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Climate Change and Migratory Species:
a review of impacts, conservation actions, ecosystem services, and indicators

B. Martay[1,4], K. H. Macphie[1,4], H. F. R. Hereward[1,2,4], M. G. Barton[1,4], K.M. Bowgen[1], J. W. Pearce-Higgins[1], R. A. Robinson[1], J. M. Williams[3], S. E. Scott[3], and C. A. Galbraith[3]

[1] British Trust for Ornithology, The Nunnery, Thetford, Norfolk, IP24 2PU
[2] British Trust for Ornithology Cymru, Thoday Building, Bangor, LL57 2UW
[3] Joint Nature Conservation Committee, Quay House, 2 East Station Road, Fletton Quays, Peterborough, PE2 8YY
[4] Led on a work package.

JNCC, BTO, Defra and CMS logos to be used as branding for the report

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Headline message:

The impacts of climate change on migratory species are wide-ranging and in many cases severe. We can reduce the negative effects of climate change on many migratory species by ensuring their habitats are healthy, well-connected and resilient. Migratory species can provide essential ecosystem services related to climate change mitigation and adaptation, and therefore considering migratory species conservation and climate change strategies holistically can maximise their impact.

Key findings:

Impacts of climate change on migratory species

Increases in temperature:

- Globally, temperatures have increased and will continue to do so. There is strong evidence that such increases in temperatures have affected most species groups. There are a wide range of ways (depending on species group) by which increased average temperatures ultimately impact migratory species; impacts are mostly negative.
- Many seabird species are negatively impacted by increases in sea-surface temperature with well-demonstrated effects on survival, breeding success and population abundance.
- 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 on these populations due to changes in the reproduction and survival of krill, a food source for marine mammals and seabirds.
- Rising temperatures can cause heat stress in terrestrial mammals and seabirds like penguins and albatrosses, impacting populations through its effects on reproductive outputs.
- Poleward range shifts are one of the most frequently demonstrated impacts of climate change on migratory animals; however, whether such impacts are positive or negative depends very much on the individual species' ecology.
- There is strong evidence for changes in the timing of migration, mostly in response to increased temperatures. Responses vary between species and groups, and impacts on population status may be either positive or negative.

Changes in Water availability

- Alongside increased temperatures, in many regions there will be a reduction in water availability, through reduced precipitation or more rapid evaporation, 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.

Extreme climate events

- The frequency and intensity 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. Habitat destruction caused by land-slips has already been observed at some seabird breeding sites. Individual events are starting to be attributed to climate change – this is no longer a future problem.

Oceanic currents and sea-level rise

- Changes in oceanic currents are likely to have far-reaching consequences, altering the nature and functioning of many marine and terrestrial ecosystems. 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.
- Globally sea-levels are rapidly rising and there is strong evidence that species breeding in low-lying coastal areas will be negatively impacted through loss of habitat e.g. turtle nesting beaches, especially in areas with high levels of human developments or exposed to storm surges.
- Changes in salinity and pH of water are predicted as CO_2 emissions increase, but, 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 knock-on impacts on any migratory species that use such habitats as nursery areas, for example.

Connectivity and resilience

- Migratory species populations are most resilient to the effects of climate change where the animals concerned can (with unimpeded (new) movements) shift ranges or change migratory behaviour to adapt to climate change-driven loss of favourable environments or conditions (e.g., too dry/too wet/too hot/or lost to sea level rise, ice melt, etc.).
- Such connectivity-related resilience can happen *either* of its own accord because of the *inherent* capabilities of the animals and the existing availability of requisite areas and resources, *or* it can be '*conservation enabled'* by e.g., barrier-removal, habitat enhancement, translocation projects, behavioural imprinting or other actions.
- Resilience is compromised when / where:
  - adaptive movements are impeded by *pre-existing barriers* (limited extent/distribution of suitable habitat; hotspots of predation pressure; existing anthropogenic barriers e.g., dams, sea walls, fences, energy infrastructure, etc.).
  - adaptive movements are impeded by new climate change-induced losses of connectivity (drying rivers, burning forests, flooded grasslands, melting sea-ice, etc.).
  - adaptive movements are impeded by human responses to climate change (shifting agricultural intensification, renewable energy developments, new reservoirs, higher sea walls and other flood defences preventing shift of suitable habitats e.g., nesting beaches, shifting areas of direct take when human populations are displaced, etc.).
  - populations are scattered/fragmented to the extent that social learning about shifting migration routes cannot be properly transmitted between individuals.

  - site fidelity/migration route fidelity behaviours prevent adaptive shifts, even when the requisite habitat connectivity is available.
  - climate-related condition-reducing effects in e.g., birds in the wintering areas ‘carries over’ to reduced productivity in the breeding areas.
  - continuity of required conditions is required along an entire migratory route, but this becomes fractured (e.g., water availability for bats; correct salinity for certain sharks).
- Resilience might, in some cases, be *improved* by climate change-induced changes in connectivity – e.g., melting sea-ice reducing the travel distance between penguin colonies and their food source has been found to improve productivity. Such situations however may be complex, involving a mix of positive and negative effects – in the penguin instance for example, closer food may also mean closer predators, and the observed productivity gain has seemingly not been enough to offset the loss of productivity from climate change-induced reduction in prey volumes.

Conservation actions to facilitate adaptation

- There is increasing confidence that conservation management can help species to adapt to climate change; it is urgent to improve the evidence base to understand what works where and when.
- There is an urgent need for those undertaking adaptation actions for migratory species to ensure they are able to monitor and evaluate the success of such actions, and to make that information available (ideally through open-access publication) so that others can learn from it.
- Actions to help people mitigate or adapt to the impacts of climate change (whether through nature-based solutions or grey infrastructure) can have negative consequences for migratory species, such as through collisions with windfarms. Mainstreaming the consideration of impacts of climate mitigation and adaptation actions upon biodiversity (and specifically CMS migratory species) in other sectors will help to reduce such impacts.
- Given that the most successful adaptation interventions are often targeted at specific species, there is value in linking understanding of climate change impacts to adaptation interventions. For migratory species, impacts on a population may occur in other jurisdictions, therefore mechanisms need to be found to support conservation where those impacts occur, even if outside a particular jurisdiction. The Convention on Migratory Species offers opportunities for such international co-operation in a number of ways, including but not limited to, formal agreements / memoranda of understanding, concerted actions, and via bilateral arrangements.
- Adaptation strategies can have far reaching impacts and thus potential trade-offs and synergies for different stakeholders or through time should be considered. Clear and transparent participatory approaches should be developed to agree adaptation objectives, as well as an adaptive management framework that incorporates monitoring, evaluation and iterative improvements to activities to ensure their long-term successes.

Ecosystem services

- Migratory species can be important for ecosystem function and climate mitigation when they form a significant part of an ecosystem or aggregate in large numbers at particular times of the year, for example to take advantage of seasonal flushes in food resources, such as ocean upwellings, insect flushes or fruiting.

- By virtue of their mobility, many ecosystem services migratory species provide are related to the movement and dispersal of seeds and nutrients (and disease potentially as a disbenefit).
- Large migratory megafauna in particular can contribute towards climate change mitigation through the decomposition of their feces, which locks carbon into the soil or seabed, as well as through more complex processes, such as maintaining trophic cascades that protect forest or seagrass beds important for carbon sequestration.
- Migratory species can also contribute towards climate change adaptation by enhancing ecosystem resilience, for example seabird guano increases the nutrients available for coral reef growth, which reduces coastal erosion.

Indicators

- To monitor the impacts of climate change on migratory species, it is important to develop indicators that are useful for policy decisions, indicative of climate change across a wide range of migratory species and relatively simple and cost-effective to monitor.
- Different groups of migratory species will have very different migration routes and be sensitive to a wide variety of climatic change impacts and thus adopting a suite of indicators will help to give a fuller picture.

Recommendations [– more work needed on this section]

a) Identify those species that, on balance, are likely to be negatively impacted by climate change, especially those that are likely to need human-mediated interventions, such as translocations, to moderate the impact of climate change;

b) Identify species which have a high probability of changing their migration routes as a result of climate change;

c) Develop guidance for Parties to promote greater understanding of the provision of ecosystem services by migratory species;

d) Propose measures to help facilitate migratory species’ range changes;

e) Provide advice on possible interventions, including nature-based solutions, in relation to conserving migratory species habitats, including maintaining or enhancing connectivity and ecosystem integrity;

f) Provide advice on how work under CMS on climate change could interact with implementation of the Kunming-Montreal Global Biodiversity Framework, including, but not limited to, area-based conservation measures, connectivity and restoration;

g) Develop an interpretation of the term “barrier”, so that there is consistency in the obligation to remove barriers to migratory species;

h) Migratory species and climate change should be considered holistically when developing conservation or climate change mitigation/adaptation strategies in order to maximise their impact.

i) Mainstreaming the climate benefits of conserving migratory species in the [climate science/industry/net zero] sector is essential to influence wider decision making processes

j) Ensuring that management interventions [to enhance the ecosystem services migratory species provide] are properly monitored and evaluated, and the results made available, will provide the evidence to inform decision-making

k) Further research on the ecosystem services migratory species can provide in relation to climate change is urgently needed, especially in the global south where climate change impacts are most greatly felt, and particularly those related to adaptation, where there is currently the greatest evidence gap.

l) Convene an international in-person workshop on migratory species and climate change to facilitate implementation of the actions above, and provide support to Party implementation of Resolution 12.21 (Rev. COP14);

Introduction

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). 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).

Migratory wildlife are subject to a wide range of environmental influences due to the large distances they travel and their reliance 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 not only require suitable habitats at each end of their migration route but also suitable conditions and habitats *en route*. 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 migratory species face 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; 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).

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. 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.

This report, commissioned by 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, provides a new review of the evidence on the impacts of climate change on migratory species, updating previous reviews conducted in 2005[1], 2006[2] and 2010[3]. In particular, it assesses 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 can be prioritized and (b) knowledge gaps identified. The report also investigates the conservation actions that can be employed to facilitate migratory species adaptation to climate change, as well as indicators of climate change impacts and adaptation. Finally, it assess the potential role migratory species can have as key components of ecosystems, particularly through providing nature-based solutions related to climate change.

[1] BTO Research Report 414. Climate Change and Migratory Species. 2005. Robert A. Robinson, Jennifer A. Learmonth, Anthony M. Hutson, Colin D. Macleod, Tim H. Sparks, David I. Leech, Graham J. Pierce, Mark M. Rehfisch and Humphrey Q.P. Crick. A Report for Defra: Research Contract CR0302.

[2] UNEP-CMS, 2006, Migratory Species and Climate Change: Impacts of a changing Environment on wild animals. ISBN 3-937429-09-3. https://www.cms.int/sites/default/files/publication/cms_pub_pop-series_migratory_species%26climate_change_e.pdf

[3] UNEP-CMS/ScC17/Inf.9. 2010 Vulnerability of migratory species to climate change. ZSL. https://www.cms.int/sites/default/files/publication/cms_climate_change_vulnerability_3_0_0.pdf.

Part 1: Impacts of climate change on migratory species

Background

A review of literature was carried out to identify 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.

Seabirds

Seabirds are a taxonomically diverse group of species that are linked by their use, to a greater or lesser extent, of marine habitats. 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 utilize 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.

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 wetland habitats, especially at lower latitudes, will reduce habitat 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. Large-scale distributional shifts (in both breeding and non-breeding distributions) in many temperate species are already being seen; these 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.

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.

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 clear, 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 wintering 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.

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 bird populations, the responses of farming to climate change will further influence how birds and agriculture interact in these regions.

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.

Bats

Evidence on how bats are being affected by climate change is limited 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 climate change related cause of mortality in bats is the installation of wind turbines as a renewable energy source to mitigate greenhouse gas emissions; specific location choices and farm designs have the potential to reduce ongoing fatality rates.

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 population-level impacts very difficult to predict. 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 Polar Bears (*Ursus maritimus*), Narwhals (*Monodon monoceros*) and Beluga whales (*Delphinapterus leucas*) 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.

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, are 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.

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 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.

Sharks, rays and skates

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 likely 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 limited evidence 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.

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 and further research is needed.

Part 2: Conservation of Migratory Species and the use of Indicators for Monitoring Climate Change Impacts

Background

Whilst the impacts of climate change on natural systems are ubiquitous, they occur in a non-uniform manner across time and space. These complexities mean that, compared to resident species, developing conservation programs to help mitigate climate change impacts on migratory species, which can span extensive geographical regions and habitat types, as well as crossing jurisdictional borders, is challenging. Although there are an increasing number of examples of conservation efforts focused on facilitating adaptation to climate change, there is limited documentation of the extent to which this is taking place, and virtually no evaluation of the effectiveness of adaptation measures in the scientific literature.

This section summarises the results of a literature review of conservation interventions that have previously been employed on migratory species, in the context of climate change. Key considerations for the conservation of migratory species are outlined, providing examples of studies that have demonstrated these. Additionally, an assessment of climate change indicators created since 2009 was undertaken, and those with potential to assess climate change impacts on migratory species were identified, building on the framework set out by Newson *et al*. (2009).

Conservation actions to facilitate climate change adaptation

A total of 51 articles that describe conservation interventions on CMS-listed (or closely related) species were reviewed in detail. All of the CMS taxonomic groups, apart from sharks, were represented, although there were biases towards some taxa (birds, reptiles and mammals), over others (insects, bats and fish). The scale of conservation interventions ranged from the broad designation of protected areas (that can benefit an extensive suite of species and habitats), to the management of particular habitats (e.g. restoration of coastal dunes for migratory birds), and fine-scale interventions to manage individuals (e.g. shading turtle nests). Only 23% of the studies involved more than one jurisdiction, despite the fact that all species considered in the review move through multiple countries during migration.

Studies reiterate several key considerations for the conservation of migratory species. For example, to provide protection through their annual cycle, species require a coherent and inter-connected network of passage and stop-over sites along their migratory routes, in addition to their breeding and wintering grounds. A combination of regional (multi-national) and local (site-specific) conservation actions will be required to achieve this. The establishment of effective networks of protected areas for migratory species, that span key migratory pathways, should be a high priority, necessitating on-going collaboration among nations. Recognising, and accounting for, the extent of climate-induced range shifts will be critical to the continued efficacy of designating protected areas, in all ecosystems.

Conservation management interventions at key points in the annual cycle are required to increase resilience to specific climate change impacts, and if based on robust evidence, can have a relatively high probability of efficacy. However, conservation programs often involve trade-offs and conflicts, as well as synergies and opportunities between multiple conservation and climate change mitigation programs (explored in detail in Part 3). These considerations include the socio-economic and cultural well-being of local communities, the conservation of multiple species and habitats, and developments aimed to mitigate the ongoing impacts of climate change. Care should thus be taken to account for these complications when implementing conservation programs, and monitoring the consequences of adaptation actions on those multiple objectives.

Indicators to assess climate change impacts on migratory species

To monitor the impacts of climate change on migratory species, it is important to develop indicators that are useful for policy decisions, indicative of climate change across a wide range of migratory species and relatively simple and cost-effective to monitor. Different groups of migratory species will have very different migration routes and be sensitive to a wide variety of climatic changes. It is therefore recommended that a suite of indicators be selected to encompass as much of that variation as possible.

Marine climate change impacts have been indicated using fish biomass, predator foraging times, population metrics of top predators, migration phenology and community-temperature index (Cherry et al. 2013; Nash et al. 2016b; Bowler & Böhning-Gaese 2017; Wilcox et al. 2018; Hanzen et al. 2019; Langan et al. 2021). These indicators use a wide range of methods such as surveys carried out by boat, tracking devices and unmanned aerial vehicles, which vary in cost and practicality. Other marine climate change indicators may become feasible with technological advances in, and reduction in cost of, methods such as environmental DNA and satellite-based remote sensing (Stephenson 2020).

Community-level metrics are being increasingly used in terrestrial species to indicate climate change impacts on biodiversity. These generally use spatial associations between species' distribution and climate to indicate climate change responses from temporal changes in species' distributions, populations or communities, but can be difficult to interpret. As an alternative, analyses of temporal changes in species' populations can be used to separate species into their likely responses to climate change, and to track change (e.g. Martay et al. 2016). Multi-species indicators, which use modelling to attribute average population change across a taxonomic group to climate, are also commonly used.

The production of indicators generally requires extensive data and thus is often restricted to well-monitored groups such as birds and butterflies, and to regions with long-term monitoring schemes. As approaches to monitoring develop and extend, for example through the use of new technologies, then our ability to track the impacts of climate change and summarise those impacts through indicators, will also expand.

Currently, monitoring of climate change adaptation is very limited. Such indicators may be process-based measures, for example monitoring the resources available for adaptation projects, or monitoring the area of land managed for adaptation; or they can be results-based measures, for example, the persistence of climate-sensitive species within protected areas (Pearce-Higgins et al. 2022).

Part 3: Migratory Species and Their Role in Ecosystems

Background

Migratory species often play a key role within the ecosystems they utilize and in connecting different ecosystems. There is a growing understanding of how species support ecosystem functionality, and how they provide ecosystem services that can deliver nature-based solutions to human challenges such as climate change. This section summarises a review on the potential roles migratory species can have as key components of ecosystems, particularly through providing nature-based solutions related to climate change. We highlight examples where the conservation of migratory species may also contribute to wider benefits for people and ecosystems, to help decision-makers begin to consider these issues in a cross-cutting and holistic way.

Migratory species as key ecosystem components

Migratory species were identified as key ecosystem components in 73 studies. Regulation and maintenance ecosystem services (covering: carbon capture, pollination, seed dispersal and pest control) were especially prominent, but other services within culture (covering: tourism, recreational activities, symbolic value and natural heritage) and provision (predominantly food) were also reported. Of these services, pollination, seed dispersal and pest control were particularly provided by migratory bird, bat and insect species groups. Larger migratory species – terrestrial and marine mammals and sharks – were particularly important in aiding carbon capture and other climate change related regulation and maintenance services.

Migratory species as nature-based solutions to climate change

The strongest evidence that the conservation of migratory species can support climate change mitigation comes from published research on carbon capture by a number of different species – especially the larger megafauna. These included, large terrestrial grazers, such as Caribou, Bison and African Elephant; large marine mammals, such as Whales and Dugongs; sharks, and cliff or island nesting seabirds. This is predominantly through the decomposition of their feces, which locks carbon into the soil or seabed, but also through more complex processes, such as maintaining trophic cascades that protect forest or seagrass beds important for carbon sequestration. Protecting these large migratory species helps to maintain these important processes, whilst the actions to conserve these species, such as designating protected areas or restoring habitats, can themselves improve the climate resilience of ecosystems.

Migratory species can also contribute towards climate change adaptation, particularly in response to climatic hazards, by enhancing ecosystem resilience. For example, seabird guano increases nutrients available for coral reef growth, which reduces coastal erosion, and terrestrial herbivore’s grazing regimes can reduce fire risk. In addition, migratory species can aid in retaining the genetic diversity of plants through pest control, pollination and seed dispersal via frugivorous and insectivorous bats and birds, and pollinating insects. However, the magnitude of benefit of this for adaptation, and the specific role of migratory species in this area, is uncertain and requires further research.

The review demonstrates that migratory species not only form significant components of many ecosystems, but also facilitate significant transfers of energy and resources across their migration routes (Bauer & Hoye 2014). However, despite the growing understanding of how certain species can aid climate change mitigation or adaptation (e.g. Díaz et al. 2006; Schmitz et al. 2023), specific studies about the importance of migratory species are uncommon, and research is required to better understand the climate change mitigation and adaptation services these species can provide, noting the much weaker evidence-base for the latter.

Case Studies

The review also contains a number of case studies, chosen to illustrate issues faced by particular species and habitats.

Case Studies relating to the Impacts of Climate Change

- African savanna
- Central Asia & the Tibetan Plateau
- High Arctic
- Wetlands around the Mediterranean Sea
- Extreme Weather Events
- Bactrian Camel *Camelus bactrianus ferus*
- Green Sturgeon *Acipenser medirostris*
- Loggerhead Turtle *Caretta caretta*
- Polar Bear *Ursus maritimus*
- Red Knot *Calidris canutus*
- Siberian Crane *Leucogeranus leucogeranus*
- Wandering Albatross *Diomedea exulans* s.l.
- Whale Shark *Rhincodon typus*
- Willow Warbler *Phylloscopus trochilus*

Case Studies relating to Migratory Species and Their Role in Ecosystems

- Cetaceans aid ocean nutrient transfer and Carbon capture
- Dugong grazing aids seagrass bed genetic diversity
- Seabird ornithogenic nutrients aid coral growth
- Bats foraging techniques aid plant survival and propagation
- Elephants as ecosystem engineers for the African savanna
- Saiga antelope aid in grassland biodiversity recovery
- Vultures Aid in Reducing Disease Transmission

References [to be added]

Each part of the review is fully referenced, as indeed are the case studies. Here the references used in this document are provided.