. (**HIGH CONFIDENCE)**

Marine mammal distribution, abundance and breeding success are often closely linked to prey availability (e.g. population declines are linked to prey declines in South American Sea Lion: Baylis *et al.* 2015; distribution of Minke and Killer Whales: Albrecht *et al.* 2021, Vogel *et al.* 2021). Krill and other copepod are important for many baleen whales (e.g. Blue Whale: Szesciorka *et al.* 2020; Blue, Bowhead and North Atlantic Right Whale: Silber *et al.* 2017; Humpback Whale: Keiper *et al.* 2005; breeding success in Southern Right Whale and Antarctic Fur Seals: Simmonds & Isaac 2007; Bestley *et al.* 2020). Baleen whale populations are generally predicted to decline due to declines in krill abundance (Learmonth *et al.* 2006). In particular population declines are predicted for Blue, Fin, Southern Right and Humpback Whale, particularly at mid- and lower-latitudes (Learmonth *et al.* 2006; Kaschner *et al.* 2011; Tulloch *et al.* 2019; Frankel *et al.* 2022).

Declines in Antarctic krill have also been linked to increased ocean acidification from increased CO_2 (Kawaguchi *et al.* 2013).

Increasing temperatures are generally linked to declining krill abundance (Simmonds & Isaac 2007; Tulloch *et al.* 2019), particularly in latitudes 50–60°S (Tulloch *et al.* 2019) as observed in the east Pacific (Szesciorka *et al.* 2020). Temperature increases, causing reduced food availability, are linked to reductions in Humpback Whale abundance and breeding success (Frankel *et al.* 2022) and are predicted to reduce populations of Blue, Fin, Southern Right and Humpback Whale (Tulloch *et al.* 2019).

Temperature increases may have a direct impact on reproductive success for some species, although this relationship may be mediated by unidentified factors such as prey availability. Examples include a strong relationship between Southern Right Whale calving success and temperature (Simmonds & Isaac 2007) and a link between warmer temperatures and low mortality in Bottlenose Dolphins observed in the northern Gulf of Mexico (Meager & Limpus 2014).

Marine mammals reliant on upwelling boundary currents (e.g. rorqual whales; López & Methion 2019) are likely to be particularly vulnerable to climate change (Nelms *et al.* 2021).

12.2.2 Reduced sea ice extent

Sea ice decline and increased variability in cover in response to climate change will generally negatively impact on population size for species associated with sea ice, but may accelerate the pole-ward range expansion in species associated with open water. **(HIGH CONFIDENCE)**

Sea ice declines are particularly detrimental to population sizes (Stirling & Parkinson 2006; Bromaghin *et al.* 2021), survival (Molnár *et al.* 2010; 2020), body condition (Derocher *et al.* 2004; Stirling & Parkinson 2006) and reproductive success (Peacock *et al.* 2011) of Polar Bears. Their main prey, seals, rely on sea ice for breeding, so declines in (mostly non-migratory) seal populations have been observed and reductions in the areas of suitable hunting habitat (Bromaghin *et al.* 2015) have led bears to undertake increasingly long migrations compromising their survival (Pagano & Williams 2021).

Sea ice declines have a mixed impact on krill. Declines may increase primary productivity in some areas, increasing both food density and the seasonal availability of food for those that feed on krill (Laidre *et al.* 2008; Simmonds & Isaac 2007; Tulloch *et al.* 2019). This has benefitted some species (e.g. arctic Bowhead Whale population growth and better body condition may be linked to low summer sea ice: George *et al.* 2015; Laidre *et al.* 2008). In contrast, in other areas, sea ice declines were linked to declines in abundance of krill (Truchon *et al.* 2013) and other prey species, for example, the density and distribution of Arctic Cod are predicted to decline due to sea ice reduction (Steiner *et al.* 2019).

Seal and sea lion species that are reliant on sea ice for breeding may be particularly vulnerable to climate change (Tynan & DeMaster 1997; Bestley *et al.* 2020). The Caspian and Grey Seals are the only CMS species that regularly breed on ice.

Sea ice declines may reduce shelter from predation (Minke Whale declines have been partly linked to sea-ice declines due to lack of shelter from predators: Risch *et al.* 2019). Ice entrapments for Beluga Whales and Narwhals may increase due to increasing variability in sea ice (Laidre *et al.* 2008).

Sea ice declines open the Arctic and Antarctic to migratory species earlier, leading to phenology shifts and greater use of polar regions by species that are less ice adapted, such as Humpback, Fin, Minke, Grey, Blue, Pilot and Killer Whales and Harbour Porpoises (Laidre *et al.* 2008; Moore & Huntington 2008; Bestley *et al.* 2020). Humpback Whale migration from Central and South America to the Antarctic peninsula has advanced by nearly 30 days in 30 years and populations appear to be increasing (Avila *et al.* 2020). Earlier migration may lead to increased competition and predation for Arctic species (Laidre *et al.* 2008).

Increases in human activity in the Arctic enabled by sea ice loss may increase levels of toxic chemicals, pollution, boat strikes, increase noise pollution (which has been shown to alter migration in Bowhead Whales and other cetaceans), and increase fisheries interactions (entanglement in fishing gear is common) (Burek *et al.* 2008). Concentrations of persistent organic pollutants in samples taken from Polar Bears are increasing due to prolonged fasting periods (due to sea ice decline) and may be causing adverse health effects (Jenssen *et al.* 2015). Fishing-related mortality has been identified as the major cause of the decline in South American Sea Lions in Uruguay (Prado *et al.* 2016). Conversely, traditional hunting of marine mammals is likely to reduce because of dangerous sea ice conditions.

Narwhals (most vulnerable), Beluga and Bowhead Whales are predicted to be particularly vulnerable to climate change due to decreasing habitat availability and increased competition from sub-Arctic species expanding their range northwards (Learmonth *et al.* 2006; Simmonds & Isaac 2007; Laidre *et al.* 2008; Moore 2008; Chambault *et al.* 2020; van Weelden *et al.* 2021). However, population declines in Arctic marine mammals have not been documented to date (Huntington *et al.* 2017). Arctic Bowhead Whale populations were increasing from 1978-2001 (some of which could reflect recovery from past over-harvesting) and had better body condition in low sea ice years (George *et al.* 2015; Laidre *et al.* 2008). There was some evidence that changes in Beluga Whale habitat selection can mitigate some effects of sea ice loss (Hauser *et al.* 2018).

12.2.3 Sea-level rise

Sea-level rise will reduce habitat availability for some coastal breeding seals **(MEDIUM CONFIDENCE)**

Seals that breed on limited patches of specific habitats will be particularly vulnerable to climate change (Bestley *et al.* 2020) and coastal habitats are also likely to be lost due to sea level rises (Simmonds & Isaac 2007).

12.2.4 Frequency of extreme weather events

Increase in storms and freshwater flooding can impact vulnerable coastal habitats, detrimentally affecting populations that rely on them, particularly for coastal species such as inshore dolphins and dugongs*.* **(LOW CONFIDENCE)**

Freshwater floods and coastal storms threaten and reduce seagrass productivity which has been linked to high mortality of inshore dolphins and dugongs (Meager & Limpus 2014), and reduced reproductive success and survival in the North Atlantic Right Whale (Lanyon & Burgess 2019).

12.2.5 Changes in ocean circulation

Changes in the frequency and intensity of El Niño/La Niña events will have significant impacts on marine mammal distribution and mortality but impacts will vary between species and locations **(HIGH CONFIDENCE)**

Oceanic weather systems events such as El Niño and La Niña are predicted to increase in frequency and intensity (McPhaden *et al.* 2020) and have a big influence on marine mammal distribution (Keiper *et al.* 2005), generally due to changes in food availability. There is low food availability for Subantarctic Fur Seal in years with La Niña events (Prado *et al.* 2016), there was almost complete mortality of Northern Fur Seal pups in an extreme El Niño year (Keiper *et al.* 2005) and low calving rates in North Atlantic Right Whale associated with NAO index shifts (Simmonds & Isaac 2007). However, some dolphins have expanded their ranges in El Niño years and retained the expansions in other years (Simmonds & Isaac 2007).

Strandings increase in response to prey declines (e.g. Subantarctic Fur Seal strandings are highest in La Niña years when food availability is low: Prado *et al.* 2016; high stranding events of Beluga and Minke Whales were seen in years with low krill abundance: Truchon *et al.* 2013). Strandings of marine mammals are associated with large-scale oceanic events more widely, although effects vary between species: strandings of Atlantic White-sided Dolphin and the Minke Whale were negatively and positively correlated with the previous year NAO index respectively, while stranding numbers of Beluga Whales were positively correlated with the previous winter NAO index (Truchon *et al.* 2013). The frequency of stranding events is predicted to rise due to climate change (van Weelden *et al.* 2021).

12.2.6 Toxins, parasites and disease

Temperature increases have been associated with increased mortality as a result of toxic algal blooms, disease and elevated parasite levels **(LOW CONFIDENCE)**

Climate change may increase or change the frequency and distribution of toxic algal blooms, probably due to increased temperature, micronutrient availability and changes in salinity (Burek *et al.* 2008). High rates of strandings across many species are associated with toxic algal blooms, e.g. Harbour Porpoise and Minke Whales (Truchon *et al.* 2013).

Infectious diseases and parasites in marine mammals have also increased over the last 30 years, linked to temperature increases and sea ice declines (Burek *et al.* 2008, Sanderson & Alexander 2020; Pilfold *et al.* 2021). Mass mortality events caused by disease have increased, particularly in pinnipeds (seal and sea lions) (Burek *et al.* 2008; Sanderson & Alexander 2020) but other examples include Mediterranean Striped Dolphins in the 1990s (Simmonds & Isaac 2007).

12.3 Adaptations and Responses

12.3.1 Distribution and range shifts

Range shifts have been observed in many species, with consequent declines in polar species and increases in subtropical and tropical species **(HIGH CONFIDENCE)**

Most marine mammals are relatively able to adapt their ranges in response to changes in temperature and food availability (e.g. pole-ward range shifts seen in sub-Arctic whales: van Weelden *et al.* 2021; Common Dolphins, White-beaked Dolphins, Harbour Porpoises, Sperm Whale: Simmonds & Isaac 2007; Dall's Porpoise: Keiper *et al.* 2005). There is evidence of historic and prehistoric climate-associated range shifts in whales, walruses, Narwhals, Common Dolphins and Harbour Porpoise (Laidre *et al.* 2008; Fontaine *et al.* 2010; Amaral *et al.* 2012).

In general, decreases in pinniped (seal and sea lion) and cetacean species richness have been predicted at lower latitudes (below 40°), along with increases at higher latitudes (Kaschner *et al.* 2011).

River dolphins, such as the Ganges River Dolphin, and coastal cetaceans and sirenians (manatees and Dugong) are likely to be particularly vulnerable to climate change due to physical constraints and limited patches of habitat (Learmonth *et al.* 2006; Simmonds & Isaac 2007).

12.3.2 Foraging behaviour

Species may alter their diet and foraging behaviour in response to climatic impacts on prey availability, but this may not compensate for losses in key prey **(LOW CONFIDENCE).**

Some species may also be able to adapt foraging behaviour to new prey species (e.g. Humpback Whales, Benson *et al.* 2002; Fleming *et al.* 2016). There is a lot of evidence of Polar Bear diet shifting to include more non-pinniped species such as ground-nesting birds (Prop *et al.* 2015), whales (Rode *et al.* 2022), fish and blueberries (Dyck & Kebreab 2009). However, these food sources are not likely to be sufficient to make up for the reduced availability of seal prey (Petherick *et al.* 2021; Rode *et al.* 2022).

12.3.3 Timing of migration

Changes in the timing of migration have been observed, with many species now arriving on the breeding grounds earlier, but population effects are mostly unknown **(LOW CONFIDENCE)**

Many migratory marine mammals may be able to change their phenology to adapt to changes in food availability and timing of sea ice melt (van Weelden *et al.* 2021). In general, whales that feed in the Antarctic and breed in the tropics now arrive in the tropics earlier (e.g. Humpback and Blue Whales: Avila *et al.* 2020; Ingman *et al.* 2021). Similarly, sub-Arctic breeding whales are now arriving earlier in the Arctic and departing later, as sea ice is present for less of the year (van Weelden *et al.* 2021).

However, as sea ice freeze-up becomes later, Polar Bear migration from land to sea ice has become later, but this risks starvation for cubs so migration cannot be delayed further (Cherry *et al.* 2013; Miller *et al.* 2022). Polar Bears are extremely vulnerable to climate change due to sea ice decline reducing hunting habitat. Populations have undergone large declines (Bromaghin *et al.* 2021) and many sub-populations are likely to go extinct over the next few decades (Castro de la Guardia *et al.* 2013). Some models predict almost complete extinction by 2100 (Hunter *et al.* 2010; Molnár *et al.* 2020).

13 Reptiles

13.1 Overview of migration patterns & distributions

There are seven species of marine turtles, all of which are listed on the CMS appendices, and six of which are listed as Endangered and/or threatened (and Flatback Turtle is listed as Data Deficient). In addition to the marine turtles, the other reptiles listed on the CMS appendices are one freshwater turtle, the Arrau Turtle, and two crocodile species. The majority of research on the climate change impacts on migratory reptiles focuses on marine turtles. Marine turtles are found in all oceans, except polar regions, but typically they nest on tropical and subtropical sandy beaches. They all migrate long distances between feeding and breeding grounds, although migration patterns vary between species and even between populations. Although populations of marine turtles have undergone historic declines as a result of harvesting (of both adults and eggs), mortality through bycatch and habitat loss, the majority of populations now appear to be on an upward trajectory as a result of sustained conservation efforts (Mazaris *et al.* 2017).

13.2 Climate change impacts

13.2.1 Increased temperature

Increasing temperatures are resulting in a higher proportion of female hatchling turtles and crocodiles. **(HIGH CONFIDENCE)**

Turtles and crocodiles have temperature-dependent sex determination (Valenzuela 2001; Hamann *et al.* 2007; Patrício *et al.* 2021) and increases in the female:male hatchling sex ratio, due to increasing temperatures, are being observed (see Poloczanska *et al.* 2009; Santidrián Tomillo & Spotila 2020 for reviews). Changes in operational sex ratios are less well understood (Rees *et al.* 2013) and are context dependent (Roberts *et al.* 2023). They may also be affected by adjacent land-use (Jensen *et al.* 2018). The population-level impact of this is likely to be positive in most populations, as there are still enough males in most populations to fertilise eggs (Perez *et al.* 2016; Santidrián Tomillo & Spotila 2020; Maurer *et al.* 2021). However, in the future, extremely limited male populations could lead to population declines through reduced fertilisation or limited genetic diversity (Mitchell & Janzen 2010) if range shifts are not possible.

13.2.2 Sea-level rise and increased storms

Rises in sea-levels and an increase in the frequency and intensity of storms are causing loss of nesting habitat **(HIGH CONFIDENCE)**

Sea level rises, and an increasing frequency and intensity of storms will cover or inundate some current marine turtle and Salt-Water Crocodile nesting beaches, leading to loss of habitat and embryo mortality (Varela *et al.* 2019), see Poloczanska *et al.* (2009), Fuentes *et al.* (2020), Patrício *et al.* (2021), Dimitriadis *et al.* (2022) and Fukuda *et al.* (2002) for reviews.

In the Mediterranean,over half of nesting sites for Loggerhead and Green Turtles are predicted by 2100 (Katselidis *et al.* 2014; Varela *et al.* 2019; Dimitriadis *et al.* 2022), and similar levels of loss are predicted in the west Atlantic for Loggerhead Turtles (Reece *et al.* 2013). One study predicted a loss of 80% of marine turtle nesting habitat by 2050 in the west Atlantic (Fuentes *et al.* 2020).

Loss of nesting habitat to sea level rise is especially a problem where there are barriers to landward movement, such as cliffs and coastal development (Katselidis *et al.* 2014; Perez *et al.* 2016; Varela *et al.* 2019).

13.3 Adaptations and responses

13.3.1 Distribution and range shifts

Pole-ward range shifts have been observed but are likely to be constrained by anthropogenic pressures in potential new areas, although conservation actions can be targeted in such areas **(MEDIUM CONFIDENCE)**

Range shifts will be the key to marine turtle adaptation to climate change, as they shift their distribution pole-ward in response to warmer temperatures (Perez *et al.* 2016). The major threat that will prevent range shifts is human coastal development and the availability of suitable nesting beaches in new areas (Fuentes *et al.* 2020). Turtles typically return to the beaches they were born to lay eggs, which may limit their ability to shift ranges, but the extent to which this occurs is not clear (Wright *et al.* 2012). There is evidence of Loggerhead turtle range shifts in the Mediterranean Sea (Girard *et al.* 2021) but more research into the ability of sea turtles to shift their ranges is required (Hawkes *et al.* 2009).

Human interventions could include shading beaches e.g. by tree planting (Mitchell & Janzen 2010), preventing coastal development on emerging nest beaches (Girard *et al.* 2021) and translocation of eggs (Hawkes *et al.* 2007).

13.3.2 Timing of migration

Phenology shifts, particularly earlier nesting, may help to prevent extreme sex ratios, if this means that the turtle eggs develop at lower temperatures because of being laid earlier in the season (Laloë *et al.* 2016).

14 Migratory Fish (Actinopterygii)

14.1 Overview of migration patterns & distributions

Many fish migrate to some extent, either within their freshwater or marine environments, or by crossing the two, with anadromous fish, such as salmon, migrating to freshwater areas to breed and catadromous fish, such as eels, migrating to marine areas to breed. Some fish, particularly pelagic species such as tuna, can migrate large distances, and are classified as Highly Mobile Species by the UN Convention on the Law of the Sea. Twenty species are listed on the CMS Appendices, of which 18 species are in the family Acipenseridae (sturgeons), with the other two species being Giant Catfish and European Eel. One species listed on Appendix II, the Chinese Paddlefish, was declared extinct in 2022. Sturgeon live in subtropical, temperate and subarctic rivers and coastal regions of Eurasia and North America. Most migratory sturgeon species live in the ocean for most of their lives but migrate, generally in the spring or early summer, to freshwater rivers and streams to spawn. Some migratory sturgeon, such as the Lake Sturgeon, are freshwater species that migrate from larger lakes and rivers to smaller streams to spawn.

Fish that migrate from oceans to freshwater have experienced dramatic population declines, often declining by over 90% since the 1970s (Limburg & Waldman 2009; He *et al.* 2019). For example, the European Sturgeon has been lost from all European rivers except one; a 99% range reduction (He *et al.* 2019). The main drivers of these declines are habitat loss (especially from damming) and degradation, overfishing and pollution (Limburg & Waldman 2009; Arthington *et al.* 2016; Ruban *et al.* 2019). Climate change represents a ‘key threat’ to migratory fish in less than 10% (31 of 358) of cases (Lascelles *et al.* 2014).

The impact of climate change on fish (not just migratory ones) has recently been reviewed by Dahms & Killen (2023). Pole-ward shifts in distribution were the fastest in tropical populations, and inversely correlated with depth shifts which, in turn, dominated at the trailing edges of population ranges, with niche a key factor influencing responses to temperature change. Temperature, river flow, salinity, oceanic conditions and changes in food webs can all have large impacts on these species, but there is also evidence of adaptability. This makes population-level impacts difficult to predict. However, the evidence suggests that climate change will have increasingly negative impacts on these species.

14.2 Climate change impacts

14.2.1 Increased temperature

Temperature increases are generally associated with reductions in spawning and survival. **(MEDIUM CONFIDENCE)**

Temperature increases in freshwater rivers and streams reduces the dissolved oxygen (Ficke *et al.* 2007) and reduces flow rates as evaporation is increased. The combination of these effects generally reduces the frequency and success of spawning in anadromous fish (Goto *et al.* 2018; Delage *et al.* 2020; Crichigno & Cussac 2022). Spawning generally occurs within a specific temperature window, so for many sturgeon species the spawning season is shortening as temperatures rise (Elisio *et al.* 2015; Limburg *et al.* 2016; e.g. Chinese Sturgeon: Zhang *et al.* 2019; Zhang *et al.* 2021). However in some species and populations warming has increased the spawning window (Domagala *et al.* 2014).

Increasing temperatures can alter fish metabolism, lowering body condition when food availability is low (e.g. Green Sturgeon: Poletto *et al.* 2018) and increasing the toxicity of pollutants (Ficke *et al.* 2007; Grunow *et al.* 2021).

Sturgeon appear to have high physiological adaptability to changes in temperature (Zhang *et al.* 2017; Jay *et al.* 2020; e.g. Siberian Sturgeon: Yang *et al.* 2023). However, cellular stress increased with temperature (e.g. Lake Sturgeon: Wassink *et al.* 2019) which reduced body condition and increased mortality in the long-term (Bard & Kieffer 2019; e.g. Russian Sturgeon: Castellano *et al.* 2017; Lake Sturgeon: Bugg *et al.* 2020).

Temperature increases reduce spawning habitat availability (e.g. Lake Sturgeon: Lyons & Stewart 2014). This has led to reduced populations for many, if not most, migratory fish (Goto *et al.* 2018) and is likely to lead to the disappearance of species at the warm edges of their ranges (Lassalle *et al.* 2010; Kynard *et al.* 2016).

Increasing temperatures may occasionally be favourable, however, high fidelity to natal spawning grounds may limit opportunities for range expansion (Rothermel *et al.* 2020). Increasing temperatures in the Baltic Sea may be favourable for European Sturgeon and it has been suggested this might facilitate re-introduction efforts there, although intensive fishing activities would need to be reduced first (Popov 2017).

Other impacts of temperature increases include increased migration distances and increased competition between juveniles as habitat is lost (Niklitschek & Secor 2005; Goto *et al.* 2018). Sturgeon migration and spawning generally occurs earlier due to rising temperatures (Limburg *et al.* 2016; Delage *et al.* 2020; del Fresno *et al.* 2021), although this can vary between populations (e.g. Lake Sturgeon: Buchinger *et al.* 2022).

Warming generally has a negative impact on fish populations (Pearce-Higgins *et al.* 2015b), and the overall effects of temperature rises are predicted to be detrimental to fish health and populations globally (Huang *et al.* 2021; Levangie *et al.* 2022).

Climate change is likely to have complex impacts on food webs that will impact migratory fish (Ficke *et al.* 2007). Warming sea surface temperatures can cause changes in timing and abundance of plankton blooms, reducing food availability for small fish (Burthe *et al.* 2012).

Increasing temperatures and changes in flow rates are also likely to impact on freshwater food availability although there is little research on this. Prey availability for Green Sturgeon is predicted to decline as temperatures increase (Vaz *et al.* 2015; Zarri & Palkovacs 2019).

In Arctic regions, warming may increase the productivity of inshore marine habitats used by anadromous fishes, but this may be counterbalanced by decreased flows in spawning rivers (Limburg & Waldman 2009).

14.2.2 Reduced flow of rivers

Alterations in river flow will impact populations, with climate-driven reductions in flow rates likely to negatively impact the abundance and breeding success of species. **(MEDIUM CONFIDENCE)**

Climate change will alter river flow patterns and increase the frequency and severity of droughts and floods, which will lessen the frequency of successful reproduction, leading to losses in suitable catchments (Limburg & Waldman 2009; Pfeiffer *et al.* 2021). For example, increased fluctuations in flow in the Volga River is thought to have contributed to declines in reproduction in Beluga and Russian Sturgeon (Ruban *et al.* 2019).

Migratory sturgeon abundance (Hammen *et al.* 2018) and reproductive success (Scarnecchia *et al.* 2019) are likely to be negatively impacted by declines in waterflow in spawning grounds, particularly in the late spring and summer (Limburg & Waldman 2009; Limburg *et al.* 2016). For example, projected declines in May river flow are predicted to increase the extinction risk for many Lake Sturgeon populations (van der Lee *et al.* 2022).

Higher flow rates can also be negative: increased winter flow rates can scour stream beds and damage spawning grounds (Limburg *et al.* 2016). Increased flow can also flush young fish out of rivers before they are physiologically ready for the transition (Limburg *et al.* 2016). High flow rates can also affect food availability: Green Sturgeon prey decreased at higher flow rates (Zarri & Palkovacs 2019).

There is a predicted increase in hurricanes which have been found to cause mass mortality events in Sturgeon. However, recruitment after hurricanes has been found to increase, making long-term impacts difficult to predict (Dula *et al.* 2022).

14.2.3 Increased acidification of water

Increased CO_2 acidifies salt and freshwater but impacts on migratory sturgeon appear to be limited so far **(LOW CONFIDENCE)**

An increase in CO_2 concentrations causes salt and freshwater to become more acidic, which has complex effects on fish physiology and marine and aquatic communities (see Havas & Rosseland 1995; Heuer & Grosell 2014; Nagelkerken *et al.* 2016 & Esbaugh 2018 for reviews). In particular, ocean acidification can reduce the growth of zooplankton (Reynolds *et al.* 2022) which could reduce food availability for sturgeon.

However, migratory sturgeons, at least, appear to be able to adapt to increasingly acidic conditions (Hannan & Rummer 2018) so there is little evidence currently of negative effects and more research is needed.

14.2.4 Changes in salinity

Changes in salinity associated with changes in the flow of freshwater may impact migratory fish, although with uncertain population-level impacts. **(LOW CONFIDENCE)**

Climate change is likely to bring changes in the salinity of estuaries and rivers. Increases in winter river discharge will decrease estuary salinity (Sardella & Kultz 2014), while temperature rises and a reduction in summer rainfall can bring brackish water further upstream in the summer (Breece *et al.* 2013). Increased summer salinity has caused spawning habitat loss in some species (Breece *et al.* 2013).

Green Sturgeon were found to be able to acclimate to salinity changes, but it did cause cellular stress in individuals, making long-term population-level impacts difficult to predict (Sardella & Kultz 2014; Vaz *et al.* 2015).

14.2.5 Changes in ocean currents

Changes in ocean currents may impact their oceanic migration, potentially affecting phenology, distribution and survival. **(LOW CONFIDENCE)**

It is predicted that climate change will alter oceanic currents and weather patterns. For example, weather events such as El Niño and La Niña are predicted to increase in frequency and magnitude (McPhaden *et al.* 2020). The impacts of these changes are likely to be complex and vary between location and species and there is no research on how predicted changes to ocean currents will affect migratory sturgeon.

Changes in the Gulf Stream could have negative impacts on the migration of American and European Eels which rely on it for food and transport (Limburg & Waldman 2009).

14.3 Adaptations and responses

14.3.1 Distribution and range shifts

Pole-ward shifts in range have been observed, but are likely to be constrained by the distribution, and accessibility, of spawning grounds **(LOW CONFIDENCE)**

There are many examples of pole-ward range shifts in migratory fish (Jeon *et al.* 2020). However, many migratory fish return to their natal spawning grounds, which will reduce their ability to shift ranges (Rothermel *et al.* 2020), so translocation may be necessary for some species if natural range shifts are not occurring. There is evidence of successful translocation of Lake Sturgeon (Boothroyd *et al.* 2018).

Conservation efforts to restore freshwater and tidal wetlands, increase floodplain connectivity, and remove dams can stabilise or increase population sizes (Limburg *et al.* 2016). However, the long-term survival of many sturgeon species such as the Adriatic and Chinese Sturgeons currently depends on artificial stocking (He *et al.* 2019).

14.3.2 Timing of migration

Earlier migration and breeding timings have been observed, but evidence is lacking as to whether this is adaptive or maladaptive **(LOW CONFIDENCE)**

Sturgeon migration and spawning generally occurs earlier due to rising temperatures (Limburg & Waldman 2009; Limburg *et al.* 2016; Delage *et al.* 2020; del Fresno *et al.* 2021). In some cases, this may be adaptive behaviour, while for some species these life-cycle stages may be driven by physiological cues and could be maladaptive.

15 Sharks, rays, skates and sawfish (Chondrichthyes)

15.1 Overview of migration patterns & distributions

The Chondrichthyes (sharks, rays and sawfish) are a large group of, mostly marine, fish, typified by their cartilaginous skeleton, possessing a series of paired gill arches and a rigid dorsal fin. They are widely distributed throughout the world's oceans, with some species spending most of their lives in the open ocean and others living or reproducing in shallow waters and coastal habitats. Migration patterns and distances vary between species, but many are migratory, and some cover large distances and are recognised as Highly Mobile Species on Annex I of the UN Convention on the Law of the Sea.

Thirty-nine species are listed on the Appendices of CMS and most of these are classified as Endangered (or, indeed, Critically Endangered) on the IUCN Red List. Since 1970, the global abundance of oceanic sharks and rays has declined by 71%, largely due to an 18-fold increase in relative fishing pressure (Dulvy *et al.* 2014; Pacoureau *et al.* 2021). Another major threat is coastal habitat loss, mainly from fishing activities such as trawling (Lawson *et al.* 2020). Somewhat remarkably, climate change has not been formally identified as a key threat to any cartilaginous fish species (Lascelles *et al.* 2014), although more recent assessments suggest that around 10% of threatened shark and ray species are impacted by climate change (in addition to overfishing), due to pole-ward range shifts (e.g. Tanaka *et al.* 2021) and habitat loss and degradation (Jorgensen *et al.* 2022).

The impacts of climate change on sharks and rays are complex, due to various physiological, behavioural and ecological changes (Heath *et al.* 2012). For most species, research on the impacts of climate change has been limited. In general, sharks and rays may be more vulnerable to climate change than most other fish, invertebrate and mammal taxa in the marine environment because they have low reproduction rates and potentially lower ability to adapt (Field *et al.* 2009; Hazen *et al.* 2013; Walker *et al.* 2021).

15.2 Climate change impacts

15.2.1 Increased temperatures

Temperature increases are likely to have widespread impacts on shark and ray distributions and populations, with many species likely to decline in abundance. **(MEDIUM CONFIDENCE)**

Temperature is a key determinant of shark and ray distribution (e.g. Silky Shark: Kindong *et al.* 2022) and some species have been shown to be extremely sensitive to very small changes in temperature (e.g. Basking sharks, Brown *et al.* 2003). There is evidence of past climate-driven changes in population size and distribution. In general, species more reliant on coastal habitats were more affected by climate change, positively or negatively depending on the species (O'Brien *et al.* 2013; Schlaff *et al.* 2014).

Abundance changes of many species are linked to temperature. Abundance changes are often mediated in the short-term by food availability, (e.g. Whale Sharks: Grose *et al.* 2020) but in the long-term by physiological thermal preferences based on metabolic rates and trade-offs (Sims 2008; Deepananda & Macusi 2012; Heath *et al.* 2012; Schlaff *et al.* 2014; Reynolds *et al.* 2022). For example, Basking Shark abundance in British waters is positively correlated with temperature, linked to increases in their copepod prey (Cotton *et al.* 2005; Robinson *et al.* 2009). Conversely, Scalloped Hammerhead Shark and *Mobula* rays declined substantially in the tropics when sea surface temperature rose by a few degrees (Osgood *et* *al.* 2021). Declines in deep-water Mediterranean sharks have also been linked to temperature increases (Cartes *et al.* 2013).

Temperature increases are predicted to lead to habitat loss for many shark species (Hazen *et al.* 2013; Jorgensen *et al.* 2022). A large decline in range extent is predicted for most open-water species in the north Pacific, with an exception for White Shark where habitat increases are predicted (Hazen *et al.* 2013). A decline in Silky and Dusky shark habitat has been predicted, particularly in south Asian waters (Diaz-Carballido *et al.* 2022).

Larger species tend to be less tolerant of high temperatures (Di Santo 2016; Vilmar & Di Santo 2022). In the North Sea, larger species have declined in recent years while smaller species have increased (Sguotti *et al.* 2016).

Smaller body size and lower body condition at warmer temperatures have been found in many species, potentially due to decreased nutrient uptake (Koenigstein *et al.* 2016; Vilmar & Di Santo 2022). However, muscle performance is improved by warmer temperatures (Vilmar & Di Santo 2022). Reproduction may be more successful and development time quicker at higher temperatures (Schlaff *et al.* 2014; Pistevos *et al.* 2015; Poulakis & Grubb 2019; Santos *et al.* 2021).

Temperature increases could reduce risk of lower temperature-related mortality events (i.e. ‘‘cold kills’’), often of juveniles or eggs, while increased temperature variability could increase this risk (Schlaff *et al.* 2014; Pistevos *et al.* 2015; Rosa *et al.* 2017; Poulakis & Grubb 2019).

Other potential impacts of temperature rise, that require more research, include competition from invading non-indigenous species; the increasing prevalence of disease (Field *et al.* 2009).

15.2.2 Increased ocean acidification

The effect of acidification on sharks and rays is very uncertain, but in general acidification is linked to declines in shark fitness. **(LOW CONFIDENCE)**

An increase in CO_2 causes seawater to become more acidic, which can reduce the growth of zooplankton and has been predicted to lead to population declines for Whale sharks and other planktivorous sharks (Reynolds *et al.* 2022).

Acidification can reduce olfactory function in sharks and rays, reducing sharks’ ability to hunt (Pistevos *et al.* 2015; Koenigstein *et al.* 2016; Jorgensen *et al.* 2022). Acidification may also affect swimming rates, skeletal density, locomotor performance, brain development and function (Pistevos *et al.* 2015; Di Santo 2016; Jorgensen *et al.* 2022; Vilmar & Di Santo 2022). However, the extent of these impacts, when interacting with temperature increases is unclear.

15.2.3 Increased frequency and severity of storms

Increased frequency and severity of storms may impact coastal habitats and salinity, with uncertain long-term impacts on species. **(LOW CONFIDENCE)**

Increasing rainfall and storms will cause declines in salinity in many coastal regions (Grose *et al.* 2020). Many shark and ray species rely on coastal habitats, particularly in juvenile stages and most species occupy very narrow salinity ranges (Schlaff *et al.* 2014).

Movement out of areas after extreme rainfall events has been noted in many species (Schlaff *et al.* 2014; Gutowsky *et al.* 2021) and declines may arise if movement is not possible or salinity increases cause habitat loss (Morash *et al.* 2016). However, some species have shown high resilience to rapid changes in salinity, e.g. Smalltooth Sawfish (Brame *et al.* 2019) and Tope Shark (Morash *et al.* 2016).

Oceanic weather systems events such as El Niño and La Niña are predicted to increase in frequency and magnitude (McPhaden *et al.* 2020) and have a big influence on shark and ray abundance, often due to changes in food availability. However, responses to these events are species and region-specific. Whale Sharks (southwest Pacific), Blue Sharks (southeast Pacific) and Scalloped Hammerhead Shark (southeast Pacific) increased during La Niña conditions (Sleeman *et al.* 2010; Adams *et al.* 2016; Osgood *et al.* 2021); Scalloped Hammerhead Shark declined during El Niño conditions (southeast Pacific; Osgood *et al.* 2021) while oceanic Manta Rays did not respond to El Niño events in the southeast Pacific but increased in the southwest Pacific (Beale *et al.* 2019; Osgood *et al.* 2021).

15.3 Adaptations and responses

15.3.1 Distribution and range shifts

Pole-ward shifts of distribution are expected but some species may be constrained by their use of specific breeding habitats **(MEDIUM CONFIDENCE)**

Temperature increases are likely to lead to pole-ward range shifts and altered migration routes (Field *et al.* 2009; Deepananda & Macusi 2012; Heath *et al.* 2012; Heupel *et al.* 2019; Osland *et al.* 2021). Examples include Scalloped Hammerhead Shark (Rodriguez-Burgos *et al.* 2022), Whale Shark (Sequeira *et al.* 2013), Basking Shark (Field *et al.* 2009) and White Shark (Bastien *et al.* 2020; Tanaka *et al.* 2021). Species reliant on particular habitats, such as reefs, may be less able to shift their range and therefore more vulnerable to climate change (Heupel *et al.* 2019).

Actions to reduce the impacts of overfishing can make additional climate change impacts less significant. Marine Protection Areas have proved to be beneficial for many sharks (White *et al.* 2017; Walker *et al.* 2021), for example a targeted fisheries ban for Undulate Ray in 2009 benefitted this and similar species (Elliott *et al.* 2020).

15.3.2 Timing of migration

Changes in migration patterns may result from increased water temperatures **(LOW CONFIDENCE)**

Changes in migration phenology have been linked to rising temperatures (Field *et al.* 2009; Schlaff *et al.* 2014). For example, the timing of sawfish movement from the shallows, where they tend to be as juveniles, to deep water is influenced by temperature (Poulakis & Grubb 2019). However, there are few documented cases of phenology changes in sharks and rays.

16 Insects

16.1 Overview of migration patterns & distributions

Insects from many groups are migratory, with some migrating long distances and having significant ecological impacts, although these are often under-appreciated (Satterfield *et al.* 2020). Most insect migration, though, involves multi-generational cycles, with a series of successive stationary and movement phases, thus the seasonal ‘journey’ is undertaken at the population rather than individual level. Hundreds of species of insects are known to migrate, particularly in the orders Lepidoptera (butterflies/moths), Orthoptera (grasshoppers), Anisoptera (dragonflies) and Hemiptera (aphids), although only one species, the migratory Monarch Butterfly is included on the CMS Appendices.

Monarch Butterflies are most commonly found in North America but also occur in Central America, South America and the Caribbean islands. There has been some expansion into Oceania coinciding with the introduction of their host plants (milkweed *Asclepias* species), and more recently towards North Africa/Southern Europe (Malcolm 2018). Not all populations of Monarch migrate, although the majority of the North American populations show a multi-generational migration moving between Canada, USA and Mexico (Dingle *et al.* 2005). They have been intensively studied and responses to climate and other factors vary between populations.

16.2 Climate change impacts

16.2.1 Increased temperatures

Monarch butterflies generally benefit from warmer and wetter conditions through spring and summer and warmer winters, but are negatively affected by more extremes, including heat in summer and cold in winter. **(HIGH CONFIDENCE)**

The abundance of Monarchs in the American Midwest in summer is higher when spring in Texas is wetter (Saunders *et al.* 2016; Saunders *et al.* 2018) and, similarly, warmer winters and warmer and wetter springs are associated with increased population sizes in Northern California; however this did not explain the long-term negative population trends in the region (Espeset *et al.* 2016).

Population size is projected to decrease in Mexico and in areas where summer temperature will increase greatly, and increase in areas that become wetter and show less extreme temperature rises (Zylstra *et al.* 2022). The increase in population size across North America in summer is suggested to currently compensate for the decrease in population over winter (Crossley *et al.* 2022; Crewe *et al.* 2019.)

However, a study comparing the contributions of climate change, deforestation and milkweed abundance suggests that the decline in Monarch population size in the past 21 years is driven more by a reduction in the abundance of milkweeds linked with the increased use of genetically modified crops (Flockhart *et al.* 2015).

The effect of temperature on developmental success differs depending on the exposure of the larval microclimate: in exposed locations, high temperatures reduce success but in shaded areas, high temperatures increase success (Yang *et al.* 2022a). The authors suggest that habitat heterogeneity may therefore buffer the impacts of climate variability.

16.3 Adaptations and responses

Climate change is likely to result in a northwards breeding range shift associated with likely changes in milkweed distribution. The effect of this on range extent is unclear, as are potential future changes in migration. ***(MEDIUM CONFIDENCE).***

Climate change is predicted to result in a northward breeding range shift. Milkweed spp. distribution is an important driver of Monarch distribution and both are predicted to expand northward. It has been suggested that these range shifts may reduce the amount of suitable habitat for Monarch Butterflies during their northward migration (Lemoine 2015; Batalden *et* *al.* 2014), but others predict the range size of suitable habitat to remain relatively consistent as the distribution shifts north (Svancara *et al.* 2019).

Temperature and precipitation can impact timing of migration, but impacts seem to be variable with some study areas demonstrating effects (New Jersey, Culbertson *et al.* 2022), whilst others do not (Ohio, Zipkin *et al.* 2012).

17 Discussion

This review builds on a growing evidence-base of the impacts of climate change on biological systems. These **impacts are increasingly apparent across a range of scales from genetic to ecosystems** (Scheffers *et al.* 2016). The increasing magnitude of climate change (and its increasing variability) means these impacts on the distribution of, and interactions between, organisms and hence ecosystems, are increasingly altered, and if not abated, will exceed the adaptive capacity of many ecosystems (Pörtner *et al.* 2021). As noted in a previous review (Robinson *et al.* 2005) of climate change impacts on migratory species, their long-distance movements makes them particularly vulnerable, exposing this to multiple and differential impacts through their annual cycle, any one of which may be limiting. That review highlighted the importance of these impacts at high latitudes, where warming has been greatest and migratory species make up the greatest proportion of biological communities. Migrants were thought to be particularly vulnerable to emerging impacts on changes in the timing of biological events (e.g. Møller *et al.* 2008), and more broadly, to impacts on highly productive seasonal habitats which their migratory movements enable them to exploit (Robinson *et al.* 2009).

This review extends and updates that previous work. Below we list the summary impact statements from each group for each broad driver of impacts and offer a brief commentary on the strength of evidence for each. In each section, groups with high confidence in the level of impacts are listed first, followed by those with medium and low confidence. But first, using those highlights, we identify what we regard as some of the key changes in the evidence available from the last decade or more of scientific research on the impacts of climate change on migratory species.

Whilst there is ongoing evidence for **warming having greater impacts on migratory species, there is now much stronger evidence for this impacting aquatic, particularly marine, environments**. This evidence is apparent across the range of taxa reviewed, including marine mammals, migratory fish, sharks and rays and seabirds. These impacts tend to be more negative than found in the terrestrial environment (Pearce-Higgins & Green 2014), and are particularly a consequence of cascading impacts through the food chain (e.g. Carroll *et al.* 2015a; Johnston *et al.* 2022). In marine systems, warming disrupts the timing and abundance of plankton food, particularly in highly seasonal shallow seas, which then affects the productivity and abundance of fish and other secondary consumers, which in turn can affect the productivity, survival, distribution and abundance of top marine predators. A key message from this report is therefore that migratory marine predators, across a range of taxa, are highly vulnerable to negative impacts of warming. Although well described in many medium and high latitude shallow seas that are highly seasonal, these processes also affect tropical species where El Niño years can reduce the breeding success of central-place foraging seabirds (e.g. Ancona *et al.* 2012) or cause mortality in marine mammals.

The impacts of temperature affecting high latitude systems are widely documented, and the evidence for these has strengthened, with mixed consequences for migratory species, either directly, or indirectly as it is more likely to increase non-migratory species (e.g. Pearce-Higgins *et al.* 2015a) with which they may compete. **Strong latitudinal gradients in the**

importance of temperature and precipitation in driving populations mean that the impacts of climate change on migratory species will differ around the world. The effects of warming will be most important at mid- and high-latitudes, whilst changes in precipitation will have the greatest impacts at low latitudes, where reduced water availability will negatively impact wetland species, such as waterbirds (e.g. Breiner *et al.* 2022) and fish (e.g. Pfeiffer *et al.* 2021), through the loss of wetlands or changes in river flow affecting migratory movements. Terrestrial species such as migratory land mammals, trans-Saharan migrants and grassland passerines (e.g. Dejene *et al.* 2021), will also be widely affected by changes in rainfall patterns in the tropics, mediated through impacts on vegetation productivity. Thus, these terrestrial systems are similarly affected by a cascade of impacts through the food chain (Ockendon *et al.* 2014). In addition, recent research has also highlighted the additional vulnerability of tropical birds and bats, particularly in arid and semi-arid environments, to extreme heat, which can cause large-scale sudden mortality (e.g. Dey *et al.* 2015). Increased frequency of heat waves may therefore be a key driver of changes in the distribution and abundance of migratory species in these environments. Tropical species are therefore particularly impacted by a combination of changes in precipitation (drought) and heat stress.

Increases in the severity of extreme events, particularly storms, can also have localised negative consequences, for example leading to the abandonment of breeding attempts in seabirds and waterbirds (Weston & Fraser 2020), or causing large-scale mortality. These events are most likely to have significant consequences for species' extinction risk if that species' has fragmented, small and localised populations. For coastal species, sea-level rise will exacerbate population vulnerability to extreme events associated with storm surges.

Overall, there is widespread evidence of **changes in the distribution and phenology of migratory species**, particularly leading to pole-ward range shifts and earlier migration and breeding in temperature-driven medium and high latitudes, but more mixed directional shifts in the tropics, depending on changes in rainfall (VanDerWal *et al.* 2013). Despite concerns about the potential for changes in phenology in drive asynchrony in the timing of resource availability and the demands of migratory species, the evidence for this having significant and large-scale population consequences remains weak (Franks *et al.* 2018; Samplonius *et al.* 2021), suggesting that direct impacts of climate change on prey abundance are more significant that changes in timing. Better understanding of the cues of that species use to time both migration departure and speed will be needed to fully assess the impact of projected changes.

A final point to emphasise is that the **evidence-base on the impacts of climate change on biodiversity is biased**, particularly from northern and higher latitudes, especially from Europe and North America, with a relative lack of research from the tropics and the Global South (Ockendon *et al.* 2014; Dahms & Killen 2023). This means there is considerable uncertainty about the impacts of climate change on species in the tropics, where the majority of species are found. Further, the strong latitudinal gradients that exist in the importance of temperature and precipitation for affecting biological systems (Pearce-Higgins *et al.* 2015b), mean that the evidence that does exist from better studied systems cannot simply be extrapolated to those understudied regions habitats and taxa. Further, as the summary below highlights, whilst some key migratory groups are relatively-well studied, particularly some of the bird groups, others are relatively poorly studied, such as bats, leading to an urgent need to better document the impacts of climate change on those taxa. Such evidence is critically important not just to inform vulnerability assessments to climate change (Foden *et al.* 2019), but also to inform climate change adaptation - with growing evidence that targeted conservation actions can actually help species adapt to climate change (Bowgen *et al.* 2022).

17.1 Increased Temperatures

Globally, temperatures have increased and will continue to do so. There is strong evidence that such increases in temperatures have affected most groups. There is a wide range of mechanisms, depending on species group, but impacts are mostly negative

17.1.1 High Confidence

Seabirds: Many seabird species show generally negative associations with sea-surface temperature with well-demonstrated effects on survival, breeding success and population abundance.

Waterbirds: The effect of increased temperatures on breeding success and survival varies between species, but generally has a short-term neutral or positive effect, at least for species breeding at higher latitudes

Marine Mammals: Temperature increases are likely to have a major impact on marine mammal populations indirectly via changes to food availability.

Reptiles: Increasing temperatures are resulting in a higher proportion of female hatchling turtles and crocodiles.

Monarch: Monarch butterflies generally benefit from warmer and wetter conditions through spring and summer and warmer winters, but are negatively affected by more extremes, including heat in summer and cold in winter.

Terrestrial Mammals: Rising temperatures can cause heat stress impacting productivity and are generally linked to population declines.

17.1.2 Medium Confidence

Waterbirds: Extreme temperatures (both hot and cold) are detrimental to waterbirds.

Afro-Palearctic Passerines: Increased temperatures generally promote an abundance of insect prey, which are the primary source of food in the breeding season (less so in the, boreal, winter months), and often results in higher breeding success, unless temperatures are extreme.

Migratory Fish: Temperature increases are generally associated with reductions in spawning and survival.

Sharks: Temperature increases are likely to have widespread impacts on shark and ray distributions and populations, with many species likely to decline in abundance.

17.1.3 Low Confidence

Raptors: The effects of temperature change appear relatively weak, with no strong impact of temperature upon breeding success.

Afro-Palearctic Passerines: Increased temperatures in the spring can lead to earlier insect emergence, and hence asynchrony with the timing of breeding.

Grassland passerines: There is growing evidence that extreme heat can have negative impacts on tropical species through sudden and catastrophic mortality. This does not appear to result from drought, but from physiological responses to heat stress.

Terrestrial Mammals: Rising temperatures may benefit some populations in cold environments by reducing the risk of severe cold limiting populations.

Bats: The impacts of temperature increases on bats is currently best described for changes in hibernation behaviour but impacts on the population are not well understood. Changes in temperature are likely to affect foraging efficiency and flight behaviour with uncertain consequences for populations. Warming may also affect the abundance of key invertebrate prey in different and contrasting ways, with variable impacts on bat populations, depending on diet, taxa and climate change context.

Marine Mammals: Temperature increases have been associated with increased mortality as a result of toxic algal blooms, disease and elevated parasite levels

17.2 Changes in water availability

Alongside increased temperatures, in many regions there will be a reduction in water availability, through reduced precipitation, increased frequency of droughts but also increased human abstraction of water, although in some areas rates of precipitation will increase. Species occurring in drier temperate and subtropical areas, or relying on freshwater habitats, will be negatively affected whether they are migratory or not. The migration of fish and waterbirds is likely to be particularly impacted by loss of wetlands and reduced river flows.

17.2.1 High Confidence

Afro-Palearctic Passerines: Annual variation in the survival and abundance of long-distance migratory passerines, especially those that spend the boreal winter in African drylands (such as the Sahel), tends to be most strongly linked (positively) to variation in rainfall there.

Terrestrial mammals: Changes in rainfall patterns are likely to have a significant impact on many terrestrial mammal populations, particularly in the tropics given strong links between rainfall, primary productivity and food resources.

17.2.2 Medium Confidence

Waterbirds: Increased precipitation can have a positive effect on breeding success, and drought a negative impact, at least on temperate breeding waterbirds. Where precipitation is predicted to fall, especially in the summer months, overall effects are likely to be negative.

Raptors: Changes in precipitation can affect breeding success, although the direction of the effect varies depending on the general climate and habitat the birds breed in. Tropical breeding raptors tend to show positive effects of rainfall on their populations through impacts on prey abundance, whilst at higher-latitudes, more negative responses to precipitation are likely due to chilling and reduced foraging opportunities.

Migratory Fish: Alterations in river flow will impact populations, with climate-driven reductions in flow rates likely to negatively impact the abundance and breeding success of species.

17.2.3 Low Confidence

Grassland Passerines: Tropical systems tend to be rainfall, rather than temperature-limited, and therefore the strongest climate change impacts on tropical migratory passerines are likely to be through changes in precipitation patterns, which are mixed, depending on location.

Bats: Reduced water availability and drought can reduce breeding success, migration and competitive dynamics amongst species.

17.3 Extreme weather events

The frequency of storms and other extreme weather events is expected to increase although, by their very nature, the pattern of occurrence is hard to predict. Evidence of long-lasting impacts is scattered, but they are likely to be negative where they do occur.

17.3.1 High Confidence

Seabirds: Increased frequency of stormy weather can impact on the survival and breeding success of some species, depending on the timing, with potential consequences for population size.

Reptiles: An increase in the frequency and intensity of storms is causing loss of nesting habitat

17.3.2 Medium Confidence

Terrestrial mammals: Where droughts are projected to increase in severity and frequency, they are likely to negatively impact populations of migratory mammals. Heavy rain and flooding can cause localised impacts, but generally appear to have weak population impacts.

Bats: The response of bat populations to extreme events is usually negative, either in terms of range contraction or population reduction.

17.3.3 Low Confidence

Marine mammals: Increase in storms and freshwater flooding can impact vulnerable coastal habitats, detrimentally affecting populations that rely on them, particularly for coastal species such as inshore dolphins and dugongs.

Sharks: Increased frequency and severity of storms may impact coastal habitats and salinity, with uncertain long-term impacts on species.

17.4 Sea-level rise

Globally sea-levels are rising and there is strong evidence that species breeding in low-lying coastal areas will be negatively impacted through loss of habitat, especially in areas with high levels of human developments.

17.4.1 High Confidence

Waterbirds: Sea-level rise is predicted to cause habitat loss, particularly at stopover sites along the migratory routes and wintering grounds.

Reptiles: Rises in sea-levels is causing loss of nesting habitat

17.4.2 Medium Confidence

Marine Mammals: Sea-level rise will reduce habitat availability for some coastal breeding seals

17.4.3 Low Confidence

Seabirds: Many seabirds are cliff-nesters, but for those nesting in low-lying areas, such as albatrosses and penguins, rising sea-levels threaten to inundate nest sites, especially where there are natural or anthropogenic barriers to movement inland.

17.5 Reductions in sea-ice extent

As temperatures increase, the area of sea-ice is reducing. Although only affecting a relatively small number of marine species, there is strong evidence of negative impacts.

17.5.1 High Confidence

Seabirds: Reductions in sea-ice extent reduce the area of high-quality foraging habitats for seabirds.

Marine mammals: Sea ice decline and increased variability in cover in response to climate change will generally negatively impact on population size for species associated with sea ice, but may accelerate the pole-ward range expansion in species associated with open water.

17.6 Changes in oceanic currents

Changes in oceanic currents are likely to have far-reaching consequences due to the scale of ecosystem alteration. There is strong evidence that migratory seabirds and marine mammals will be impacted, but evidence for other groups (such as migratory fish) is so far apparently lacking due, in part, to the difficulties of gathering evidence.

17.6.1 High Confidence

Seabirds: Large-scale changes in oceanic currents can greatly alter food availability, especially for central-place foragers like seabirds that have to return to a specific location (the breeding colony).

Marine mammals: Changes in the frequency and intensity of El Niño/La Niña events will have significant impacts on marine mammal distribution and mortality but impacts will vary between species and locations.

17.6.2 Low Confidence

Migratory Fish: Changes in ocean currents may impact their oceanic migration, potentially affecting phenology, distribution and survival.

17.7 Changes in water chemistry

Changes in salinity, due to altered freshwater flows, and increases in oceanic acidity are predicted as CO_2 emissions increase. However, so far, there is limited published evidence of impacts on migratory species directly. It should be noted that such changes are having marked impacts on particular marine habitats, such as coral reefs, which will have impacts on any migratory species that use such habitats as nursery areas, for example.

17.7.1 Low Confidence

Migratory Fish: Changes in salinity associated with changes in the flow of freshwater may impact migratory fish, although with uncertain population-level impacts. Increased CO2 acidifies salt and freshwater but impacts on migratory sturgeon appear to be limited so far.

Sharks: The effect of acidification on sharks and rays is very uncertain, but in general acidification is linked to declines in shark fitness.

17.8 Human adaptation

The size and scale of renewable energy developments is increasing rapidly with the potential for significant direct mortality in both birds (notably raptors and seabirds) and bats (Thaxter *et al.* 2017), although long-term population impacts are harder to quantify.

17.8.1 Medium Confidence

Bats: Wind turbines pose a substantial threat to many bat species and have been shown to be a major cause of mortality.

17.9 Distribution and range shifts

Pole-ward range shifts are one of the most frequently demonstrated impacts of climate change and will affect all groups of migratory animals, however, whether such impacts are positive or negative depends very much on the individual species ecology.

17.9.1 High Confidence

Seabirds: The response of seabird distribution ranges to climate change varies among species; shifts or expansions that have been observed are most often pole-wards.

Waterbirds: Pole-ward/elevational range shifts have been observed and are predicted to intensify throughout a wide range of wetland and coastal bird species.

Marine mammals: Range shifts have been observed in many species, with consequent declines in polar species and increases in subtropical and tropical species.

17.9.2 Medium Confidence

Raptors: Changes in temperature and precipitation are expected to influence species distribution ranges, with some current evidence of range losses.

Afro-Palearctic Passerines: Migratory passerines are shifting/expected to shift pole-ward in both their breeding and wintering grounds, though the Sahara presents a barrier for those north of the Equator in their African wintering grounds.

Terrestrial Mammals: Pole-wards range shifts have been observed and predicted. However, the ability of terrestrial mammals to shift their ranges in response to climate change is often unknown and may be restricted by lack of suitable habitat within areas of suitable climate and barriers that prevent range shifts. The combined changes in rainfall and temperatures are predicted to cause range contractions in many species, due to reductions in food availability, while, for some species, particularly those with ranges that are heavily restricted by human activities and land-use, direct climate change impacts on distribution may be hard to discern.

Bats: Range expansions and shifts towards higher latitudes have been observed in a few species and are predicted for many more.

Reptiles: Pole-ward range shifts have been observed but are likely to be constrained by anthropogenic pressures in potential new areas, although conservation actions can be targeted in such areas

Sharks: Pole-ward shifts of distribution are expected but some species may be constrained by their use of specific breeding habitats.

Monarch Butterfly: *Climate change is likely to result in a northwards breeding range shift associated with likely changes in milkweed distribution. The effect of this on range extent is unclear, as are potential future changes in migration.*

17.9.3 Low Confidence

Waterbirds: Whilst species vary in their capacity to alter migratory routes, shorebirds seem highly site faithful, with changes only coming about as young birds learn new routes. For other species adult birds appear able to occupy new wintering areas.

Marine Mammals: Species may alter their diet and foraging behaviour in response to climatic impacts on prey availability, but this may not compensate for losses in key prey

Migratory Fish: Pole-ward shifts in range have been observed, but are likely to be constrained by the distribution, and accessibility, of spawning grounds.

17.10 Phenology

There is strong evidence for changes in the timing of migration, mostly reflecting increased temperatures. Responses vary between species and groups and impacts on population status may be either positive or negative.

17.10.1 High Confidence

Waterbirds: The timing of migration and breeding is most often advancing in response to warmer temperatures, with generally positive impacts on breeding success.

Afro-Palearctic Passerines: Temperature, in particular, positively influences the timing of breeding and spring arrival, although these effects can be modified by more local weather conditions en route.

Seabirds: Seabirds may be vulnerable to mismatch with the timing of spring peaks in prey abundance, as a result of the timing of those peaks being strongly temperature-dependent. Temperature-related reductions in prey abundance can also limit the ability of seabirds to shift their timing of breeding.

17.10.2 Medium Confidence

Seabirds: The timing of migration or breeding can be sensitive to temperature and large-scale atmospheric systems, though responses vary within and between species.

Raptors: The timing of migration and onset of breeding responds to temperature and precipitation, though responses vary among species.

17.10.3 Low Confidence

Seabirds: Some species may have adaptive responses to variations in climate that allow them to alter migratory routes or destinations.

Terrestrial mammals: Some changes in birthing and migration phenology have been seen in migratory mammals, but cues for when to breed may be maladaptive.

Bats: The results of studies to date suggest the timing of migration in bats is more affected by weather conditions, such as precipitation and wind, than temperature.

Marine Mammals: Changes in the timing of migration have been observed, with many species now arriving on the breeding grounds earlier, but population effects are mostly unknown.

Migratory Fish: Earlier migration and breeding timings have been observed, but evidence is lacking as to whether this is adaptive or maladaptive

Sharks: Changes in migration patterns may result from increased water temperatures.

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19 Appendix 1 Species names

		Appendices	Instruments
Seabirds			
Adélie Penguin	*Pygoscelis adeliae*		
African Penguin	*Spheniscus demersus*	II	CMS, AEWA
Atlantic Puffin	*Fratercula arctica*		
Yellow-nosed Albatross	*Thalassarche chlororhynchos*	II	CMS, ACAP
Balearic shearwater	*Puffinus mauretanicus*	I	CMS
Blue-footed Booby	*Sula nebouxii*		
Brünnich's Guillemot	*Uria lomvia*		
Bulwer's Petrel	*Bulweria bulwerii*		
Common Tern	*Sterna hirundo*	II	CMS, AEWA
Cory's Shearwater	*Calonectris borealis*		
Crested Auklet	*Aethia cristatella*		
Emperor Penguin	*Aptenodytes forsteri*		
Galápagos Penguin	*Spheniscus mendiculus*		
Gentoo Penguin	*Pygoscelis papua*		
Glaucous Gull	*Larus hyperboreus*		
Great Shearwater	*Puffinus gravis*		
Herring Gulls	*Larus argentatus*		

Light-mantled Sooty Albatross	*Phoebetria palpebrata*	II	CMS, ACAP
Little Penguin	*Eudyptula minor*		
Magellanic Penguin	*Spheniscus magellanicus*		
Manx Shearwater	*Puffinus puffinus*		
Pacific Loon	*Gavia pacifica*		
Parakeet Auklet	*Aethia psittacula*		
Ringed-billed Gull	*Larus delawarensis*		
Roseate Tern	*Sterna dougallii*	II	CMS, AEWA
Shag	*Gulosus aristotelis*		
Snow Petrel	*Pagodroma nivea*		
Sooty Shearwater	*Puffinus griseus*		
Southern Fulmar	*Fulmarus glacialoides*		
Southern Rockhopper Penguin	*Eudyptes chrysocome*		
Waterbirds			
American White Pelican	*Pelecanus erythrorhynchos*		
Barnacle Geese	*Branta leucopsis*	II	CMS, AEWA
Black-Necked Crane	*Grus nigricollis*	I	CMS
Black-tailed Godwit	*Limosa limosa*	II	CMS, AEWA
Dalmatian Pelican	*Pelecanus crispus*	I&II	CMS, AEWA

Great Bittern	*Botaurus stellaris*	II	CMS, AEWA
Great White Pelican	*Pelecanus onocrotalus*	I&II	CMS, AEWA
Greater Flamingo	*Phoenicopterus roseus*		
Lesser Snow Goose	*Anser caerulescens caerulescens*		
Northern Lapwing	*Vanellus vanellus*	II	CMS, AEWA
Pink-footed Goose	*Anser brachyrhynchus*	II	CMS, AEWA
Purple Heron	*Ardea purpurea*	II	CMS, AEWA
Red-crowned Crane	*Grus japonensis*	I	CMS
Redshank	*Tringa totanus*	II	CMS, AEWA
Semipalmated Sandpiper	*Calidris pusilla*	I	CMS
Slavonian Grebes	*Podiceps auritus*	II	CMS, AEWA
Whimbrel	*Numenius phaeopus*	II	CMS, AEWA
White-headed Duck	*Oxyura leucocephala*	I	CMS, AEWA
White Stork	*Ciconia ciconia*	II	CMS, AEWA
Whooping Crane	*Grus americana*		
Raptors			
Aplomado Falcon	*Falco femoralis*		
Arctic Peregrine Falcon	*Falco peregrinus tundrius*		
Eurasian Scops Owl	*Otus scops*		Birds of Prey (Raptors)

Golden Eagle	Aquila chrysaetos	II	CMS, Birds of Prey (Raptors)
Little Owl	*Athene noctua*		
Montagu's Harrier	*Circus pygargus*	II	CMS, Birds of Prey (Raptors)
Oriental Honey Buzzard	*Pernis ptilorhynchus*	II	CMS, Birds of Prey (Raptors)
Red Kite	*Milvus milvus*	II	CMS, Birds of Prey (Raptors)
Snowy Owl	*Bubo scandiacus*		Birds of Prey (Raptors)
Wedge-tailed Eagle	*Aquila audax*		
Afro-Palearctic Passerines			
Alpine Swift	*Tachymarptis melba*		
Barn Swallow	*Hirundo rustica*		
Black-throated Blue Warbler	*Setophaga caerulescens*		
Great Reed Warbler	*Acrocephalus arundinaceus*		
Reed Warbler	*Acrocephalus scirpaceus*		
Sand Martin	*Riparia riparia*		
Sedge Warbler	*Acrocephalus schoenobaenus*		
Tree swallow	*Tachycineta bicolor*		

Grassland Passerines			
Budgerigar	*Melopsittacus undulatus*		
Carnaby’s Black Cockatoo	*Zanda latirostris*		
Little Bustard	*Tetrax tetrax*	I&II	CMS
Red-billed Quelea	*Quelea quelea*		
Zebra Finch	*Taeniopygia castanotis*		
Terrestrial Mammals			
African Elephant	*Loxodonta africana*	II	CMS, 1979: West African Elephants
Asian Elephant	*Elephas maximus*	I	CMS
Chimpanzee	*Pan troglodytes*	I&II	CMS
Giraffe	*Giraffa camelopardalis*	II	CMS
Gobi Bear	*Ursus arctos gobiensis/isabellinus*	I	CMS
Goitered Gazelle	*Gazella subgutturosa*	II	CMS, Central Asian Mammals Initiative
Eastern Gorilla	*Gorilla beringei*	I	CMS, Gorilla Agreement
Western Gorilla	*Gorilla gorilla*	I	CMS, Gorilla Agreement
Grevy’s Zebra	*Equus grevyi*	I	CMS

Leopard	*Panthera pardus*	II	CMS, African Carnivores Initiative, Central Asian Mammals Initiative
Lion	*Panthera leo*	II	CMS, African Carnivores Initiative
Przewalski’s Horse	*Equus ferus przewalskii*	I	Central Asian Mammals Initiative, CMS
Saiga Antelope	*Saiga tatarica*	II	Central Asian Mammals Initiative, Saiga Antelope
Wild Dog	*Lycaon pictus*	II	CMS, African Carnivores Initiative
Marine Mammals			
Antarctic Fur Seals	*Arctocephalus gazella*		
Atlantic White-sided Dolphin	*Lagenorhynchus acutus*	II	CMS, ASCOBANS
Beluga	*Delphinapterus leucas*	II	CMS
Blue Whale	*Balaenoptera musculus*	I	CMS, ACCOBAMS, Pacific Islands Cetaceans
Bottlenose Dolphin	*Tursiops truncatus*	I&II	ASCOBANS, Western African Aquatic Mammals, CMS, ACCOBAMS
Bowhead Whale	*Balaena mysticetus*	I	CMS

Caspian Seal	*Pusa caspica*	I&II	CMS
Common Dolphin	*Delphinus delphis*	I&II	CMS, ASCOBANS, ACCOBAMS, Western African Aquatic Mammals, Pacific Islands Cetaceans
Dall's Porpoise	*Phocoenoides dalli*	II	CMS
Dugong	*Dugong dugon*	II	CMS, Dugong
Fin Whale	*Balaenoptera physalus*	I&II	ACCOBAMS, CMS, Pacific Islands Cetaceans
Ganges River Dolphin	*Platanista gangetica*	I&II	CMS
Grey Seal	*Halichoerus grypus*	II	CMS, Wadden Sea Seals
Harbour Porpoise	*Phocoena phocoena*	II	CMS, ASCOBANS, ACCOBAMS, Western African Aquatic Mammals
Humpback Whale	*Megaptera novaeangliae*	I	CMS, ACCOBAMS, Pacific Islands Cetaceans
Killer Whale	*Orcinus orca*	II	CMS, ACCOBAMS, ASCOBANS, Western African Aquatic Mammals, Pacific Islands Cetaceans
Minke Whale	*Balaenoptera acutorostrata*		
North Atlantic Right Whale	*Eubalaena glacialis*	I	CMS, ACCOBAMS

Northern Fur Seal	*Callorhinus ursinus*		
Polar Bear	*Ursus maritimus*	II	
South American Sea Lion	*Otaria flavescens*	II	CMS
Southern Right Whale	*Eubalaena australis*	I	CMS, Pacific Islands Cetaceans
Sperm Whale	*Physeter macrocephalus*	I&II	CMS, ACCOBAMS, Pacific Islands Cetaceans
Subantarctic Fur Seal	*Arctocephalus tropicalis*		
White-beaked Dolphin	*Lagenorhynchus albirostris*	II	CMS, ASCOBANS
Bats			
Bechstein's Bat	*Myotis bechsteinii*	II	CMS, EUROBATS
Daubenton's Bat	*Myotis daubentonii*	II	CMS, EUROBATS
Greater Horseshoe Bat	*Rhinolophus ferrumequinum*	II	CMS, EUROBATS
Greater Long-nosed Bat	*Leptonycteris nivalis*		
Indian Flying Fox	*Pteropus giganteus*		
Kuhl's Pipistrelle Bat	*Pipistrellus kuhlii*	II	CMS, EUROBATS
Lesser Horseshoe Bat	*Rhinolophus hipposideros*	II	CMS, EUROBATS
Natal Long-fingered Bat	*Miniopterus natalensis*	II	CMS
Nathusius's Pipistrelle Bat	*Pipistrellus nathusii*	II	CMS, EUROBATS

Natterer's Bat	*Myotis nattereri*	II	CMS, EUROBATS
Soprano Pipistrelle	*Pipistrellus pygmaeus*	II	CMS, EUROBATS
Savi's Pipistrelle Bat	*Hypsugo savii*	II	CMS, EUROBATS
Mexican Free-Tailed Bat	*Tadarida brasiliensis*	I	CMS
Noctule Bat	*Nyctalus noctule*	II	CMS, EUROBATS
Reptiles			
Arrau Turtle	*Podocnemis expansa*	I&II	CMS
Green Turtle	*Chelonia mydas*	I	CMS, IOSEA Marine Turtles, Atlantic Turtles
Loggerhead Turtle	*Caretta caretta*	I	CMS, IOSEA Marine Turtles, Atlantic Turtles
Salt-water Crocodile	*Crocodylus porosus*	II	CMS
Migratory Fish			
Adriatic Sturgeon	*Acipenser naccarii*	II	CMS
Beluga Sturgeon	*Huso huso*	II	CMS
Chinese Sturgeon	*Acipenser sinensis*	II	CMS
European Sturgeon	*Acipenser sturio*	I&II	CMS
Green Sturgeon	*Acipenser medirostris*	II	CMS
Lake Sturgeon	*Acipenser fulvescens*	II	CMS

Russian Sturgeon	*Acipenser gueldenstaedtii*	II	CMS
Siberian Sturgeon	*Acipenser baerii*	II	CMS
Sharks			
Basking Shark	*Cetorhinus maximus*	I&II	CMS, Sharks
Blue Shark	*Prionace glauca*	II	CMS
Dusky Shark	*Carcharhinus obscurus*	II	CMS, Sharks
Manta Ray	*Mobula/Manta birostris*	I&II	CMS, Sharks
Scalloped Hammerhead Shark	*Sphyrna lewini*	II	CMS, Sharks
Silky Shark	*Carcharhinus falciformis*	II	CMS, Sharks
Smalltooth Sawfish	*Pristis pectinata*	I&II	CMS, Sharks
Tope Shark	*Galeorhinus galeus*	II	CMS
Whale Shark	*Rhincodon typus*	I&II	CMS, Sharks
White Shark	*Carcharodon carcharias*	I&II	CMS, Sharks