Climate change and migratory species: a review of impacts, conservation actions, indicators and ecosystem services

Part 2 – Conserving migratory species in the face of climate change

Department for Environment Food & Rural Affairs
JNCC
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CMS

The Convention on the Conservation of Migratory Species of Wild Animals (CMS, also known as the Bonn Convention, after the city in which 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 co-operative actions between Range States.

The key issue of climate change was first discussed at the fifth meeting of the CMS Conference of the Parties (CoP5) in 1997 and has been addressed at multiple subsequent CoPs.

In support of this work, the Government of the United Kingdom of Great Britain and Northern Ireland (through a contract to the British Trust for Ornithology (BTO) funded by the Department of Environment, Food and Rural Affairs via the Joint Nature Conservation Committee (JNCC)) commissioned a review of the latest evidence on the impacts of climate change on migratory species, with regard also to conservation actions, indicators and ecosystem services.

The results of this review are presented in three parts:

Part 1 – Impacts of climate change on migratory species
Part 2 – Conserving migratory species in the face of climate change
Part 3 – Migratory species and their role in ecosystems.

A Summary for Policy Makers is also available.
Access the full review at jncc.gov.uk/climate-migratory-species-report/

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Climate change and migratory species: a review of impacts, conservation actions, indicators and ecosystem services

Part 2 – Conserving migratory species in the face of climate change

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Summary

Whilst the impacts of climate change on natural systems are ubiquitous, they are occurring in a non-uniform manner across time and space. These complexities mean that developing conservation programmes 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 particularly challenging in comparison to the design of programmes for resident species. Part 2 of this review focusses on describing interventions that have been made to date to conserve migratory species in the context of climate change, and on how indicators can be used for monitoring climate change impacts.

Through a review of the latest scientific literature, we discovered that although there are an increasing number of examples of conservation efforts promoting adaptation to climate change, there is limited documentation of the full extent to which this is taking place, and virtually no evaluation of the effectiveness of adaptation measures. Drawing on the articles we identified, however, we have been able to outline key considerations for the conservation of migratory species, and provide examples of studies that have demonstrated these.

Foremost amongst these considerations is that, to maximise effectiveness and value for money, conservation interventions should, as far as possible, be based on robust evidence; furthermore, ongoing monitoring and re-evaluation is critical to the success of any conservation programme. This is especially true in a multi-species context where (1) the drivers may be indirect and interact with each other, and (2) the consequences of conservation actions might be conflicting for different taxonomic groups. This report thus proposes some additional steps to the Convention on the Conservation of Migratory Species of Wild Animals (CMS) Framework for Action, including structured monitoring prior to implementing actions, followed by ongoing monitoring and evaluation of adaptation actions so that they can be adjusted as part of an adaptive management framework.

One mechanism by which change can be monitored is through the use of indicators, and Part 2 of this review also considers the potential to develop ecological indicators of the impacts of climate change on migratory species, building on the evidence for impacts identified in Part 1. We conducted a rapid assessment of climate change indicators created since 2009 to highlight promising indicators that could be used to assess the climate change impacts on migratory species using the framework set out by Newson *et al.* (2009). We also discuss the urgent need to identify and test outcome-based indicators of climate change adaptation, to allow the effectiveness of adaptive measures and outcomes to be assessed as part of that monitoring and evaluation framework.

In developing this report, we reviewed in detail a total of 51 articles that describe conservation interventions on CMS-listed (or closely related) species. All 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. To provide protection through their annual cycle, species require a coherent and interconnected network of passage and stopover sites along their migratory routes, in addition to maintaining habitats on 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 ongoing 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.

If based on robust evidence, conservation management interventions at key points in the annual cycle can have a relatively high probability of efficacy in increasing resilience to specific climate change impacts. However, conservation programmes often involve trade-offs and conflicts, as well as synergies and opportunities, between multiple conservation and climate change mitigation programmes (explored in detail in Part 3 of this review). These considerations include the socio-economic and cultural well-being of local communities, the conservation of multiple species and habitats, and developments aimed at mitigating the ongoing impacts of climate change. Care should thus be taken to account for these complications when implementing conservation programmes and monitoring the consequences of adaptation actions on those multiple objectives. Indicators of climate change impacts can assist in monitoring climate change impacts across species and the effectiveness of conservation interventions. However, further work is required to identify the most appropriate indicators for each region.

Contents

1 Introduction

As the world's climate continues to change at an unprecedented pace, the availability of suitable habitats for vulnerable wildlife, like migratory species, continues to decline. Rising temperatures, altered rainfall patterns, rising sea levels, the erosion of coastal habitat and extreme weather events all have an impact on the survival of migratory species (Part 1 of this review; Trouwborst 2012). Such changes are difficult to predict, and are occurring in a non-uniform manner across space and time. This uncertainty means that, compared to support for resident species, it is particularly challenging to develop conservation programmes to help mitigate these impacts on migratory species, which span extensive geographic regions and rely on multiple habitat types. These complexities are exacerbated when migratory routes span multiple jurisdictions since a coherent, co-ordinated response among nations is required (Robinson *et al.* 2009; Groves *et al.* 2012; Ranius *et al.* 2023).

A number of studies outline decision support frameworks to help guide the development of conservation plans, some of which have been specifically designed with migratory taxa in mind (Silva *et al.* 2018; D'Aloia *et al.* 2019; Foden *et al.* 2019). The CMS recognises the need to consider climate change, and a discussion paper presented to the 5th Sessional Committee of the CMS Scientific Council (UNEP/CMS/ScC-SC5/Doc.6.4.5) included a Framework for Action for conserving CMS species in the context of climate change, among other threats. Depending on the presence of 'barriers' across a species' existing range (including its migratory route), the framework directs users to the appropriate conservation action(s), including conservation, restoration, adaptation and translocation interventions. This report places the framework in the context of the broader literature, including any existing conservation actions applied to migratory species. The success and lessons learned from previous conservation programmes can complement and further develop the existing CMS Framework for Action.

Although there are an increasing number of examples of climate change adaptation being undertaken (e.g. http://www.cakex.org/), there is limited evidence of the extent to which adaptation is taking place and virtually no evaluation of the effectiveness of adaptation measures in the scientific literature (IPCC 2022). Effective monitoring across migratory ranges and evaluation of adaptations can be difficult due to a range of conceptual, analytical and practical challenges (Fuller *et al.* 2021; Pearce-Higgins *et al.* 2022), but there is growing evidence that adaptation actions can help species respond to climate change. For example, in a recent study, Bowgen *et al.* (2022) performed a literature review in which they assessed the efficacy of conservation interventions to help species adapt to climate change. Overall, 30% of studies reported a positive impact on populations also affected by a climate variable. Management that targeted particular species was found to be most effective, with a 73% modelled probability of being beneficial, compared to more generic interventions associated with habitat management or site protection, although these have the potential to impact a wider range of species. The authors noted that there was a broad suite of species and ecosystems considered, concluding that there is strong potential, and an urgent need, for further work in this field.

Our review takes a similar approach to Bowgen *et al.* (2022), but places a specific focus on migratory species (and does not include a systematic assessment of the efficacy of a study's intervention). Specifically, the literature review was conducted with the aims of:

- describing conservation strategies categorised by the International Union for Conservation of Nature (IUCN) (2012) that have previously been employed with the specific aim of conserving migratory species in the context of climate change;
- outlining key considerations for the conservation of migratory species, and providing examples of studies that have demonstrated these;
- placing our findings in context of the CMS Framework for Action; and
- discussing how conservation initiatives can involve local communities, and exploring consequences from a social perspective (cultural and economic outcomes).

Part 1 of this review assessed the evidence of the impact of climate change on (mostly) individual migratory species. It is evident from that review that communicating the varying impacts of climate change succinctly and clearly across over six hundred species listed in the CMS is a challenging task. An alternative is to use more easily monitored indicators, which are known to be linked to climate change or our response to it, to signal both the impacts of climate change on a wide suite of migratory species and the extent to which such impacts are being addressed.

Past indicators of climate change impacts have included metrics on organisms (e.g. body condition, behavioural aspects, phenology of biological events), populations (e.g. trends in abundance or recruitment of species or a group of species) or communities (e.g. biodiversity, ratio of cold-adapted species to warm-adapted species) (Philippart *et al.* 2011). Most commonly, bioindicators use metrics relating to the populations of a group of species (Siddig *et al.* 2016). As different physical and ecological processes will be driving changes for different species and ecosystems, and some species will respond positively to climate change while others respond negatively, a suite of indicators will be required to facilitate interpretation across a broad coverage of taxonomic groups, habitats and regions.

Indicators can be very valuable in providing a cost-effective early warning of environmental impacts if used appropriately (Landres *et al.* 1988; Carignan & Villard 2002). However, it is important to interpret them carefully, and use them cautiously for planning purposes, as they may be affected by confounding factors and may change in their usefulness over time and space (Lindenmayer & Likens 2011; Pearce-Higgins *et al.* 2015).

Newson *et al.* (2009) developed a framework for identifying indicators of climate change impacts on migratory species. They recommended evaluating potential indicators based on a range of criteria that can be split into three broad categories: climate change indicators should be *usable* (easy to understand and with policy relevance), *useful* (specific, sensitive and responsive to climate change) and *available* (good quality data at a reasonable cost) (Newson *et al.* 2009).

To complement the literature search on conservation interventions, these criteria were used to review literature on developing indicators to monitor climate change impacts on migratory species with the aim of:

- highlighting indicators developed since 2009 that could be used to assess the climate change impacts on migratory species;
- discussing recommendations and identifying important considerations and research needs in developing appropriate indicators of climate change impacts; and
- demonstrating the urgent need to identify and test outcome-based indicators of climate change adaptation measures (Morecroft *et al.* 2019; Pearce-Higgins *et al.* 2022).

While species listed in Appendices I and II of the CMS (CMS Appendices, hereafter) were the primary focus, studies of closely related non-listed migrant species (subspecies, or species of the same genus) were also included, to broaden the database. In addition, whilst some countries in North America, particularly, are not signatories of the CMS, studies based on CMS species on this continent were nevertheless included, on the assumption that their management is applicable and relevant to other geographical regions.

2 Methods

2.1 Conservation strategies for migratory species

A recently published literature review by Bowgen *et al.* (2022) assessed the success of established conservation strategies for mitigating the impacts of climate change on *all* terrestrial fauna (marine species were omitted). Bowgen *et al.*'s review was used as a starting point for our literature review: firstly, relevant studies cited within it were identified, and then their literature search was repeated to find articles published more recently (i.e. since 2018; detailed methods are described in S1). Specifically, searches were conducted using Web of Science and Google Scholar, with various combinations of relevant search terms (S1 Table 1). Articles were first filtered by title, then by abstract, and then by results, and any that were deemed to be irrelevant were removed from the database (S1 Table 1). Modelling studies were included where deemed appropriate (unlike the review by Bowgen *et al.* 2022, S1).

Relevance was based on a set of questions with regards to: (1) the migratory status of the species; (2) whether a conservation intervention was performed; and (3) whether adaptation to the impacts of climate change was among the key motivations for the intervention (S1 Table 2). Note that articles were initially filtered for species in the CMS Appendices only, and then additional studies on closely related species were also included, but no further searches to expand the literature to migratory species in general were conducted (i.e. no further supplementary searches were performed). In addition to articles retrieved in the primary literature review, studies cited within a number of recent review articles were also included (listed in S2 Table 1). For each article, where possible, information was extracted pertaining to: (1) the scale at which the intervention was applied according to those defined by the IUCN (2012); (2) the type of action; and (3) the geographic location and the number of jurisdictions (countries) involved.

2.2 The use of indicators for migratory species

As noted above, Newson *et al.* (2009) developed a framework to evaluate 17 potential indicators of climate change impacts on migratory species (see Table 1 within Newson *et al.* 2009). In Part 2 of this review, we have identified indicators that have been created or proposed since 2009, carrying out a rapid assessment of the literature in two steps. First, Google Scholar (which indexes a wide range of science- and policy-oriented material) was used to look at papers that referenced Newson *et al.* (2009). Secondly, a Google Scholar search was carried out for papers after 2009 using the search terms "climate change impacts indicator species" and "climate change indicator adaptation"; and with "climate indicator" in the title. In these searches, particularly relevant references were identified based on their title and abstract. Relevant references in these papers were also followed, and specific searches were conducted where gaps were identified.

Each study that was deemed to be relevant was allocated into one of six groups, based on species traits considered. These six groups consisted of: metrics on organisms ((1) behavioural aspects and (2) phenology of biological events); populations ((3) trends in abundance or recruitment of species (or a small selection of species) or (4) population trends comprehensively across a group of species)); (5) community-level metrics (e.g. ratio of cold-adapted species to warm-adapted species); and (6) indicators of climate change adaptation. The indicators identified in the review were assessed, using a simplified framework adapted from Newson *et al.* (2009), to assess the extent to which they are:

- *usable* (clear aims, easy to understand and communicate, and with policy relevance);
- *useful* (specific, sensitive and responsive to climate change); and
- *available* (good quality data, available, widely applicable, at a reasonable cost and with available or potential long-term monitoring).

3 Results

3.1 Conservation strategies for migratory species

A total of 51 articles were found in the literature review that focussed on specific conservation interventions aimed at facilitating migratory species' adaptation to the impacts of climate change (Tables 1 and 2). Among the species represented, 44 (86% of total) are listed in the CMS Appendices I and II, while the remaining seven (14%) were closely related migratory species. There were biases towards some taxonomic groups over others, with a large proportion of the articles focusing on birds (n = 21 studies, 41% of total), terrestrial mammals (n = 14, 27%) and reptiles (n = 7, 13%). In contrast, insects were represented by one study, and bats and marine mammals by two studies each (Tables 1 and 2).

Grouping articles by conservation action (IUCN 2012) also revealed biases to some strategies over others. Nearly half of the studies (n = 24, 47%) considered the designation of protected areas (*land/water protection*) as the primary action (Table 1). Three-quarters of these (n=18) performed predictive modelling to assess mismatches under future climate scenarios, while the remaining six relied on observational data (i.e. no predictive modelling was used for assessment). Twenty (39%) articles performed some form of *species management*, whilst only seven (13%) considered *land/water management*. Of these studies that conducted a direct intervention (Table 2), eleven (30%) aimed at mitigating the impacts of climate change on reproductive output, whether through manipulating nests, controlling predation or providing nest boxes. A further ten (27%) managed habitat and resources in either breeding, over-wintering or stopover sites along migratory routes (in the context of migration timing). Three studies aimed to remove direct barriers along species' migratory paths. Finally, single studies reported a cessation of human interference (hunting), translocation of individuals, or changes in the phenology of migration (achieved indirectly, through the management of livestock in the region).

Table 1. Summary of 24 articles that compared current protected areas (PA) with either observed (O) historical changes in species distributions, or modelled projections (P) of future distributions (Method). The expected status of the PA under future climates is listed as suitable (species remain within the PA) or unsuitable (species distribution is predicted to shift over the PA boundary), as highlighted by authors within the results or discussion sections within the article (not the opinions of the authors of this report). Species marked with * are those not in the CMS Appendices (but are migratory), and values in brackets after the geographic region are the number of countries considered within each study.

Species/ species group	Method	Geographic region	Status of PA	Reference
Insects				
Monarch Butterfly	O	North America (1)	Suitable	Perez-Miranda *et al.* 2020
Birds				
301 waterbirds (165 in CMS Appendices)	P	Europe, Africa, central Asia (> 40)	Evaluation of PA – suitability of critical sites declines to a greater extent in Africa and the Middle East, compared to Eastern Europe	Breiner *et al.* 2022
97 waterbirds (70 in CMS Appendices)	O	Europe (26)	Evaluation of PA – communities in specifically managed PA adapt to climate change faster than others	Gaget *et al.* 2022
61 waterbirds (46 in CMS Appendices)	O	Europe and North Africa (41)	Evaluation of PA – abundances of waterbirds in protected wetlands increasing faster than unlisted wetlands (although region dependent)	Pavón-Jordán *et al.* 2020
25 waterbirds (22 in CMS Appendices)	P	Europe (21)	Suitable	Pavón-Jordán *et al.* 2019
197 waterbirds (139 in CMS Appendices)	P	Europe and Africa (> 40)	Depends on species, season and location. General reductions in suitability for dispersive species and breeding periods but increases for passage and wintering periods	Nagy *et al.* 2022
11 migratory birds (5 in CMS Appendices)	P	Europe (1)	Suitable	Gillingham *et al.* 2015

Species/ species group	Method	Geographic region	Status of PA	Reference
Red-crowned Crane	P	Himalayas (3)	Unsuitable: distribution shifting	Liu *et al.* 2020
Red-crowned Crane	P	East Asia (1)	Unsuitable: distribution shifting	Gong *et al.* 2021
Bony fish				
23 species*	P	South America (4)	Unsuitable: distribution shifting	Bailly *et al.* 2021
Reptiles				
Loggerhead Turtle	P	Europe (1)	Unsuitable: sea level rise causes beach to become unsuitable for nesting	Katselidis *et al.* 2014
Marine mammals				
18 cetaceans (all in CMS Appendices)	O	Europe (1)	Unsuitable: correct location, but too small	Herrera *et al.* 2021
North Atlantic Right Whale	O	North America (1)	Unsuitable: ‘hotspots’ are shifting away from the protected area	Quintana-Rizzo *et al.* 2021
Terrestrial mammals				
Wildebeest*	O	Sub-saharan Africa (2)	Unsuitable: species shifting towards the boundary of PA	Thirgood *et al.* 2004
Gorilla	P	Sub-saharan Africa (3)	Variable: but most models suitable	Thorne *et al.* 2013
Himalayan Brown Bear (Gobi Bear)	P	Himalayas (2)	Unsuitable: distribution shifting	Dar *et al.* 2023
Himalayan Brown Bear (Gobi Bear)	P	Himalayas (2)	Unsuitable: distribution shifting	Mukherjee *et al.* 2021
Asian Elephant	P	East Asia (1)	Unsuitable: Correct location, but fragmented and too small	Li *et al.* 2019
Snow Leopard	P	Himalayas (6)	Unsuitable: distribution shifting	Forrest *et al.* 2012
Snow Leopard	P	Himalayas (11)	Unsuitable: distribution shifting	Li *et al.* 2022
Three ungulates (including Goitered Gazelle)	P	Central Asia (1)	Unsuitable: distribution shifting	Malakoutikhah *et al.* 2020

Species/ species group	Method	Geographic region	Status of PA	Reference
Kiang, Tibetan Gazelle	P	East Asia (1)	Unsuitable: distribution shifting	Zhang *et al.* 2022
Caribou*	O	North America (1)	Suitable, but could be expanded	Johnson *et al.* 2022
Saiga Antelope	P	Central Asia (1)	Suitable, but could be expanded	Singh & Milner-Gulland 2011

Table 2. Summary of 18 articles describing the results of a direct intervention buffering the impacts of climate change on species or their habitats. CMS Action refers to the action defined within the CMS Framework for Action, where A = Adaptation, R = Restoration and T = Translocation. Those marked with LWM indicate studies categorised into *land/water management;* all other studies focused on *species management*. Species marked with * are those not in the CMS Appendices (but are migratory), and numbers in brackets after the geographic region are the number of countries considered within each study.

Species/ species group	Intervention	CMS Action	Climate change impact	Geographic region	Reference
Birds					
Snowy Plover **Least Tern**	Relocation of nests and predator control	R, T	Rising temperature	North America (1)	Koenen *et al.* 1996
Magellanic Penguin*	Increases in vegetation cover over nests	A, R	Rising temperature	South America (1)	Stokes & Boersma 1998
Common Tern	Multiple (habitat modification, reduction in human disturbance and predation)	A, R, T	Rising temperature	North America (1)	Morris *et al.* 1991
Four species (Common Tern)	Altered elevation of nests	A	Storm surges and increased flooding	North America (1)	Rounds *et al.* 2004
Black-tailed Godwit	Provision of wetland habitat for nesting and foraging	R LWM	Rising temperature, altered rainfall	Europe (1)	Márquez-Ferrando *et al.* 2014
Three species (including Dunlin)	Restoration of wetland habitat	R LWM	Rising temperature	North America (1)	Reynolds *et al.* 2017

Species/ species group	Intervention	CMS Action	Climate change impact	Geographic region	Reference
Northern Lapwing	Provision of wet features in the landscape	A	Altered rainfall	Europe (1)	Eglington *et al.* 2010
Northern Bald Ibis	Provision of fresh water	A	Drought	North Africa (1)	Smith *et al.* 2008
Hen Harrier	Cessation of human interference	R ^{LWM}	Rising temperature	Europe (1)	Whitfield *et al.* 2008
Lesser Kestrels	Provision of nest boxes	A	Extreme heat events	Europe (1)	Catry *et al.* 2011
13 seabirds (including Laysan Albatross and Black-footed Albatross)	Modelling – habitat management	A	Sea level rise and storm surges	North America (1)	Reynolds *et al.* 2015
Piping Plover*	Modelling – habitat management	A	Sea level rise	North America (1)	Sims *et al.* 2013
Waterbirds (habitat)	Modelling – habitat availability	A	Sea level rise and storm surges	East Asia (1)	Wikramanayake *et al.* 2020
Bony fish					
Green Sturgeon	Restoration of migratory route	R, T ^{LWM}	Advanced seasonal timing	North America (1)	Steel *et al.* 2019
Brown Trout* **European Grayling***	Restoration of migratory route	R, T ^{LWM}	Advanced seasonal timing	Europe (1)	van Leeuwen *et al.* 2016
Brown Trout*	Modelling – altered management practices	R, T ^{LWM}	Advanced seasonal timing	Europe (1)	García-Vega *et al.* 2018
Reptiles					
Olive Ridly Turtle **Leatherback Turtle**	Watering nests	A	Rising temperature	South America (1)	Hill *et al.* 2015
Green Turtle	Watering and shading nests	A	Rising temperature	Oceania (2)	Smith *et al.* 2021

Species/ species group	Intervention	CMS Action	Climate change impact	Geographic region	Reference
Green Turtle	Watering and shading nests	A	Rising temperature	Oceania (1)	Jourdan & Fuentes 2015
Leatherback Turtle **Hawksbill Turtle** **Green Turtle**	Shading and translocation of nests	A	Rising temperature	Central America (1)	Esteban *et al.* 2018
Leatherback Turtle	Shading of nests	A	Rising temperature	Central America (1)	Patino-Martinez *et al.* 2012
Leatherback Turtle	Shading of nests (and explore options for tree planting)	A	Rising temperature	Oceania (1)	Wood *et al.* 2014
Bats					
Brown Pipistrelle	Provision of roosting boxes	A	Extreme heat events	Europe (1)	Flaquer *et al.* 2006
Greater Horseshoe	Habitat restoration surrounding roosts - afforestation and agri-environment schemes	R ^{LWM}	Complements warmer temperatures	Europe (1)	Froidevaux *et al.* 2017
Terrestrial mammals					
Scimitar-horned Oryx	Translocation of individuals	T	Altered rainfall	Sub-Saharan Africa (1)	Mertes *et al.* 2019
Elk (Wyoming, USA)*	Provision of food to young	A	Altered rainfall	North America (1)	Smith & Anderson 1998
Saiga Antelope	Vaccination of livestock prior to the arrival of adults in spring	A	Changes in migration phenology	Central Asia (1)	Khanyari *et al.* 2022

Of the 24 articles that focussed on protected areas, eleven (47%) were undertaken within the borders of a single country only (e.g. within the United Kingdom, Finland, Spain). Only eight articles (33%) encompassed a regional area (e.g. Europe, the Himalayas, or more than three adjacent countries). Three studies captured the migratory routes of species between continents, including Europe, Africa and Central Asia, all of which focused on migratory waterbirds (Pavón-Jordán *et al.* 2020; Breiner *et al.* 2022; Nagy *et al.* 2022). With this in mind, there was a geographical bias across studies, with 13 (25%) and 11 (21%) studies being conducted within Europe and North America respectively. Whilst 12 studies were performed within Asia, these were relatively evenly split across the broad continent, between the Himalayas (alpine habitats, five studies), Central Asia (steppe and semi-arid desert habitats, two studies) and East Asia (tropical/coastal habitats, three studies). North Africa, Central America and South America were, in contrast, less well represented (one, two and two studies, respectively).

3.2 The use of indicators for migratory species

Eighty-eight papers reference Newson *et al.* (2009), although only 14 papers were relevant to indicating climate change impacts on migratory species. We identified a further 39 papers published since 2009 about indicators of climate change impacts on biodiversity relevant to migratory species.

Twelve of the papers examined multi-species indicators, which generally averaged population trends comprehensively across a taxonomic group of species (Table 3). Nine papers used similar data, but investigated change at the community level by comparing the trends of cold-adapted and warm-adapted species. Eleven papers examined phenological changes, although the link to climate change indicators was often weak (Table 3).

The papers focussed most commonly on birds (19 papers in total), with papers examining bat (6) and fish (6) indicators also common (Table 3). The papers relating to bat indicators highlighted recent technological advances in biodiversity monitoring, reviewed by Stephenson (2020), which will improve our ability to develop climate change indicators, especially in regions where traditional biodiversity monitoring is challenging. There were also recent papers that discussed the possibility and urgency of developing indicators of climate change adaptation (Morecroft *et al.* 2019; Pearce-Higgins *et al.* 2022). The usability, usefulness and availability of these indicators is discussed below in Section 4 (Table 4).

Table 3. Papers relevant to climate change indicators found in our literature search, divided by the type of indicator they were related to and the taxonomic group examined.

Indicator type	Birds	Terrestrial mammals	Bats	Marine mammals	Fish and sharks	Reptiles	Insects	General review
Behavioural change	Wilcox *et al.* 2018			Wilcox *et al.* 2018				
Phenological change	Dolenec 2013; Farnsworth *et al.* 2016; Thackeray *et al.* 2016; Franks *et al.* 2018a	Thackeray *et al.* 2016	Stepanian & Wainwright 2018; Haest *et al.* 2021	Cherry *et al.* 2013; Thackeray *et al.* 2016	Peer & Miller 2014; Thackeray *et al.* 2016; Langan *et al.* 2021	Mazaris *et al.* 2009	Thackeray *et al.* 2016	Anderson *et al.* 2013 (marine)
Single-species (or small selection of species) population metrics	Trivelpiece *et al.* 2011; Cook *et al.* 2014; Zmarz *et al.* 2015	Shilla 2014		McClatchie *et al.* 2016; Hazen *et al.* 2019	Hazen *et al.* 2019			Hazen *et al.* 2019 (marine top predators)
Multi-species (comprehensive across taxonomic group) population metrics	Eglington & Pearce-Higgins 2012; Renwick *et al.* 2012; Martay *et al.* 2017; Fraixedas *et al.* 2020	Martay *et al.* 2017	Jones *et al.* 2013; Border *et al.* 2017; Martay *et al.* 2017		Nash *et al.* 2016a, 2016b		Martay *et al.* 2017; Newson *et al.* 2017	Parmesan *et al.* 2013; Oliver & Morecroft 2014; Korner-Nievergelt *et al.* 2022

Indicator type	Birds	Terrestrial mammals	Bats	Marine mammals	Fish and sharks	Reptiles	Insects	General review
Community Temperature Index and other community-level indicators of climate change impacts	Devictor *et al.* 2008; Gregory *et al.* 2009; Clavero *et al.* 2011; Devictor 2012; Pearce-Higgins *et al.* 2015; Pérez-Granados & Traba 2021		Tuneu-Corral *et al.* 2020		Bowler & Böhning-Gaese 2017		Devictor 2012; Martay *et al.* 2016	
Indicators of climate change adaptation								Morecroft *et al.* 2019; Prober *et al.* 2019; Bowgen *et al.* 2022; Pearce-Higgins *et al.* 2022

4 Analysis of results and discussion

4.1. Conservation actions and climate change

4.1.1 Land/water protection

Many vulnerable migratory species rely on protected areas during breeding and over-wintering, and at stopovers during migration. While such designated areas may become redundant as areas of habitat suitability and range envelopes shift beyond their static boundaries, ongoing distribution shifts are likely to be facilitated by the presence of large areas of suitable habitat, such as provided by protected areas, close to currently occupied ranges (Howard *et al.* 2023). Thus, it has recently been recognised that the inclusion of climate change impacts in the designation of protected areas is critical to their continued success. Indeed, during the literature search a number of reviews were identified that emphasised this point, in terrestrial (Ranius *et al.* 2023), marine (Wilkes *et al.* 2019), coastal (Wikramayake *et al.* 2020) and freshwater systems (Bower *et al.* 2015).

The suitability of existing protected areas under future climate scenarios varied among the articles in the database (Table 1). Protected areas in the United Kingdom, for example, are expected to remain suitable for migratory avian species (such as many passerines, Stone Curlews and European Nightjars (Gillingham *et al.* 2015)), as their distributions shift poleward. Thirgood *et al.* (2004) tracked annual movements of Wildebeest during their migration across the Serengeti, to find that the species spent 90% of their time within currently protected areas. Migration routes have changed slightly since the 1970s, however, such that herds spend a greater proportion of their time close to reserve boundaries, where they are vulnerable to persecution. Ongoing assessment of the protected area is therefore required to ensure any further shifts in the species' range are accounted for.

Predictive modelling studies can provide an indication of the efficacy of current protected areas under future climate scenarios. For example, distribution models of the Himalayan Brown Bear (Gobi Bear) project that their distribution will fall well outside current protected areas (Mukherjee *et al.* 2021), and work is required to address this mismatch. Similar findings were found for the Red-crowned Crane in China (Liu *et al.* 2020; Gong et al. 2021). Herrera *et al.* (2021) showed that marine reserves in the Canary Islands are currently not large enough to protect a number of endangered cetacean species, and they also call for a revision of these reserves in light of projected climate change-induced distribution shifts.

Protected areas typically encompass extensive, but contiguous, regions, such that they benefit multiple species and habitats (Thomas & Gillingham 2015). In the context of migratory species, and particularly those listed in the Appendices of the CMS that traverse across multiple jurisdictions, this conservation strategy provides valuable opportunities for multinational co-operation. Only a quarter of the studies that considered protected areas encompassed multiple jurisdictions, however, and so it appears that the potential for co-ordinated conservation approaches has not yet been fully realised.

4.1.2 Land/water management

Four articles were found that applied conservation interventions to mitigate the impacts of climate change on habitat quality and availability for migratory species (Table 2), including different restorative and adaptive actions. For example, reproductive output of the declining Hen Harrier in Wales increased due to cessation of human interference (persecution), combined with increases in May temperature (Whitfield *et al.* 2008). In North American rivers, where Green Sturgeon are declining, opening a dam later in the autumn season supported delayed migration patterns (Steel *et al.* 2019). Indeed, leaving the dam open all year round (after decommissioning) allowed for unhindered migration, a higher number of individuals reaching their spawning grounds, and a rapid increase in population abundance. The seasonal management of fishways in Norway has also been implicated in the early-spring and late-autumnal migration patterns of the salmonid European Grayling and Brown Trout respectively (van Leeuwen *et al.* 2016, and see García-Vega *et al.* 2018).

Habitat modifications might also come about unintentionally, through changes in land use surrounding a population's key habitat. An over-wintering population of Black-tailed Godwit in Spain has grown over recent decades due to an increase in agricultural production in the region (Márquez-Ferrando *et al.* 2014). New rice fields and fish farms adjacent to the colonies support more abundant and diverse invertebrate communities, important prey for this largely coastal species. In contrast, in the absence of such resources, populations of the Black-tailed Godwit that over-winter in northern Africa have steadily declined (Márquez-Ferrando *et al.* 2014). In the UK, population recoveries of the Greater Horseshoe Bat have been attributed to a combination of habitat restoration (afforestation), improved management (agri-environment schemes) and climatic conditions that have become more suitable for the species' breeding and survival (Froidevaux *et al.* 2017). Management of land and water at local scales allows for a degree of flexibility, such that practices can be adapted to account for specific threats on a case-by-case basis. However, the success of conservation actions at one site along a migratory route relies on the appropriate management of habitats across the remainder of a species' range.

4.1.3 Species management

Conservation actions that focus on the management of species can have immediate and tangible outcomes, and can be performed over a relatively short timeframe (e.g. in response to extreme climatic events). Thirteen articles that applied a direct intervention on a CMS species were found, although there were biases towards certain taxonomic groups and conservation actions (Table 2). With the exception of one study on each of the Brown Pipistrelle Bat (Flaquer *et al.* 2006), the Elk (Smith & Anderson 1998) and the Scimitar-horned Oryx (Mertes *et al.* 2019), all other studies considered either reptiles or birds. Indeed, six studies focused on manually regulating temperature within turtle nests, to reduce feminisation rates in hatchlings (Table 2; see Part 1 of this review for a description of temperature-dependent sex determination). Such interventions included cooling nests with sea water (Jourdan & Fuentes 2015; Smith *et al.* 2021), erecting shade cloths over the nests (Patino-Marinez *et al.* 2012; Wood *et al.* 2014), and relocating eggs to a cooler side of an island (Esteban *et al.* 2018). Conversely, whilst the sex of Estuarine Crocodile hatchlings is also determined by nest temperature, no studies reporting similar conservation actions for this species were found.

In addition to turtles, direct interventions have helped to buffer bird nests from extreme events like heat waves and storm surges (Table 2). For example, manual elevation of nests improved reproductive rates of the Common Tern, in comparison to those that remained at sea level and were thus subject to floods (Rounds *et al.* 2004). Similarly, lifting nests to higher ground and erecting predator-proof fences helped to maintain the productivity of Snowy Plover and Least Tern colonies (Koenen *et al.* 1996) in the USA. Finally, in Argentina, the restoration of native vegetation around Magellanic Penguin rookeries has helped to lower temperature within the nests (by increasing shade), as well as reduce predation on eggs and chicks (Stokes & Boersma 1998) - a relatively simple intervention that has improved the reproductive success of the colony.

It should be stressed that direct interventions must be well informed to avoid any unintended consequences. For example, nest boxes were provided to the Lesser Kestrel in an attempt to support a declining population in Portugal (Catry *et al.* 2011). Wooden boxes with a southerly aspect became very hot under extreme heat events, however, causing increased mortality and reduced fitness of fledglings. Similar effects were reported in a study of the Brown Pipistrelle Bat: in a human-modified landscape (rice fields in Spain), the provision of breeding boxes for this species improved reproductive output, however the proper location of boxes was deemed to be critical to avoid mass die-offs during heat waves (Flaquer *et al.* 2006).

In addition to extreme heat and storm surges, direct interventions have been employed to reduce the effects of drought. Supplementary water sources were provided for the Northern Bald Ibis near the species' Moroccan breeding grounds (Smith *et al.* 2008). A significant improvement in reproductive output was reported, especially during 'dry' years (although the effect was significant in all years) and this intervention is now an integrated part of the ongoing conservation of the species.

Similarly, although not in direct response to drought, the provision of 'wet' features in the increasingly dry landscape of southern England acts to supplement prey abundances of Northern Lapwings, helping to stabilise population declines of this species (Eglington *et al.* 2010), a measure that applies positively across breeding waders (Franks *et al.* 2018b). With increasing evidence that summer drought conditions can reduce the availability of soil invertebrates to migratory species that feed on them (Pearce-Higgins & Morris 2023), habitat management to reduce artificial drainage, or to raise water levels, is likely to have a generic beneficial impact in such systems as a mechanism to increase their resilience to hot, dry conditions (e.g. Carroll *et al.* 2011).

In peatlands, (re-)wetting of landscapes can also have wider adaptation and mitigation benefits, reducing the risk of wildfire with associated carbon emissions (Kirkland *et al.* 2023), reducing carbon loss associated with the oxidation of the peat, improving water quality and reducing downstream flood risk (Martin-Ortega *et al.* 2014; Bonn *et al.* 2016), and restoring general habitat condition. While species-management interventions have generally been shown to be successful, they are limited in terms of scalability, particularly in remote areas like the Pacific Islands (in the case of critically endangered turtles). Moreover, they do not necessarily provide sustainable, long-term solutions in the absence of broader conservation measures, such as designating protected areas and regulating hunting or bycatch.

Many of the articles focus on changes in population abundance, survival, reproductive output or sex determination, reflecting a potential mismatch between the response traits considered and the most commonly reported responses of migratory species to climate change (see Part 1 of this review). Rather than declining population size, for example, a key impact of climate change is the altered timing of migration, and mismatches in trophic interactions that come about when interacting species within an ecosystem adapt at different rates (Bradshaw & Holzapfel 2006; Thackeray *et al.* 2016). However, only four studies were found that addressed the altered timing of migrations, these being of freshwater fish (van Leeuwen *et al.* 2016; Garcia-Vega *et al.* 2018; Steel *et al.* 2019) and the Saiga Antelope (Khanyari *et al.* 2022). This could reflect a relatively weak evidence base in support of mismatch driving population declines in migratory species (Samplonius *et al.* 2021).

4.2 Considerations for migratory species

4.2.1 Coordinated responses across jurisdictions

The conservation of migratory species, especially those in the CMS Appendices, requires coordination amongst multiple jurisdictions. Some articles in our database particularly highlighted where such management is required. For example, distribution models of the Snow Leopard revealed that this species' range is predicted to shift northward from Nepal into China, with the authors of that study calling for greater collaboration between the two nations (Li *et al.* 2022). Similarly, the Vulnerable Red-crowned Crane is projected to shift distribution from China into Russia and Mongolia (Liu *et al.* 2020). The ongoing conservation of such species will require close collaboration between countries.

Formal legislation, regulations and other policy tools can ensure effective collaboration between nations when mitigating the impacts of climate change on migratory species. The Ramsar Convention, for example, which aims to conserve global wetlands that are critical for migratory birds, has implemented several resolutions since its inception in 1971 to directly address climate change impacts on these important habitats (Gitay *et al.* 2011). Legally binding regulations on marine fishery practices are another example where international laws can help to conserve migratory species as they traverse across international borders and into areas beyond national jurisdictions (Gjerde *et al.* 2008, and see section 4.2.3 for further discussion of dynamic conservation strategies). While work remains to ensure the most relevant biological data are readily available to policy makers and managers (Dunn *et al.* 2019), these existing agreements provide working frameworks into which policy changes, that aim to mitigate climate impacts, can be applied (e.g. Sahri *et al.* 2020).

Migratory species encounter a broad suite of threats, which can differ between their breeding and wintering grounds, and along their migration routes. As such, in addition to the protection of broad regions through protected areas, there is a requirement for fine-scale interventions that are optimised for local conditions. Such an integrated approach was demonstrated by Morris *et al.* (1991), who employed a number of conservation actions for the Common Tern in the Canadian Great Lakes region. At one breeding colony, managers reduced human disturbance and predation of eggs from Ring-billed Gulls, and restored various aspects of the species habitat. These interventions were deemed a success, as the population has since recovered. At a nearby colony, however, ecologists focused more on vegetation control, the exclusion of nesting gulls, reduction of human disturbance and the construction of new habitat. The abundance of Common Tern at this colony initially stabilised, but then continued to decline. The authors proposed that the disappointing outcome at the second colony was due to, among other reasons, closer proximity to a large urban centre and greater exposure to mammalian predators. Despite the different outcomes, this work demonstrates the need for multiple, complementary interventions running concurrently at any given location, as well as a site-specific approach.

4.2.2 Conservation of migratory routes

Migratory species are generally poorly covered by protected areas, with only 9% of migratory birds' ranges adequately covered compared to 45% of non-migratory species (Runge *et al.* 2015). There are existing gaps in coverage across the annual cycle of many migratory species, particularly in relation to the protection of important passage habitats and locations, which climate change will exacerbate, given its impact on species distributions and movements. In response, the establishment of effective networks of protected areas for migratory species should be a high priority (Johnston *et al.* 2013), not just to protect existing sites and populations, but to provide nearby areas of suitable habitat for range-shifting species to colonise (e.g. Gillingham *et al.* 2015; Howard *et al.* 2023). Importantly, this requires international action and co-ordination, as noted earlier. Combining regional (multi-national) and local (site-specific) conservation actions is required to conserve coherent and interconnected migratory routes. Indeed, migratory species rely not only on suitable winter and breeding habitat, but also 'stepping stones' along their migratory path. For example, nature reserves in south-east China provide some sanctuary for Asian Elephants under both current and a future (2050) climate scenario (although suitable habitat is likely to be severely restricted in the latter) (Li *et al.* 2019). The authors note, however, that these protected areas are small and fragmented, and hence can only support small elephant populations that are likely to become unviable. To adequately conserve this species, protected corridors are required between the reserves to allow migration. For some groups, such as migratory shorebirds, these 'stepping stone' habitat patches are separated by thousands of kilometres, so are required to be highly productive in order to provide sufficient food resources to fuel the next stage of their migration (Piersma & Lindström 2004).

The establishment and conservation of interconnected migratory pathways in marine habitats has seen some success. One such approach is the creation of 'sister sanctuaries', which are paired marine reserves that together aim to conserve wintering, breeding and migration grounds of endangered marine migrants (Di Sciara *et al.* 2016). Conservation managers in the USA, Dominican Republic, Martinique and Guadaloupe, for example, are working together to protect sanctuaries in the breeding and feeding grounds of the Humpback Whale (Hoyt 2012); similar networks of reserves are found in the North and East Pacific, among others (Chin *et al.* 2017).

Another example is that of the Special Protection Area network established under the EU Birds Directive (EC/79/409), modelled to be important for continuing to support internationally important breeding seabird and migratory waterbird populations in the UK under future climate change scenarios (Johnston *et al.* 2013). The network has also been recently demonstrated to provide effective conservation benefit to the rare and conservation priority habitat specialists that rely on them, and to better support cold-adapted bird species vulnerable to climate change (Barnes *et al.* 2023), particularly towards their southern range margin (Gillingham *et al.* 2015).

4.2.3 Dynamic conservation strategies

Technological advances in animal tracking, satellite imagery and data processing can facilitate the development of new conservation strategies that can address the considerations outlined above. ‘Dynamic’ management tools, for example, aim to provide targeted actions that are flexible in time and space (D’Aloia *et al.* 2019; Maxwell *et al.* 2020). ‘Mobile marine protected areas’ are designated areas whose boundaries shift in line with shifts in target species or habitats, including the movements of migratory species. Such frameworks can be designed to change from daily to seasonal timeframes, as required. Practices reflecting this dynamic approach are already well integrated into management programmes of fishery industries. Longline fishing zones in Australian seas, for example, are dictated by shifting abundances of Southern Bluefin Tuna: updates of the species’ movements are provided, almost in real-time, so that restrictions can be adjusted and quotas are not exceeded (Hobday *et al.* 2011). In the North Pacific, a volunteer-based programme, ‘Turtle Watch’, tracks turtle migration and sea surface temperature, to apply restrictions on fishing during critical periods of the species’ life-cycles (Howell *et al.* 2015). Mobile protected areas have also been implemented, or proposed, for the Saiga Antelope (Bull *et al.* 2013) and Canadian Caribou (Taillon *et al.* 2012).

Climate change is altering the timing and distance of migratory routes of species, although such responses have been found to vary from year to year, in part depending on local weather conditions (which can also act as a phenological cue). An increasing proportion of European wildfowl and wading birds are shifting their winter distribution towards the north-east in response to milder winter temperatures (e.g. Maclean *et al.* 2008; Pavón-Jordán *et al.* 2015). These responses are particularly driven by warmer winters in Scandinavian and central European breeding grounds, as individuals undertake shorter migrations and ‘short-stop’ before they reach more traditional, milder wintering grounds of western and southern Europe (Burton *et al.* 2020). These shifts mean that having a network of protected sites is increasingly important in a changing climate to maintain protection of critical habitats and populations (Johnston *et al.* 2013; Pavón-Jordán *et al.* 2015). Importantly, though, warmer sites that may no longer be regularly used as species shift their distribution should still be maintained as they can then become reoccupied and important during colder winters. This means that an integrated dynamic approach to protected area networks is required, which considers the protection, management and creation of sites in order to maximise the resilience of the network, and the species that use it, to a changing climate (Dodd *et al.* 2010).

Dynamic habitat management has also been successfully employed in wetlands in the USA to conserve migrating wetland birds, including Dunlin (Reynolds *et al.* 2017; Table 2). These species rely on ephemeral wetlands in the southern United States on their southward migrations. The distribution of species within the wetlands, however, varies between years depending on rainfall and cropping patterns. This means that traditional, fixed designation boundaries would need to encompass an unnecessarily large area to provide suitable habitat in any one year. In this instance, farmers within the wetland region were invited to participate in a conservation programme in which they received funds, through a reverse-auction process, to manage part of their cropping land as wetland habitat for the species (Reynolds *et al.* 2017). Follow-up monitoring confirmed that fields included in the programme supported higher abundances of birds in comparison to those that were not included. This initiative is performed on an annual timeframe, allowing for targeted, cost-effective management, in critical habitat, when required. Where resources are available, such programmes could be adapted to migratory species in other ecosystems (e.g. Polar Bears and African ungulates) to track migrations in real-time and impose targeted conservation actions in the relevant locations.

4.3 Wider considerations for conservation

4.3.1 Trade-offs and synergies

While there is a growing push towards climate change mitigation to reduce greenhouse gas emissions and combat climate change, there is little sign that emissions will decrease substantially in the near future, and thus there is an urgent need to consider the potential for adaptation to reduce the risks that climate change poses to species, alongside adaptation in other sectors of human society. These twin adaptation goals can result in synergies and opportunities, but also conflicts and trade-offs, between different responses to climate change (Morecroft *et al.* 2019). For example, large-scale tree planting has been suggested as a win-win for biodiversity conservation and climate change mitigation, but inappropriate planting has the potential for significant negative consequences for open country species of conservation concern, such as across tropical savannas or northern peatlands of Europe, both of which are important habitats for migratory species (e.g. Pálsdóttir *et al.* 2022). Conversely, the restoration of natural hydrological regimes on those peatlands has the potential to deliver climate change mitigation, nature-based solutions to improving water quality and reducing downstream flood risk, and climate change adaptation.

Another example of synergistic benefits is provided by Johnson *et al.* (2022), who mapped biodiversity hotspots, the presence of unique species with high conservation value, climate refugia, and soil carbon storage (which, if released, would add to Canada's total carbon emissions), all within the broad distribution of Caribou. The authors demonstrate that, by protecting the Caribou's habitat, a number of other biodiversity and ecosystem services would also be conserved, and propose that the species could be used as a 'proxy' for the future designation of protected areas across the region. Ecosystem services provided by migratory species, and the far-reaching benefits associated with their conservation, are discussed in detail in Part 3 of this review.

Designating areas for protection can have substantial ramifications for local communities, through the exclusion of agriculture (and added pressures on food security), urban growth, housing and industrial activities, thereby compromising economic stability (see Lamprey *et al.* 2022). Therefore, the costs of incorrectly allocating protected areas are not trivial, especially for developing nations. In northern Uganda, researchers have identified key forest habitat which provides a corridor that links two protected areas and is essential for the migration of Chimpanzees, among other fauna. In recent years, however, pressure from agriculture (subsistence and commercial), non-indigenous tree plantations, oil extractions and urban growth has progressively encroached onto this important corridor, such that only small, fragmented patches now remain (and researchers predict that 99% of the habitat will be lost by 2025 (Lamprey *et al.* 2022)). Conservation interventions are thus urgently required, but ecologists stress that any work must engage local communities and provide a viable economic alternative to current, consumptive industries.

Indeed, the conservation of migratory species should aim to benefit local communities, enhancing economic and cultural well-being (which, in turn, generally improves conservation outcomes). In contrast to the example described above, a long-term conservation programme for Chimpanzees in the Kigali National Park in western Uganda has improved a number of socio-economic outcomes in villages adjacent to the national park (Thompson *et al.* 2020). At any given time, the programme employs up to 25 staff from local communities, and since its inception in 1987, it has helped to develop health, literacy and scholarship programmes, as well as sustainable energy initiatives. In return, the ongoing persistence of Chimpanzees in the park is largely due to a well-informed and engaged local community, which has taken ownership of the conservation of the species.

Migration events can also provide opportunities for seasonal eco-tourism and wildlife festivals, with associated benefits including the formation of protected areas, revenue specifically for conservation, economic benefits to the broader community, protection from other damaging industries, and increased public awareness and participation in wildlife protection (Hvenegaard 2011). Migratory marine species, including rays, sharks, whales and Dugongs, can provide unique tourism 'experiences' and viable economic alternatives to fisheries and mining. Such alternatives (if conducted appropriately) are particularly valuable for developing nations, for which resources for environmental conservation can be limited (Mustika *et al.* 2020; Gonzalez-Mantilla *et al.* 2021). Moreover, a network of such programmes, across multiple jurisdictions, can help to maintain coherent migratory pathways (O'Malley *et al.* 2013). Conservation programmes can also be integrated into forestry, farming or fishing policies, whereby stakeholders receive subsidies for performing conservation actions (Froidevaux *et al.* 2017; Reynolds *et al.* 2017).

4.3.2 Accounting for uncertainties

Given the uncertainties over the effectiveness of different interventions and future climate scenarios, there is an urgent need both to expand the evidence base to improve decision making (IPCC 2022) and to effectively monitor and evaluate the success of interventions (Pearce-Higgins *et al.* 2022). Conservation actions should always be based on robust evidence (as far as possible), and ongoing monitoring and re-evaluation is critical to the success of any conservation programme (see Chin *et al.* 2017), and for the avoidance of any unexpected consequences (e.g. Catry *et al.* 2011). The CMS Framework for Action, outlined in UNEP/CMS/ScC-SC5/Doc.6.4.5, was produced with the aim of guiding conservationists to the most appropriate type of intervention for a migratory species or habitat, given a specific set of circumstances. The framework can be employed multiple times during the course of a species recovery (or protection), and adjustments made to the course of action as required. Whilst it was not intended to be all encompassing, the framework could be further developed to provide specific guidance on: (1) initial planning; (2) initial monitoring; (3) evaluation of the intervention; and (4) adaptation or refinement of the intervention should it be required (Grantham *et al.* 2010; Watchorn *et al.* 2022).

This feedback loop is important for a number of reasons, particularly in the context of climate change (Pearce-Higgins *et al.* 2022). Firstly, as climate suitability changes and species' distributions shift in time and space, the priorities for conservation in particular regions or locations may change, so that programmes are essentially conserving 'moving targets'. This means conservation objectives may need to evolve over time and robust monitoring protocols need to be put in place. Secondly, ecological models, which are often used to identify the most vulnerable species, and inform the location and management of protected areas, come with a range of assumptions and uncertainties, especially for rare (data-deficient) species (Foden *et al.* 2019). As more data are collected and integrated into models, the accuracy of predictions can improve (or, at least, be better informed). Finally, there is often a time lag before species begin to respond to an intervention, particularly for late-successional species, making the evaluation of its 'success' difficult (Watts *et al.* 2020). For this reason, a range of different indicators may be required that track improvements in enabling conditions and adaptation actions on the ground, before then considering the impact of those actions on ecological conditions, species' responses to climate change, and, ultimately, the status of species, communities and ecosystems (Pearce-Higgins *et al.* 2022).

4.4 Indicators of climate change impacts and adaptation

4.4.1 Migratory species indicators of climate change

Irrespective of the conservation approach employed, all strategies require timely intervention and thus rely on efficient and accurate monitoring of species' responses to climate change. Scientists and policy makers are seeking indicators to summarise and track the complex impacts of climate change across a wide range of species (Gregory *et al.* 2009; Clavero *et al.* 2011), both as a policy tool to monitor progress and allocate resources, and to aid engagement and awareness of the problem. Newson *et al.* (2009) identified a range of indicators of climate change impacts on migratory species, generally using population-level metrics, such as abundance and reproductive success. Since that review, there has been a range of developments, both technologically and statistically, that will improve our ability to monitor climate change impacts on biodiversity. The key changes since 2009 are the development of climate-related community metrics and large technological advances, and a reduction in cost for (automated) biodiversity monitoring (Stephenson 2020), although these will not be applicable to all systems. Most recently, the development of indicators of climate change adaptations (i.e. human interventions to facilitate climate change adaptation) has been identified as an urgent priority (Morecroft *et al.* 2019; Pearce-Higgins *et al.* 2022). Examples of climate change adaptation actions include habitat restoration, site management and invasive species control (Bowgen *et al.* 2022).

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. The usability, usefulness and availability of each type of indicator is discussed below (Table 4). 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.

Table 4. Recent indicators of climate change impacts and adaptation relevant to migratory species. These were assessed using a simplified framework adapted from Newson *et al.* (2009).

Indicator	(a) Usability Easy to communicate and with policy relevance	(b) Usefulness Specific, sensitive and timely indication of climate change impacts	(c) Availability Widely available, good quality, preferably long-term data
Foraging time of Australian seabirds and pinnipeds (Wilcox *et al.* 2018)	Used to indicate climate change impacts. Foraging time is likely to be associated with long-term changes in population size. This indicator **may lack policy relevance** and be hard to communicate unless the link between foraging times and population sizes is confirmed. Applicability to other taxonomic groups was not assessed but is likely to reflect resources used by other taxa.	Foraging time is **sensitive** to climate change and is **more responsive to climate change** than diet, body mass, breeding phenology, breeding success and population size. **Specificity was not assessed**.	Monitoring foraging time usually involves expensive tracking devices and requires individuals to be caught. This may make long-term monitoring **inaccessible** for monitoring marine climate change impacts, but useful where tracking projects are carried out.

Phenological changes in breeding and migration across many taxonomic groups (Thackeray *et al.* 2016)	Phenological changes are a key signal of the biological impacts of climate change but the link between phenological change and population change is limited (Samplonius *et al.* 2021). In general, bird species that show greater advances in migration and breeding phenology have more positive population trends (Franks *et al.* 2018a; Kolecek *et al.* 2020). The **policy relevance of phenology indicators may therefore be unclear**. The aims when using phenological indicators should be clarified.	Phenological changes are generally strongly linked to climate change, although can be linked to other factors such as photoperiod (Anderson *et al.* 2013) (**variable specificity**). Short-term changes can often be linked to weather (**good responsivity**) but phenological change is very variable between species (Thackeray *et al.* 2016) (**variable sensitivity**) and may not reflect wider population changes.	Weather surveillance radars have been used to monitor bat and bird migration phenology (Farnsworth *et al.* 2016; Haest *et al.* 2021). Citizen science schemes are often used to monitor bird and butterfly phenology (Thackeray *et al.* 2016; Franks *et al.* 2018a). Professional schemes such as light-trap monitoring and suction traps have been used to monitor insect phenology (Thackeray *et al.* 2016).
Population trends of Hippos, Waterbucks, Wildebeest and African Elephants (Shilla 2014)	Used to indicate climate change impacts. These species are charismatic species and important for ecosystem services, which would give them **high public interest**. However, it is **unclear how much trends reflect climate change impact**s and how applicable these indicators are to other species.	Species that were considered to be **sensitive** to climate change were selected. However, population trends of these species will be heavily impacted by other environmental changes, indicating **very low specificity**.	The availability of data was not discussed. Long-term monitoring of these species is currently carried out in some locations.

Marine top predators The use of metrics relating to marine top predators to indicate climate and other changes are reviewed by Hazen *et al.* (2019). Examples include California Sea Lion juvenile mortality (McClatchie *et al.* 2016), and seabird breeding success (Cook *et al.* 2014).	Monitoring top predators is **likely to reflect broader ecosystem health** and can help guide conservation efforts (Hazen *et al.* 2019). **Charismatic species** such as Polar Bears may help to **capture public attention**.	Species that are **sensitive and responsive to climate change impacts should be selected**. Predators with a **specialised diet, or those with highly restricted ranges, are likely to be more sensitive** to ecosystem change, e.g. Antarctic penguins are sensitive to environmentally-mediated changes in the abundance or distribution of krill (Euphausia superba) (Trivelpiece *et al.* 2011; Hazen *et al.* 2019). **Indicators based on reproductive success are often more responsive** to environmental change than those based on abundance changes in long-lived predators (Cook *et al.* 2014).	Many marine predators are relatively easy to observe compared to other marine species, which aids monitoring. However, monitoring marine predators can be expensive. Technological advances, such as improvements in automated sampling, are likely to improve the accessibility of these indicators in the future (Hazen *et al.* 2019). An example of remote sampling includes using unmanned aerial vehicles to monitor penguin populations (Zmarz *et al.* 2015).
Marine fish biomass (Nash *et al.* 2016a, 2016b)	Used to indicate impact of fisheries. If changes in fishery activity were accounted for, this could be used to indicate climate change impacts. Applicability to other taxonomic groups has not been assessed.	The indicator was found to be influenced by habitat so **habitat should be accounted for to improve specificity**. More research would be required to test **sensitivity and responsiveness**, after accounting for fishery activity.	Fish biomass monitoring is commonly undertaken so research into using currently available data in conjunction with data on fishery activity could be a cost-effective method to develop a marine climate change indicator.

Multi-species population metrics Averaged population trends across a group of species. These will respond to a variety of environmental factors, so modelling must be carried out to estimate climate-driven population changes (Fraixedas *et al.* 2020). For example, the climate change impacts on birds, mammals and insect groups were modelled in Martay *et al.* (2017).	These **can be clear and easy to communicate** if the climate change impacts on populations can be disentangled from other environmental changes. This approach can also be used to compare the relative impact of climate and other changes, which has **high policy relevance**. An example is the finding that climate change has had a relatively minor impact on UK bird populations compared to changes in land use intensity (Eglington & Pearce-Higgins 2012).	It can be **very challenging to attribute population trends to climate change** (Parmesan *et al.* 2013; Fraixedas *et al.* 2020). The mechanisms of climate change impacts and the interaction between climate and land use change are poorly understood (Oliver & Morecroft 2014). Additionally, species' responses to increasingly frequent extreme events can be difficult to predict. It is therefore **important to carry out modelling work to ensure that these indicators are specific, sensitive and responsive** to climate change.	Typically, these indicators require long-term, large-scale monitoring of a group of species to develop these indicators, **restricting their use to better monitored regions and taxa**. The robustness of indicators is improved by the inclusion of rare species (as these may be at the edge of their range), which requires more extensive monitoring (Renwick *et al.* 2012; Korner-Nievergelt *et al.* 2022).

Community Temperature Index (Devictor *et al.* 2008) and other **community-level indicators** of climate change impacts. These compare population trends of cold- and warm-adapted species within a group of species. Climate change impacts are indicated by a rise in warm-adapted species relative to cold-adapted species. Community-level indicators of climate change have been used in European countries for birds (Devictor *et al.* 2008; Gregory *et al.* 2009), butterflies (Devictor 2012), moths (Martay *et al.* 2016), marine fish (Bowler & Böhning-Gaese 2017) and bats (Tuneu-Corral *et al.* 2020).	Since 2009, there has been increasing use of robust community-level indicators (Morecroft *et al.* 2019). They can be **used to highlight regions and habitats where climate change impacts are greatest** (Pearce-Higgins *et al.* 2015). A disadvantage of these compared to averaged multi-species indices is that **they are less intuitive and more difficult to communicate than simple population trends** or biodiversity measures: they indicate climate-driven changes in species assemblages, but not whether species or biodiversity are generally declining. Indicators based on **bat communities** have been identified as having **high policy relevance** as bats often indicate invertebrate abundance, provide a range of ecosystem services such as pollination, and correlate with responses of other taxa (Jones *et al.* 2009; Tuneu-Corral *et al.* 2020). However, bats generally undertake shorter migrations than migratory birds, so indicators based on bat community metrics will not represent all of the climate change that many migratory birds experience across their cross-continental migration routes.	These indicators have been found to be more **responsive, sensitive** and **specific** to climate change than multi-species population metrics (Devictor *et al.* 2008; Pearce-Higgins *et al.* 2015; Martay *et al.* 2016). However, these indicators can be influenced by other environmental factors (Clavero *et al.* 2011; Pearce-Higgins *et al.* 2015). The **specificity** of these indicators can be improved by taking species' responses to other factors, such as habitat, into account (Bowler & Böhning-Gaese 2017). These indicators may **lack sensitivity** if research is not conducted to identify which aspects of weather species respond to (Martay *et al.* 2016). It is important to note that climate change indicators can change in effectiveness over time, and short-term impacts can differ from long-term impacts, so a dynamic assessment of indicators and modifications is important (Morecroft *et al.* 2019; Pearce-Higgins *et al.* 2022).	Typically, developing these indicators requires long-term, large-scale monitoring of a group of species, **restricting their use to better monitored regions and taxa**. Data for these indicators are often collected via citizen science (e.g. the UK's Breeding Bird Survey, Pearce-Higgins *et al.* 2015), but professional data collection is sometimes required (e.g. Martay *et al.* 2016). There have been recent advances and cost reductions in acoustic monitoring of bats using passive monitors that can be left in the field, and software to identify species from their calls, with little expert input (Jones *et al.* 2013). Passive acoustic bat monitoring can be combined with citizen science to maximise the scale and extent of monitoring possible (Border *et al.* 2017). This makes bats a good candidate group for indicating climate change impacts on terrestrial biodiversity, especially in regions where large-scale monitoring of other taxonomic groups is challenging. Acoustic monitoring may be applicable to other taxa in the future such as birds and insects (Newson *et al.* 2017; Pérez-Granados & Traba 2021).

Indicators of climate change adaptation Indicators can be **process-based** measures of **input** (e.g. resources available), **activity** (e.g. area of land managed), and **output** (e.g. condition of the managed habitat); or they can be **results-based** measures of **outcomes** (e.g. the persistence of climate-threatened species within protected areas compared to outside these areas) and **impact** (e.g. change in species extinction risk) (Pearce-Higgins *et al.* 2022).	The IPCC (2022) states that although many adaptation plans and strategies have been developed to protect ecosystems and biodiversity, there is limited evidence of the extent to which adaptation is taking place and **very limited evaluation of the effectiveness of adaptation measures** in the scientific literature (Bowgen *et al.* 2022). Two recent papers have identified the **urgent need to identify and test outcome-based indicators of climate change adaptation**, to allow the effectiveness of adaptive measures and outcomes to be assessed (Morecroft *et al.* 2019; Pearce-Higgins *et al*. 2022).	There are **conceptual challenges**: what is climate change adaptation and what does success look like (Pearce-Higgins *et al.* 2022)? In some cases, adaptation may seek to reduce the negative impacts of climate change on species and ecosystems, whilst in others it may be used to facilitate desirable climate-driven change (Prober *et al.* 2019; Pearce-Higgins *et al.* 2022). There are also **analytical challenges**: firstly, it can be challenging to attribute observed ecological changes in the absence of adaptation to climate change; secondly, it can be challenging to attribute observed responses to adaptation interventions (Pearce-Higgins *et al.* 2022).	There are **practical challenges**: indicators of climate change adaptation generally require large-scale or long-term data, and it can be unclear how to measure success in the short term versus a long-term target (Pearce-Higgins *et al.* 2022).

4.4.2 Indicators of marine climate change impacts

Marine climate change impacts have been indicated using fish biomass, predator foraging times, population metrics of top predators, migration phenology and a Community Temperature Index (Cherry *et al.* 2013; Nash *et al.* 2016b; Bowler & Böhning-Gaese 2017; Wilcox *et al.* 2018; Hazen *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). Current examples include using eDNA of marine species to indicate the impacts of oil extraction and the effectiveness of marine reserves (Lanzen *et al.* 2021; Sanchez *et al.* 2022). Remote sensing has been used to create indicators of primary productivity (Kulk *et al.* 2020), which will impact migratory marine species. Further research to compare these indicators, taking into account regional differences in species, resources and current monitoring, would allow the most appropriate indicators to be identified for use.

4.4.3 Indicators of terrestrial climate change impacts

Over the past fifteen years, there has been increasing use of community-level metrics in terrestrial species to indicate climate change impacts on biodiversity (e.g. the Community Temperature Index: Devictor *et al.* 2008). These have generally relied upon using spatial associations between species' distribution and climate to indicate climate change responses from temporal changes in species' distributions, populations or communities. 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. Modelling can be very challenging, making multi-species indicators likely to be less specific to climate change than community-level metrics. However, efforts should be made to understand the impact of other environmental factors on both of these types of indicator (Bowler & Böhning-Gaese 2017), to ensure specificity to climate change.

Community metrics of change can be difficult to interpret. Whilst indicators based on overall changes in the abundance of particular species groups (e.g. Eglington & Pearce-Higgins 2012; Martay *et al.* 2017) can be used to indicate positive or negative responses in overall species abundance, other measures of change such as the Community Temperature Index may be caused either by increases in the abundance of one group of species, or declines in another (e.g. Oliver *et al.* 2017). The production of indicators generally requires large-scale and long-term monitoring of all species within a taxonomic group. This has traditionally restricted use to well monitored groups such as birds and butterflies, and to regions with long-term monitoring schemes (Devictor *et al.* 2008), with a range of challenges elsewhere (e.g. Stephenson *et al.* 2017). As approaches to monitoring develop and extend, for example through the expansion of citizen science approaches globally (e.g. Sullivan *et al.* 2014), or through the use of new technologies (e.g. Newson *et al.* 2017; Pérez-Granados & Traba 2021), then our ability to track the impacts of climate change and summarise those impacts through indicators will also expand. For example, the technological advances and reduction in costs of passive acoustic bat monitoring makes community-level indicators of climate change impacts on bats much more accessible (Tuneu-Corral *et al.* 2020).

4.4.4 Indicators of climate change adaptation

There is an increasing need for climate change adaptation measures, either to reduce the negative impacts of climate change on species and ecosystems, or to facilitate desirable climate-driven change (Morecroft *et al.* 2019; Pearce-Higgins *et al.* 2022). Currently, monitoring of climate change adaptation is very limited. Indicators can 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, for example the persistence of climate-sensitive species within protected areas (Pearce-Higgins *et al.* 2022).

5 Conclusions and recommendations

The relatively small number of articles found on conservation interventions for migratory species was, to some extent, surprising, given the increasing volume of climate change research in recent decades (see Part 1 of this review). Indeed, the library was substantially larger when only one or two of the three selection criteria were applied (e.g. “intervention and climate change” or “intervention”), and further searches with relaxed filtering rules and a broader set of search terms would expand the database and provide greater insight. In addition, many conservation actions applied to resident species could also be applied to migrants. For example, at least two articles documenting successful conservation strategies on closely related non-migrant species (subspecies or congenerics) to those in the CMS Appendices were found, including food provisioning and predator control of San-Clementine Loggerhead Shrikes (Heath *et al.* 2008), and the translocation of Hawaiian Monk Seals (Baker *et al.* 2011). Further, ecologists on the Chatham Islands have successfully restored dune habitat by replacing invasive plants with native species, providing nest sites for the resident Chatham Island Oystercatcher. To complement this habitat modification, volunteers routinely moved nests from the shoreline up into the dunes, to avoid flooding from storm surges. These relatively simple interventions led to a doubling of the population’s size within six years (Moore 2005; Moore & Williams 2005), and could equally be applied to migratory shorebirds in the CMS Appendices.

Despite finding fewer articles than expected, we were able to identify a number of key actions that would facilitate the conservation of migratory species under climate change. In particular, interventions to conserve migratory species in the face of climate change should aim to do the following:

- Establish effective networks of protected areas for migratory species, including a coherent and interconnected network of passages, with safe stopover sites.
- Involve multiple jurisdictions, where necessary, when developing and implementing conservation strategies. This is particularly relevant to species in the CMS Appendices.
- Adopt integrated approaches to conservation which make use of new technologies, such as those that can track species movements in real-time (among others).
- Utilise existing management frameworks, which outline the ongoing monitoring of the conservation impacts, and include adjustments to actions/objectives where required.
- Engage local communities at all steps in the conservation programme, balance trade-offs, and expediate synergies when they arise (including socio-economic outcomes).
- Focus on migratory species that are known to deliver broader ecosystem services and nature-based solutions, and monitor these synergistic effects (detailed in Part 3 of this review).

Given strong evidence that targeted interventions for particular species have a strong likelihood of success in helping species adapt to climate change (Bowgen *et al.* 2022), understanding the impacts of climate change on migratory species as a precursor to devising effective interventions will also be a high priority for those seeking to conserve the most threatened species. General measures to restore ecosystems and protected habitats, for example through large-scale protected area networks, are likely to benefit a relatively large number of species reliant on those systems, habitats and networks (Bowgen *et al.* 2022). However, conservationists must keep in mind that the management of wider ecosystems is likely to have mixed results depending on the species (i.e. winners and losers), and so ongoing monitoring of impacts is required.

To this end, the use of indicator species for monitoring the impacts of climate change should be a key consideration moving forward. Indicators could provide an important tool for policy makers and scientists to use to chart progress towards biodiversity aims and to identify where further resources are required. There has been recent progress in developing multi-species indicators based on population trends and community change, but these indicators are only possible where extensive monitoring is carried out. Furthermore, climate change impacts will vary between groups of species and migratory routes. It is therefore recommended that a suite of indicators be selected to encompass as much of that variation as possible. A suite of indicators may also be useful to provide indicators that are optimised for different uses. For example, different metrics may be more valuable to policy makers, conservation practitioners and for public engagement. This review has identified a range of examples of recent indicators of climate change impacts and adaptation, and discussed the benefits and limitations of these indicators. More specifically, to determine which indicators would be most appropriate for monitoring the climate change impacts on CMS species, further work is required to determine the following:

- The aims and policy relevance for CMS climate change indicators should be clearly defined. Key audiences and where to publish the indicators should be identified.
- The breadth of these indicators should be considered. Should they be regional or global? What suite of indicators would be required to indicate climate change impacts broadly across all CMS species, or would indicators be taxon-specific?
- How can effective climate change adaptation be indicated given uncertainty over the goals of adaptation and the variable timescales of climate change impacts, all of which will vary with context, including across migratory cycles?
- What modelling would be appropriate to test the specificity, sensitivity and responsiveness of these indicators? What data would be best to enable that modelling?
- What data are available to create these indicators? Is this data available globally? What methods of data collection could be used where appropriate data does not currently exist? What funding and support could be provided to fill gaps in data collection?

In addition to the need for more robust indicator species, this review identifies some additional knowledge gaps pertaining to specific taxonomic groups that could be addressed with further research, and would align with recommendations of the IPCC (2022) on the need to monitor and evaluate adaptation interventions as they are put in place. For example, whilst there are many studies documenting the impacts of climate change on Polar Bears (Part 1 of this review; Peacock 2011), no articles describing an actual management intervention were found. Tangible conservation interventions on fish, bats and long-distance terrestrial migrants in the CMS Appendices also appear to be missing, and are not well represented in the list of indicatory species identified thus far. There are, however a number of recent review articles documenting the impacts of climate change on these taxa (primates: Bernard & Marshall 2020; ungulates: Berger *et al.* 2004; fish: Tamario *et al.* 2019, Waldman & Quinn 2022; bats: Frick *et al.* 2020). The broader review on climate change adaptation interventions identified that birds are relatively well studied but had a terrestrial and freshwater focus, and failed to identify studies on fish and other marine species (Bowgen *et al.* 2022). These mismatches indicate that, although the need for climate-related interventions is recognised, barriers remain when it comes to putting conservation plans into action.

6 References

Note: * = paper identified in the main review process of conservation review (section 2.1). ** = paper identified from literature reviews of conservation review (section 2.1). *** = papers identified in the indicator review (section 2.2)

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7 Supplementary materials

7.1 S1: Detailed methods of conservation strategies for migratory species

To begin, literature cited by Bowgen *et al.* (2022) was considered. This study assessed articles on *all* terrestrial fauna (marine species were omitted), published up to and including 2017, and so studies from their database that focused on migratory species were extracted. Their literature search was then repeated, to find articles published more recently. Specifically, a search was conducted on 10/05/2023 in Web of Science (incorporating the Web of Science Core Collection, BIOSIS Citation Index, MEDLINE(r), Zoological Record, KCI_Korean Journal Database and SciELO citation Index databases), using the basic search bar (searching in 'topic'). In the interests of time, searches were constrained to 2018–search date inclusive, which produced 28,517 results (but note that only the top 1,000 most relevant articles were considered further, S1 Table 1). Search terms included:

((shift* OR change* OR colon* OR extinc*) AND (rang* OR communit* OR expansion* OR distribut*) AND "climate change" AND (conserv* OR adapt*) AND (specie* OR ecolog*)).

This search was repeated on Google Scholar, with search terms listed as key words, in which 420 articles were retrieved (S1 Table 1). As noted above, Bowgen *et al.* (2022) focussed on terrestrial and freshwater systems, deliberately excluding the marine environment because, conceptually, the impacts of climate change and potential adaptation responses in the marine environment are very different to terrestrial. This review, however, is more focussed on types of intervention strategies, rather than the underlying mechanisms of climate change impacts, and so studies that focussed on migratory marine species were included as well.

Articles were first filtered by title, and then by abstract, and then results, and any that were deemed to be irrelevant were removed from the database (S1 Table 1). Relevance was based on the following questions:

- Is the species in the CMS Appendices (or is it closely related to species on the list)?
- If yes, does the study apply a conservation intervention?
- If yes, does the intervention buffer the species from one or more climate change impacts (defined in Part 1 of this review)?

Whilst many of the retrieved studies assessed the impacts of climate change on migratory species (reviewed in Part 1), relatively few considered the outcomes of a conservation intervention focussed on buffering the impacts of climate change on migratory species (n = 38, S1 Table 1). Therefore, to expand the database, studies cited within a number of recent review articles were also included (S1 Table S2), some of which were focussed on a specific taxonomic group (e.g.

turtles: Patricio *et al.* 2021), whilst others discussed a particular conservation strategy (e.g. use of artificial structures: Watchhorn *et al.* 2022). Note that articles for CMS-listed species were initially filtered, and then later included additional studies on closely related species, but no further searches were conducted to expand the literature to migratory species in general (i.e. no further supplementary searches were performed).

S1 Table 1. Flow table listing the number of articles in the database after successive filtering steps. Note that review articles are included in the first three steps, but are removed from the final database counts (bottom row of the table). Papers found within review articles are also listed. 'Taxa' refers to whether the species is migratory or not (S3 Table 1), and 'topic' describes papers that are not relevant to this study (e.g. genetic analyses, laboratory experiments on species' thermal tolerances, vulnerability assessments, fishery or agricultural policies). Review articles, from which 13 studies were sourced, are listed in S2 Table 1.

Filtering step	Bowgen *et al.* 2022	Web of Science	Google Scholar	Literature reviews*	Total
Initial search total	77	28,517 (1,000)	420	-	1456
Articles remaining after duplicates removed	77	1,000	292	-	1369
Articles remaining after title and abstract filtered by taxa and topic	38	156	40	-	232
Articles remaining after results filtered for intervention to buffer climate change impacts.	**16**	**9**	**13**	**13**	**51**

For each article, where possible, information for the following metrics was extracted:

- The scale at which the intervention was applied, according to those defined by the IUCN (2012): land/water protection, land/water management or species management (S1 Table 2, and see Bowgen *et al.* 2022).
- The type of action, according to the CMS Framework for Action: Conservation, Restoration, Adaptation, Translocation (S1 Table 2).
- The geographic location, and whether the intervention involved multiple jurisdictions (countries).

Modelling studies were included (unlike Bowgen *et al.* 2022, where they were excluded), where they: (1) compared future predicted distributions with protected areas; (2) compared predicted phenological events (e.g. opening of fishways for seasonal migration); or (3) tested an explicit change in a species habitat, for example, the impacts of sea level rise on turtle nesting habitat (Katselidis *et al.* 2014). Articles were grouped and reported by relevant conservation action, listed by the IUCN (2012).

S1 Table 2. Potential conservation actions defined by the IUCN (2012), and utilised by Bowgen *et al.* (2022), in the context of the CMS Framework for Action, with examples of each and how they might be expected to buffer against climate change impacts.

IUCN Conservation Action classification	CMS Action Strategy	Examples of intervention	Climate change impact buffered against
Land/water protection	Conservation	Protection of habitat by designation of reserves	Long-term changes in climate and habitat suitability
Land/water management	Restoration	Removal of invasive species. Reduction of bycatch/ hunting	Interactive stressors between abiotic stress and competition/predation
Land/water management	Adaptation	Artificial reefs. Expansion of wetlands. Controlled burns	Extreme events like coral bleaching, drought, fire and storm surges. Long-term changes in climate suitability, including sea level rise
Species management	Adaptation	Provision of nest boxes, food or water. Spraying bat or bird colonies with water. Cooling of nests	Extreme events like drought, storm surges, heat waves and gradual rises in temperature
Species management	Translocation	Assisted migration. Reintroduction or translocation of individuals. Relocation of nests	Disrupted environmental cues (temperature and photoperiod). Long-term changes in climate suitability, including sea level rise

7.2 S2: Summary of articles considered in review of conservation strategies

S2 Table 1. A summary of review articles cited within Part 2, with focal taxonomic group or habitat, and the broad topic (along with the review title) listed. Thirteen articles were found from eight reviews, which are also listed.

Review	Taxa or habitat	Topic	Title	References extracted for literature search
Bezanson & McNamara 2019	Primates	Conservation and management of species	The what and where of primate field research may be failing primate conservation	
Berger 2004	Terrestrial mammals	Conservation and management of species	The last mile: How to sustain long-distance migration in mammals	
Bernard & Marshall 2020	Primates	Climate change	Assessing the state of knowledge of contemporary climate change and primates	Thorne *et al.* 2013
Bower *et al.* 2015	Freshwater fish	Protected areas	Is there a role for freshwater protected areas in the conservation of migratory fish?	
Bowgen *et al.* 2022	Terrestrial, coastal and aquatic systems	Conservation and climate change	Conservation interventions benefit species impacted by climate change	
Di Sciara *et al.* 2016	Marine mammals	Conservation approaches to marine ecosystems	Marine migrants	
Foden *et al.* 2019	All species	Vulnerability to climate change	Assessing vulnerability of species to climate change	Forrest *et al.* 2012
Frick *et al.* 2020	Bats	Conservation and management	Major threats to global bat conservation	Flaquer *et al.* 2006
Groves *et al.* 2012	All species	Conservation and climate change	Incorporating climate change into systematic conservation planning	Grantham *et al.* 2010

Review	**Taxa or habitat**	**Topic**	**Title**	**References extracted for literature search**
Hvenegaard 2011	Migratory species (primarily birds in North America)	Wildlife festivals	Potential benefits of wildlife festivals	
Maxwell *et al.* 2020	Marine migrants	Dynamic conservation	Mobile protected areas for biodiversity on the high seas	
Patricio *et al.* 2021	Marine turtles	Conservation and climate change	Climate change and marine turtles: Recent advances and future directions	Katsedelis *et al.* 2014; Patrinio-Marinez *et al.* 2014; Wood *et al.* 2014; Hill *et al.* 2015; Jourdan & Fuentes 2015
Peacock *et al.* 2011	Polar Bears	Conservation and management	Conservation and management of Canada's Polar Bears (*Ursus maritimus*) in a changing Arctic	
Pearce-Higgins *et al.* 2022	All species	Climate change and indicators	A framework for climate change adaptation indicators for the natural environment	
Ranius *et al.* 2023	All species	Climate change and protected areas	Protected area designation and management in a world of climate change: a review of recommendations	
Robinson *et al.* 2009	Migratory species	Climate change and migration	Travelling through a warming world: climate change and migratory species	Thirgood 2004
Runge *et al.* 2015	Migratory species	Dynamic conservation	Conserving mobile species	

Review	**Taxa or habitat**	**Topic**	**Title**	**References extracted for literature search**
Tamario *et al.* 2019	Freshwater fish	Management and climate change	Ecological and evolutionary consequences of environmental change and management actions for migrating fish	van Leeuwen *et al.* 2016
Waldman & Quinn 2022	Freshwater fish	Management and climate change	North American diadromous fishes: Drivers of decline and potential recovery in the Anthropocene	
Watchorn *et al.* 2022	Various (including insects, birds, bats, coral, reptiles)	Artificial habitat structures	Artificial habitat structures for animal conservation: design and implementation, risks and opportunities	Catry *et al.* 2011; Esteban *et al.* 2018
Wilkes *et al.* 2019	Freshwater fish	Management and climate change	Not just a migration problem: meta-populations, habitat shifts, and gene flow are also important for fishway science and management	
Wikramayake *et al.* 2020	Coastal habitat	Management and climate change	A climate adaptation strategy for Mai Po Inner Deep Bay Ramsar site: Stepping stone to climate proofing the East Asian-Australasian Flyway	

7.3 S3: Species list

S3 Table 1. List of species considered in articles within the literature review. Species marked with * are migratory, but not CMS-listed. Where species are included in CMS Appendix I or II (or both), the CMS instruments for conservation are also provided. Note that, where studies considered more than 25 species, or grouped species into assemblages, individual species are not listed (Pavón-Jordán *et al.* 2020; Breiner *et al.* 2022; Gaget *et al.* 2022; Nagy *et al.* 2022). Note: key to abbreviations at end of the table.

Common name	Scientific name	CMS Appendix	Conservation instruments
Insects			
Monarch Butterfly	*Danaus plexippus*	II	CMS
Actinopterygii (Bony fish)			
Southern Bluefin Tuna	*Thunnus maccoyii*		
Brown Trout*	*Salmo trutta*		
European Grayling*	*Thymalluys thymallus*		
Green Sturgeon	*Acipenser medirostris*	II	CMS
Reptiles			
Hawksbill Turtle	*Eretmochelys imbricata*	I&II	CMS, IOSEA Marine Turtles, Atlantic Turtles
Green Turtle	*Chelonia mydas*	I	CMS, IOSEA Marine Turtles, Atlantic Turtles
Leatherback Turtle	*Dermochelys coriacea*	I&II	CMS, IOSEA Marine Turtles, Atlantic Turtles
Loggerhead Turtle	*Caretta caretta*		CMS, IOSEA Marine Turtles, Atlantic Turtles
Olive Ridley Turtle	*Lepidochelys olivacea*		CMS, IOSEA Marine Turtles, Atlantic Turtles
Aves: Waterbirds			
Northern Bald Ibis (Waldrapp, Hermit Ibis)	*Geronticus eremita*	I&II	CMS, AEWA
Barnacle Goose	*Branta leucopsis*	II	CMS, AEWA
Bewick's Swan	*Cygnus columbianus*	II	CMS, AEWA
Black-tailed Godwit	*Limosa limosa*	II	CMS, AEWA
Black-throated Diver	*Gavia arctica*	II	CMS, AEWA
Brent Goose	*Branta bernicla*	II	CMS, AEWA
Chatham Island Oystercatcher	*Haematopus chathamensis*		
Common Coot	*Fulica atra atra*	II	CMS, AEWA

Common name	Scientific name	CMS Appendix	Conservation instruments
Common Goldeneye	*Bucephala clangula*	II	CMS, AEWA
Common Pochard	*Aythya ferina*	II	CMS, AEWA
Common Scoter	*Melanitta nigra*	II	CMS, AEWA
Common Teal	*Anas crecca*	II	CMS, AEWA
Dunlin	*Calidris alpina*	II	CMS, AEWA
Eurasian Wigeon	*Anas penelope*	II	CMS, AEWA
Gadwall	*Anas strepera*	II	CMS, AEWA
Goosander	*Mergus merganser*	II	CMS, AEWA
Greater White-fronted Goose	*Anser albifrons*	II	CMS, AEWA
Greylag Goose	*Anser anser*	II	CMS, AEWA
Mallard	*Anas platyrhynchos*	II	CMS, AEWA
Mute Swan	*Cygnus olor*	II	CMS, AEWA
Northern Lapwing	*Vanellus vanellus*	II	CMS, AEWA
Northern Pintail	*Anas acuta*	II	CMS, AEWA
Northern Shoveler	*Anas clypeata*	II	CMS, AEWA
Piping Plover*	*Charadrius melodus*		
Red-breasted Merganser	*Mergus serrator*	II	CMS, AEWA
Red-crested Pochard	*Netta rufina*	II	CMS, AEWA
Red-crowned Crane	*Grus japonensis*	I	CMS
Redshank	*Tringa totanus*	II	CMS, AEWA
Red-throated Diver	*Gavia stellata*		
Ring-billed Gull	*Larus delawarensis*		
Slavonian Grebe	*Podiceps auritus*	II	CMS, AEWA
Smew	*Mergellus albellus*	II	CMS, AEWA
Snowy/Kentish Plover	*Charadrius alexandrinus*	II	CMS, AEWA
Stone Curlew	*Burhinus oedicnemus*	I	CMS
Tufted Duck	*Aythya fuligula*	II	CMS, AEWA
Whooper Swan	*Cygnus cygnus*	II	CMS, AEWA
Aves: Seabirds			
Black-footed Albatross	*Phoebastria nigripes*		CMS, ACAP
Common Tern	*Sterna hirundo hirundo*	II	CMS, AEWA
Laysan Albatross	*Phoebastria immutabilis*		CMS, ACAP
Least Tern*	*Sternula antillarum*		
Magellanic Penguin	*Spheniscus magellanicus*		

Common name	Scientific name	CMS Appendix	Conservation instruments
Aves: Raptors			
Hen Harrier	*Circus cyaneus*	I	CMS, Raptors
Lesser Kestrel	*Falco naumanni*	I&II	CMS, Raptors
Aves: Landbirds			
European Nightjar	*Caprimulgus europaeus*		
Loggerhead Shrike	*Lanius ludovicianus mearnsi*		
Mammalia: Bats			
Brown Pipistrelle Bat	*Hypsugo imbricatus*		
Greater Horseshoe Bat	*Rhinolophus ferrumequinum*	II	CMS, EUROBATS
Soprano Pipistrelle	*Pipistrellus pygmaeus*	II	CMS, EUROBATS
Mammalia: Marine mammals			
Atlantic Spotted Dolphin	*Stenella frontalis*		Western African Aquatic Mammals
Blainville's Beaked Whale	*Mesoplodon densirostris*		ASCOBANS, ACCOBAMS, Western African Aquatic Mammals, Pacific Islands Cetaceans
Bottlenose Dolphin	*Tursiops truncatus*	I&II	CMS, ASCOBANS, Western African Aquatic Mammals, ACCOBAMS
Bryde's Whale	*Balaenoptera edeni*	II	CMS, Pacific Islands Cetaceans
California Sea Lion	*Zalophus californianus*		
Common Dolphin	*Delphinus delphis*	I&II	CMS, ASCOBANS, ACCOBAMS, Western African Aquatic Mammals, Pacific Islands Cetaceans
Cuvier's Beaked Whale	*Ziphius cavirostris*		CMS, ASCOBANS, ACCOBAMS, Western African Aquatic Mammals, Pacific Islands Cetaceans
Dugong	*Dugong dugon*	II	Dugong
Dwarf Sperm Whale	*Kogia sima*		ACCOBAMS, Western African Aquatic Mammals, Pacific Islands Cetaceans

Common name	Scientific name	CMS Appendix	Conservation instruments
False Killer Whale	*Pseudorca crassidens*		ACCOBAMS, ASCOBANS, Pacific Islands Cetaceans, Western African Aquatic Mammals
Fin Whale	*Balaenoptera physalus*	I&II	CMS, ACCOBAMS, Pacific Islands Cetaceans
Gervais' Beaked Whale	*Mesoplodon europaeus*		ASCOBANS, ACCOBAMS, Western African Aquatic Mammals
Hawaiian Monk Seal	*Neomonachus schauinslandi*		
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
North Atlantic Right Whale	*Eubalaena glacialis*	I	CMS, ACCOBAMS
Polar Bear	*Ursus maritimus*	II	CMS
Risso's Dolphin	*Grampus griseus*	II	CMS, ACCOBAMS, ASCOBANS, Western African Aquatic Mammals, Pacific Islands Cetaceans
Rough-toothed Dolphin	*Steno bredanensis*		ASCOBANS, ACCOBAMS, Western African Aquatic Mammals, Pacific Islands Cetaceans
Sei Whale	*Balaenoptera borealis*	I&II	CMS, ACCOBAMS, Pacific Islands Cetaceans
Short-finned Pilot Whale	*Globicephala macrorhynchus*		ASCOBANS, ACCOBAMS, Western African Aquatic Mammals, Pacific Islands Cetaceans
Sperm Whale	*Physeter macrocephalus*	I&II	CMS, ACCOBAMS, Pacific Islands Cetaceans
Striped Dolphin	*Stenella coeruleoalba*	II	CMS, ASCOBANS, ACCOBAMS, Western African Aquatic Mammals, Pacific Islands Cetaceans

Common name	Scientific name	CMS Appendix	Conservation instruments
Mammalia: Terrestrial mammals			
Asian Elephant	*Elephas maximus*	I	CMS
Caribou*	*Rangifer tarandus*		
Chimpanzee	*Pan troglodytes*	I&II	CMS
Eastern Gorilla	*Gorilla beringei*	I	CMS, Gorilla Agreement
Elk (Wyoming, USA)*	*Cervus canadensis*		
Gobi Bear	*Ursus arctos gobiensis/ isabellinus*	I	CMS
Goitered Gazelle	*Gazella subgutturosa*	II	CMS, Central Asian Mammals Initiative
Hippopotamus	*Hippopotamus amphibius*		
Kiang	*Equus kiang*	II	CMS, Central Asian Mammals Initiative
Saiga Antelope	*Saiga tatarica*	II	Central Asian Mammals Initiative, Saiga Antelope
Scimitar-horned Oryx	*Oryx dammah*	I&II	CMS, Sahelo-Saharan Megafauna
Snow Leopard	*Uncia uncia*	I	CMS, Central Asian Mammals Initiative
Tibetan Gazelle	*Pantholops hodgsonii*		Central Asian Mammals Initiative
Waterbuck	*Kobus ellipsiprymnus*		
Wildebeest*	*Connochaetes taurinus*		

Key to abbreviations: **IOSEA Marine Turtles** = Memorandum of Understanding on the Conservation and Management of Marine Turtles and their Habitats of the Indian Ocean and South-East Asia; **Atlantic Turtles** = Memorandum of Understanding concerning Conservation Measures for Marine Turtles of the Atlantic Coast of Africa; **AEWA** = Agreement on the Conservation of African-Eurasian Migratory Waterbirds; **ACAP** = Agreement on the Conservation of Albatrosses and Petrels; **Raptors** = Memorandum of Understanding on the Conservation of Migratory Birds of Prey in Africa and Eurasia; **EUROBATS** = Agreement on the Conservation of Populations of European Bats; **West African Aquatic Mammals** = Memorandum of Understanding concerning the Conservation of the Manatee and Small Cetaceans of Western Africa and Macaronesia; **ASCOBANS** = Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas; **ACCOBAMS** = Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area; **Pacific Islands Ceteceans** = Memorandum of Understanding for the Conservation of Cetaceans and their Habitats in the Pacific Islands Region; **Saiga Antelope** = Memorandum of Understanding concerning Conservation, Restoration and Sustainable Use of the Saiga Antelope; **Gorilla Agreement** = Agreement on the Conservation of Gorillas and their Habitats; **Dugong** = Memorandum of Understanding on the Conservation and Management of Dugongs (Dugong dugon) and their Habitats throughout their Range.

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