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MIGRATORY SPECIES AND THEIR ROLE IN ECOSYSTEMS

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

Summary:

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

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

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

Part 3 - Migratory Species and Their Role in Ecosystems

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Summary

Migratory species often play a key role within the ecosystems they utilise and in connecting different ecosystems. There is a growing understanding of how species support ecosystem functionality, and how they provide ecosystem services that can deliver nature-based solutions to human challenges such as climate change.

As Part 1 highlights, migratory species are particularly vulnerable to climate change and this presents challenges for their conservation. Part 2 highlights some possible mitigation and adaptation practices already in place. Here we identify the various important roles migratory species perform through ecosystem services or as nature-based solutions and provide examples of the wider benefits of conserving these species for biodiversity and associated habitats.

We carried out a rapid review of the literature to highlight the potential roles migratory species can have as key components of ecosystems and then narrow these down to specifically identify nature-based solutions related to climate change. Our main aim is to highlight examples where the conservation of migratory species may also contribute to wider benefits for people and ecosystems, to help decision-makers begin to consider these issues in a cross-cutting and holistic way. We were unable to be comprehensive in the time available and would recommend that further in-depth assessments of the literature, and particularly engagement with species and regional experts, to explore these issues further.

Migratory species were identified as key ecosystem components in 73 studies. Regulation and maintenance ecosystem services (covering: carbon capture, pollination, seed dispersal and pest control) were especially prominent, but other services within culture (covering: tourism, recreational activities, symbolic value and natural heritage) and provision (predominantly food) were also reported. Of these services, pollination, seed dispersal and pest control were particularly provided by migratory bird, bat and insect species groups. Larger migratory species – terrestrial and marine mammals and sharks - were particularly important in aiding carbon capture and other climate change related regulation and maintenance services. Conserving migratory had the potential to improve ecosystem resilience, helping to mitigate the impacts of (increasingly frequent) climatic hazards. A small number of ecosystem disservices/maladaptations were noted.

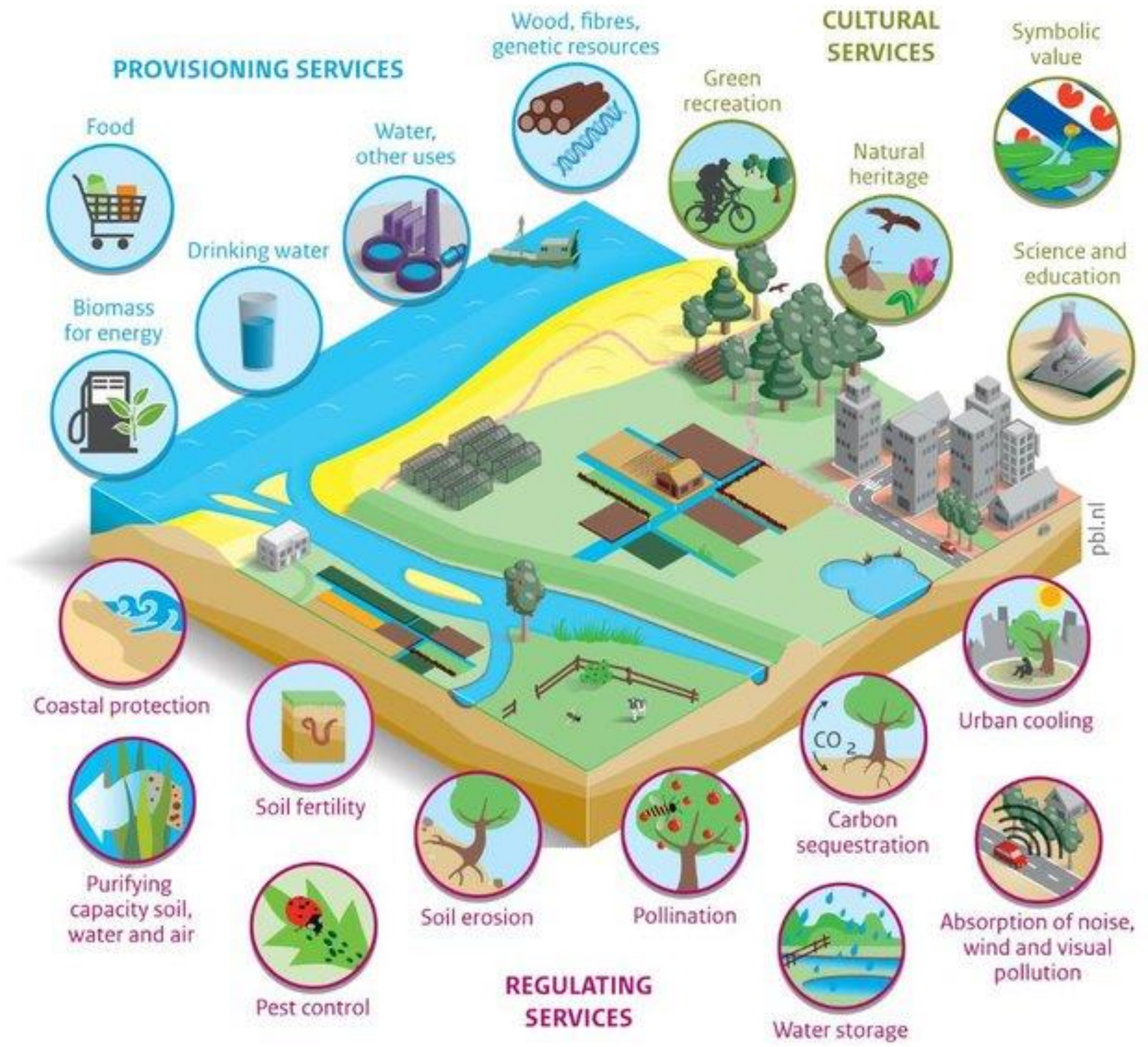
Content

1 Introduction

As reviewed in Part 1, biodiversity is strongly impacted by climate change drivers in addition to more long-standing threats (Díaz *et al*. 2006; Maxwell *et al*. 2016). This is particularly true for species that migrate as they are subject to changes in a greater range of, often well separated, locations which need to exist as a coherent network, both spatially to facilitate the migratory journey, and temporally, as they often rely on specifically timed seasonal resource peaks (Learmonth *et al*. 2006; Robinson *et al*. 2009; Winkler *et al*. 2014). Billions of individuals undertake migratory journeys annually, connecting ecosystems across the globe (Bauer & Hoye 2014). Given their ubiquity, both geographically and taxonomically (e.g. around 20% of birds and 30% of marine mammals are migratory), migratory species not only form significant components of many ecosystems, but also facilitate significant transfers of energy and resources.

Part 2 continued on from this, to review the range of mitigation and adaptation practices, which have previously been employed to help conserve migratory species in the face of climate change, among other threats. Alongside the increasing interest in these potential roles humans can play in providing appropriate ecosystem management to support ecosystem services, there is also a growing understanding of how some migratory species make important contributions to the overall functioning of ecosystems, providing the potential mitigation of (some) climate change impacts (e.g. Díaz *et al*. 2006; Schmitz *et al*. 2023). The nature of the roles these species provide has been framed in a variety of ways, including as Ecosystem Engineers (e.g. Jones, Lawton and Shachak 1994), or as providing Ecosystem Services (e.g. Harrison *et al*. 2014; Kleemann *et al*. 2020), Nature-based Solutions (e.g. Malhi *et al*. 2020) or Natural Climate Solutions (e.g. Schmitz *et al*. 2023).

For the purposes of this report, we concentrated on the three overarching Ecosystem Services terms outlined by the Common International Classification of Ecosystem Services (CICES): Regulation and Maintenance, Provisioning, and Culture (CICES 2023; e.g. Harrison *et al.* 2014; Fig. 1). Some of these services provide important nature-based solutions to human challenges that are not directly relevant, or are only indirectly linked, to the processes of climate change (e.g. tourism, food provisioning, symbolic value, natural heritage) but which are nevertheless vital services to human wellbeing (e.g. Whelan, Şekercioğlu & Wenny 2015) and ecosystem functioning (e.g. Díaz *et al*. 2006; Civantos *et al*. 2012). Several though are directly linked to climate change through carbon capture, or enhancing ecosystem resilience to extreme events, such as flooding, sea-level rise, droughts, heatwaves and wildfire (defined by International Union for the Conservation of Nature (IUCN), IUCN 2023; e.g. Schmitz *et al*. 2023).



Source: PBL, WUR, CICES 2014

Figure 1. Overview of the CICES' three 'Sections' (Regulating and Maintenance, Provisioning and Cultural services) and the associated 'Divisions'. Koets *et al*. 2017.

In a global context, conservation of migratory species is led by the Convention on the Conservation of Migratory Species of Wild Animals (1979) (CMS, also known as the Bonn Convention), which provides a global platform for the conservation and sustainable use of migratory animals and their habitats. The topic of climate change was introduced to CMS in 1997 (UNEP/CMS/Recommendation 05.05) and has been the topic of subsequent CoPs. Most recently, Resolution 12.21 calls on Range States to address the effects of climate change, despite the remaining uncertainty surrounding the full scale of the impacts of climate change on migratory species and to assess what steps are necessary to help migratory species cope with climate change. In advance of CMS CoP14, the Sessional Committee of the CMS Scientific Council will consider climate change at its meeting in July 2023. To inform these discussions there is a need to determine the role migratory species play in ecosystem management and consequently climate change regulation.

In this rapid review, we aim to 1) review and highlight the roles migratory species play as key components of ecosystems and specifically as ecosystem service providers, and then 2) identify the role migratory species have/could have in nature-based solutions to help adaptation or mitigation to climate change, providing more detailed examples of some of these as case-studies. We primarily focus on those species listed on Appendices I and II of the CMS, but draw on studies of non-listed migratory species, where relevant, to highlight key climate change related nature-based solutions.

2 Methods

A preliminary search was conducted on 14/04/2023 in Web of Science (databases searched in are detailed in S1), using the below search terms and produced 10,149 results.

The search terms were:

> ((Climate* OR “Global warming” OR “Sea-level rise” OR “Global environmental change”)
>
> AND
>
> (“keystone service*” OR “nature based solution*” OR “natural climate solution*” OR “climate change adaptation” OR “climate change mitigation” OR “ecological service*” OR “trophic rewilding”)
>
> AND
>
> (specie* OR ecolog* OR “bio* diversity” OR ecosystem))

From these results, the WoS refine filter was used to extract the term migratory, using the search term: ("migrat*") as an initial filtering step (324 results). The first 100 results were skimmed for relevance at title and abstract level. Relevance was based on the following questions:

- Is a species as a key component of ecosystem(s) talked about? (Y/N)
- If yes, which ecosystem service does it fit into? (broad categories: Regulation and Maintenance, Provisioning and/or Culture. Specific services identified and noted under each category)
- Is the solution/service aided by migratory species? (Y/N)
- If yes, is it a nature-based solution/ecosystem service? (Y/N)
- If yes, does it help mitigate climate change? (Y/N)
- If yes, is the nature-based solution aiding: reducing greenhouse gas emissions, carbon capture and/or ecosystem resilience?
- If ecosystem resilience, which broad category of climate threat is it aiding: rainfall, temperature, snow, wind/storms (all of these include category specific extreme events).

Of the initial 100 results, just five were deemed to detail a species as a key component of an ecosystem(s) and of these, all five were deemed relevant to migratory species aiding climate change as nature-based solutions. Based on this preliminary search, additional search terms were added to ensure additional key terms were included for a broader search. Note that 'ecosystem functioning' was not included in the final set of search terms due to this adding many irrelevant papers to the research results. The main search was conducted on 18/04/2023 and 19/04/2023 in Web of Science (databases searched in are detailed in S1), using the below search terms and produced 30,366 results.

The search terms were:

> ((Climate* OR "Global warming" OR "Sea-level rise" OR "Global environmental change")
>
> AND
>
> ("keystone service*" OR "nature based solution*" OR "natural climate solution*" OR "climate change adaptation" OR "climate change mitigation" OR "ecosystem service*" OR "trophic rewilding" OR "ecosystem approach" OR "ecosystem based adaptation" OR "ecological restoration")
>
> AND
>
> (specie* OR ecolog* OR "bio* diversity" OR ecosystem))

From this search, the results were similarly filtered down to extract the term migratory, using the search term: ("migrat*") which left 902 results. The first 100 of this search were skimmed (26/04/2023-27/04/2023).

Finally, to extract any further papers from this same search, further search terms were used to individually filter the ("migrat*") search per species group using similar search terms as in WP1 methods, detailed in a supplementary table (S2 Table 1; dates the searches were conducted: 18/04/2023-19/04/2023).

Additional supplementary *ad hoc* searches were conducted to fill in known gaps. We highlight in the reference list studies from the main or supplementary searches using * = main search and ** = supplementary searches.

The results of all the searches were combined and duplicates removed (table of PRISMA flow - Table 1).

Table 1. PRISMA flow table of sifting of research studies identified by Web of Science search and the total supplementary studies added.

Sifting criteria	WoS search	**Total**
Initial search total	336	336
Filtered for ecosystem service provided by migratory species	**48**	**48**
Number of duplicates removed	18	18
Total number remaining after duplicates removed	**30**	**30**
Filtered for climate change solutions from migratory species (duplicates removed)	**28**	**28**
Supplementary searches	**-**	**43**
Total number of papers filtered for ecosystem service(s) provided by migratory species		**73**
Total number of papers detailing nature climate change solution(s)		**71**

3 Results

Of the 379 results (main searches = 336, supplementary searches = 43), a total of 73 studies identified migratory species as key components of an ecosystem (Figure 2A). The roles performed by these species varies - from soil aeration and nutrient cycling/movement to predator-prey trophic cascades to pollination and seed dispersal - but all enable ecosystems to function and benefit biomes more broadly. These can also be framed as various ecosystem services, be it as Regulation and Maintenance, Provisioning and/or Culture (CICES 2023) which open up a broad set of ecosystem services that migratory species enable. From this study, the services identified were predominantly within Regulation and Maintenance (covering: carbon capture, pollination, seed dispersal, soil fertility and pest control), but also within Provision (predominantly food via hunting) and Culture (covering: tourism, recreational activities, symbolic value and natural heritage) (Fig. 2B&3; S3 Table 2).

Of the different species groups, the highest number of studies were found for birds (n = 30, 41%) and terrestrial mammals (n = 28, 38%), with relatively few being found for the remaining species groups (Figure 2B). Of the broad categories of ecosystem services, all three (or a combination of the three) were identified in the studies for birds, terrestrial mammals, marine mammals and bony fish, whereas only Regulation and Maintenance were highlighted in the studies for bats and the sharks and rays; and a combination of Cultural and Regulation and Maintenance was highlighted studies on insects. In addition, only for birds and terrestrial mammals were disservices/maladaptations identified (in 7, 9%, of papers). Geographically, these studies spanned the world, from various terrestrial mammals across North America, parts of Africa and China; bats, birds and insects across Europe, Africa, South America and India; seabirds across Atlantic, Pacific and Indian Ocean coastal cliffs and islands; marine mammals - cetaceans migrating to and from the Arctic and in the Pacific and Dugong in the coastal waters of Oceania; sharks in the Caribbean; and fish in the Arctic, North America and Europe (Fig. 4).

Many of the ecosystem services we identified are directly or indirectly linked to climate change regulation. Here, we focus on the results of species providing direct or indirect links to climate change regulation. However, the Provisioning and Cultural services would also be important to consider given the wider cultural and economic wellbeing impacts of climate change, but we deem this to be outside the scope of this section and suggest this would merit further investigation. We concentrated on the climate change linked services/ nature-based solutions (defined by IUCN; IUCN 2023). Consequently, 71 of the remaining 73 identified studies were deemed relevant, which included nature-based solutions which are key to carbon capture and ecosystem resilience to climate change (further divided into: fire risk, coastal erosion, water quality/flooding and plant genetic isolation - pollination, seed dispersal, nutrient cycling, pest and disease control; Fig. 4, Table 2).

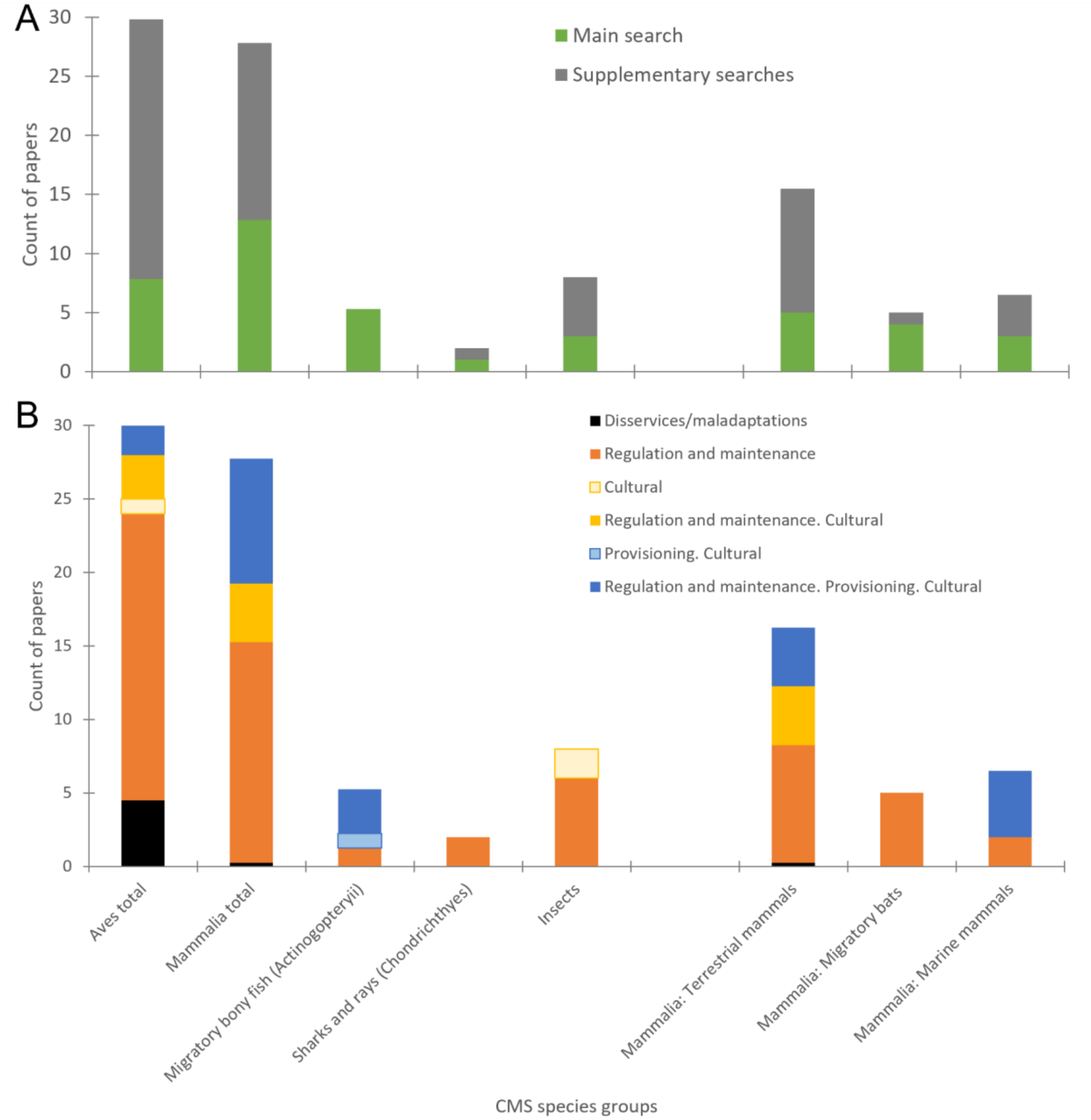


Figure 2. Count of papers from different CMS species groups (totals for each group on left and then the mammalia group is split down further on right) A) comparing the main search to the supplementary searches and B) comparing the different services provided by each species group. NB: this is a count compiled from this study's main and supplementary search results and is not an exhaustive list.

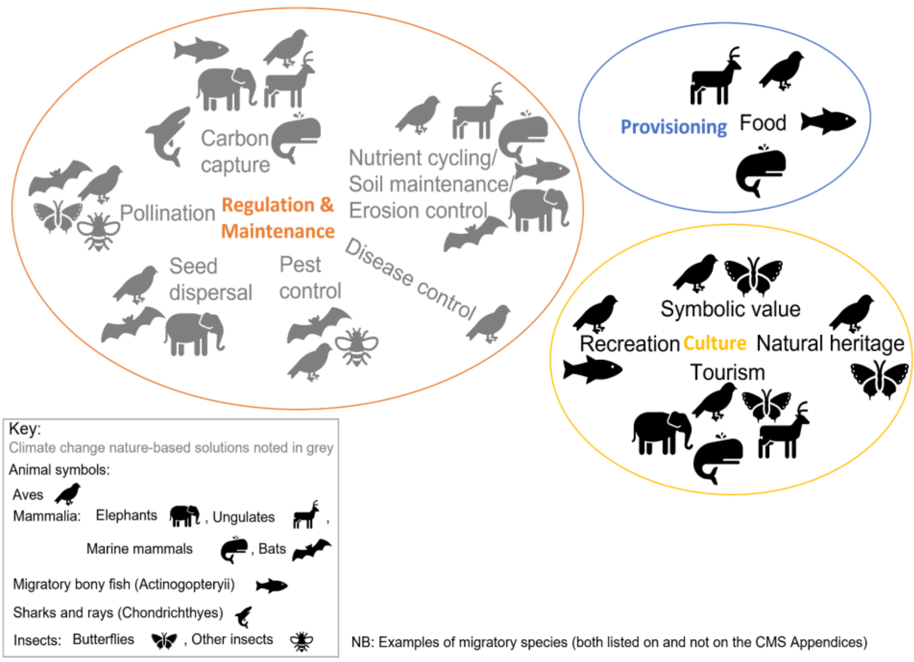


Figure 3. Schematic of the three types of services (Regulation and Maintenance - left & orange, Provisioning - top right & blue, and Culture - bottom right & gold), with specific examples from each of these and icons around each to show which CMS species group(s) provide these services (note some examples are from species not currently listed on CMS Appendices). Grey services and symbols indicate climate change specific nature-based solutions. NB: this is a count compiled from this study's main and supplementary search results and is not an exhaustive list.

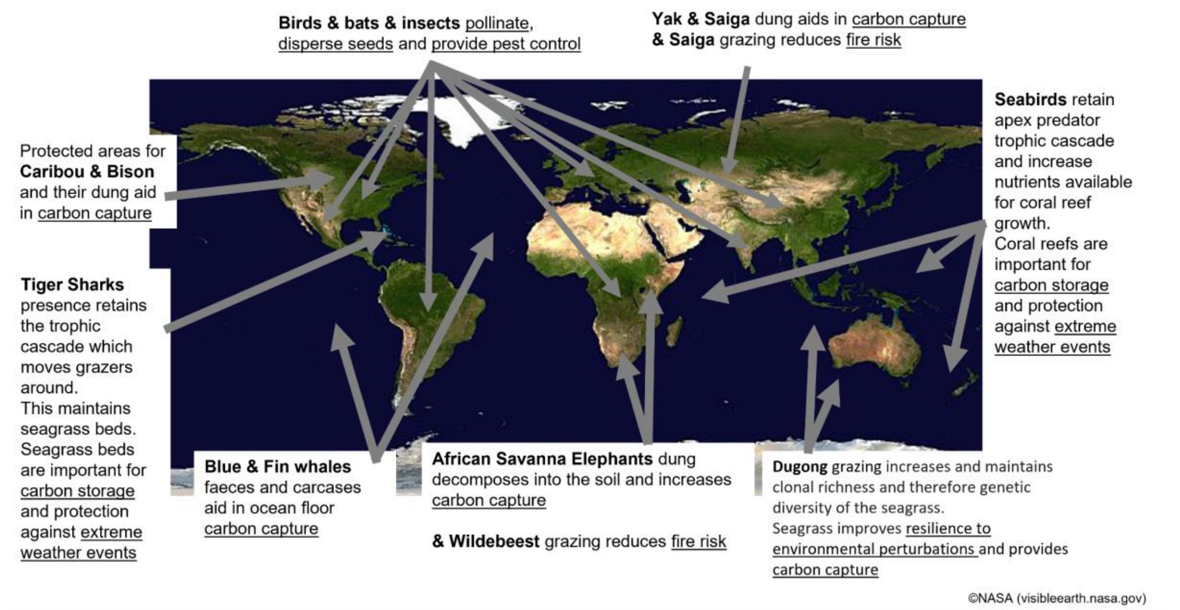


Figure 4. World map showing example migratory species (some listed on CMS Appendices and some not currently listed) and the climate change related services they provide with rough geographical locations of where they can be found. References and more details of the studies can be found in Table 2. NB: this is an example list compiled from this study's main and supplementary search results and is not an exhaustive list.

Table 2. Directly linked climate change related ecosystem services/ nature-based solutions compiled from this study. NB: this is a summary compiled from this study's main and supplementary search results and is not an exhaustive list.

CMS species group	Habitat	Species	Service(s)	References
Carbon capture:				
Terrestrial mammals	Boreal woodland	Caribou	Safeguarding soil carbon through protecting woodland and grassland	Johnson *et al*. 2022
	Grassland	Bison	Keeping snow compact retains carbon in the grassland. Dung left on grassland increases carbon storage	Gilgert & Zack 2010; Schmitz *et al*. 2023
	Alpine grassland	Yak	Dung left on the grassland increases carbon storage	Zhang *et al*. 2016
	Steppes and semi-desert habitats of Central Asia	Saiga Antelope	Dung left on the grassland increases carbon storage	Brinkert *et al*. 2016
	African Savanna	African Savanna Elephants	Elephant dung decomposes into the soil and increases carbon storage	Sandhage-Hofmann *et al*. 2021
Marine Mammals	Ocean	Whales	Whale excretion and sinking carcasses increases carbon storage	Malinauskaite *et al*. 2022a,b; Pearson *et al*. 2023; Schmitz *et al*. 2023

	Seagrass beds	Dugongs	Moderate Dugong grazing aid in retaining genetic diversity in seagrass beds (a globally important carbon store) making them more resilient to environmental perturbation	Preen 1995; McMahon *et al*. 2017
Bony Fish	Rivers-Ocean	Anadromous fish	Fish excretion in the ocean and carcasses in riparian habitat increases carbon storage	Wilcove 2008; Almeida *et al*. 2023
Sharks	Seagrass beds	Tiger Sharks	Tiger shark presence retains the trophic cascade which moves seagrass grazers around. This maintains seagrass beds	Atwood *et al*. 2015; Gallagher *et al*. 2022
Seabirds	Coastal areas	Breeding seabirds (e.g. Red-footed Booby)	Seabird predation retains the trophic cascade and their guano goes into the water, increases the nutrients available for coral to grow which reduces coastal erosion	Savage 2019; Berr *et al*. 2023
Ecosystem resilience services:				
Species important for retaining genetic diversity of plants				
Aves	Forest	Corvidae (Crows) Northern Nutcracker	Seed dispersal to enable forest advancement	Pesendorfer *et al*. 2016; Holtmeier 2012
	Forest	Frugivorous thrushes	Seed dispersal	Rodríguez-Pérez *et al*. 2017

	Oak savanna	Insectivores (Parulidae - Neotropical migrants)	Pest control	Wood & Pidgeon 2015
	Agriculture	Waterbirds: Asian Openbill Stork, Black-headed Ibis	Pest control	Menon 2021
	Agriculture	Insectivores Afro-Palearctic Nearctic - Neotropical migrants	Pest control	Kleemann *et al*. 2020; Jedlicka *et al*. 2021
	Grassland	Insectivores (Icteridae)	Pest control. Pollination	Bedford *et al*. 2013
	Grassland - Forests	Hummingbirds (Trochilidae)	Pollination	Leimberger *et al*. 2022
	Agriculture (Lowquat, *Eriobotrya japonica*) Shrubs (*Salvia* spp.)	White-eyes (e.g. Mountain white-eye, Orange River White-eye)	Pollination	Fang, Chen & Huang 2012 Wester & Claßen-Bockhoff 2006
	Shrubs (*Salvia* spp.)	Sunbirds (e.g. Southern Double-collared Sunbird)	Pollination	Wester & Claßen-Bockhoff 2006
Bats	Forest and volcanic plateau	Mexican Long-tongued, Mexican Long-nosed and Mexican Lesser long-nosed	Nectivorous bats pollinate and disperse seeds as well as provide pest control	Burke, Frey & Stoner 2021
	Forest	Megabats/ Flying foxes/ Old World Fruit Bats (Pteropodidae)	Important pollinators and seed dispersers as well as pest regulators	Frafjord 2007
	Forest	Neotropical leaf-nosed bats (Phyllostomidae)	As frugivores they distribute tree seeds enabling	Ramírez-Fráncel *et al*. 2021

			forest range shift expansions. Needed due to climate change. Also provide pest control	
	Agriculture	Brazilian/ Mexican Free-tailed Bats	Pest control of moths	Krauel, Westbrook & McCracken 2015; Lopez-Hoffman *et al*. 2017
	Agriculture	Bats	Pest control (reduced benefit due to white-nose syndrome)	Manning & Ando 2022
Bony fish	From oceans to rivers	Migratory bony fish	Nutrient transfer	Wilcove 2008; Kovach *et al*. 2013; Beard *et al*. 2019; Steiner *et al*. 2019; Hare *et al*. 2021; Almeida *et al*. 2023
Insects	Generally in Europe	Insects	Aid in long-distance pollination	Tzilivakis *et al*. 2015; Satterfield *et al*. 2020; Hawkes *et al*. 2022
	Globally	Hoverflies (Syrphidae, e.g. Marmalade Hoverfly)	Aid in long-distance pollination and pest control	Doyle *et al*. 2020; Jia *et al*. 2022
	Europe-Africa	Painted Lady Butterfly	Aid in pollination	Hawkes *et al*. 2022
				Rainfall
Terrestrial mammals	Wetlands	Bison	Wallow in wetlands, modifies the habitat of wetlands, aiding in fooding management	Gilgert & Zack 2010; Johnson *et al*. 2012

Temperature				
Aves	Forest	Corvidae (crows) Northern Nutcracker	Seed dispersal to enable forest advancement	Pesendorfer *et al*. 2016; Holtmeier 2012
Aves: waterbirds	Grassland, UK-Iceland	Pink-footed Goose	Long-distance disperser of plant seeds enabling plants to disperse to cooler latitudes	Lovas-Kiss *et al*. 2023
Terrestrial mammals	African Savanna Steppes and semi-desert habitats of Central Asia	African savanna ungulates (including wildebeest) Saiga Antelope	Grazing regimes reduce fire risk	Dobson 2009; Holdo *et al.* 2009; Schmitz *et al*. 2023 Brinkert *et al*. 2016
Wind/storms/ extreme weather events				
Marine Mammals	Seagrass beds	Dugong	Moderate Dugong grazing aid in retaining genetic diversity in seagrass beds (a globally important carbon store) making them more resilient to environmental perturbation which helps reduce coastal erosion	Preen 1995; McMahon *et al*. 2017
Sharks	Seagrass beds	Tiger sharks	Tiger shark presence retains the trophic cascade which moves seagrass grazers around. This maintains seagrass which helps reduce coastal erosion	Atwood *et al*. 2015; Gallagher *et al*. 2022

Seabirds	Coastal habitats	Breeding Seabirds	Seabird predation retains the trophic cascade and their guano goes into the water, increases the nutrients available for coral to grow which reduces coastal erosion	Savage 2019; Berr *et al*. 2023

4 Discussion of ecosystem services provided by each of the species groups

4.1 Aves: General

There are various different bird species/groups within the CMS Appendices that contribute to the Regulation and Maintenance and/or Cultural ecosystem services (Sekercioglu 2002; Whelan, Wenny & Marquis 2008).

Some migratory birds do not fit into the subsequent categories of Aves and so are summarised together here. The ecosystem services they provide are various Regulation and Maintenance ecosystem services within various different habitats globally. These habitats include grassland, forest, agriculture (e.g. coffee farms), providing pest control (both insects and weeds), seed dispersal and pollination (Wester & Claßen-Bockhoff 2006; Fang, Chen & Huang 2012; Bedford *et al*. 2013; Whelan, Şekercioğlu & Wenny 2015; Wood & Pidgeon 2015; Anderson *et al*. 2016; Rodríguez-Pérez *et al*. 2017; Kleemann *et al*. 2020; Jedlicka *et al*. 2021; Leimberger *et al*. 2022; Table 2). This is important because plants, especially isolated plants, rely on animals for pollination and seed dispersal (Kremen *et al*. 2007). Seed dispersal includes many plants needing to expand their range polewards as a range shift response to climate change (Hansson, Dragusch & Shulmeister 2021) and various different species groups aid in this, including a species of bird (Northern Nutcracker; not currently listed on the CMS Appendices; Holtmeier 2012). However, the ability for these and other animals to perform these services has been impacted by different factors such as the loss of biodiversity, anthropogenic impacts of habitat loss/increased habitat patchiness (Fricke *et al*. 2022) and climate change induced range shift changes to higher elevations and latitudes (Hansson, Dragusch & Shulmeister 2021). This has been particularly noted for some long-distance seed-dispersers, but the same study also noted the positive role of introduced species as substitute dispersers (Fricke *et al*. 2022). For isolated plants this is an increasing concern in light of maladaptation due to climate change induced phenological mismatches of migration timings by pollinators/seed dispersers (Bedford *et al*. 2013).

4.2 Aves: Seabirds

Many coastal nesting seabirds are listed by CMS (Appendix I or II; see Part 1 for details) and are important migratory species influencing both terrestrial and marine habitats. During the breeding season, seabirds return to colonies bringing nutrients (in the form of guano, feathers and remnants of prey items) from across the globe back to cliff edges and, often isolated, islands. Seabirds not only aid in nutrient cycling through nest building and burrow nesting, but their guano also increases nutrients in the surrounding coastal area, both land and sea (Berr *et al*. 2023). This nutrient seepage aids carbon capture of the surrounding habitats (*e.g.* coral reefs) and reduces coastal erosion through ensuring top-down trophic cascades (Lorrain *et al*. 2017; Savage 2019; Berr *et al*. 2023). This is further exemplified by a study that compared the nutrients left by seabirds on rat infested and rat-free islands that found invasive rats disrupted the nutrient cycle and substantially decreased the available nutrients on and around the islands (Graham *et al*. 2018). However, further research is needed to establish the vulnerability Nitrogen enriched corals may have to coral bleaching, especially specifically Nitrogen from seabird guano (Lorrain *et al*. 2017). Finally, burrow-nesting seabirds are considered to be ecosystem engineers because they are important for the regulation and maintenance of soils, providing aeration and nutrient cycling (McKechnie 2006).

4.3 Aves: Waterbirds

Waterbirds, specifically geese, storks, ibis and cranes, provide a variety of services within Regulation and Maintenance (pest control, seed dispersal, carbon capture and maintenance of soil health) as well as Culture through tourism and symbolic value (Buij *et al*. 2017; Beard *et al*. 2019; Menon 2021; Valkó *et al*. 2022; Lovas-Kiss *et al*. 2023), and Provisioning, through hunting (Lopez-Hoffman *et al*. 2017).

One positive example is the Pink-footed Goose (CMS Appendix II; Least Concern on the IUCN Red List) which migrates between the UK and Iceland. It is a long-distance disperser of plant seeds, which enables plants to disperse to cooler latitudes, shifting their range in response to climate change (Lovas-Kiss *et al*. 2023). However, one of the studies highlighted an ecosystem disservice where a disproportionate increase in geese density meant there were higher levels of grazing and so the carbon captured by the tundra decreased (Buij *et al*. 2017). This was similarly modelled by Beard *et al*. (2019), who concluded that if Brant Geese (non-CMS) arrived earlier to their breeding grounds (which would be beneficial for their breeding success) their grazing of a species of sedge, *Carex subspathacea*, would reduce its growth and genetic diversity and cause the tundra to turn from a carbon sink to a carbon source. Furthermore, three other papers have shown that with increased densities of migratory birds in wetland patches, the number of droppings can lead to eutrophication, thus negatively impacting plants and other communities (Kerbes, Kotanen & Jefferies 1990; Manny, Johnson & Wetzel 1994; Post *et al*. 1998). This issue could potentially be mitigated through habitat restoration and improved land management (Morecroft *et al*. 2019).

4.4 Aves: Raptors

Raptors aid in Regulation and Maintenance services (through pest control, especially of rodents in agriculture, and through consuming livestock carcasses) and Culturally (as food, natural heritage and symbolic value) (Markandya *et al.* 2008; Whelan, Wenny & Marquis 2008; Donázar *et al*. 2016). One study has identified three species of vulture which were found to help regulate and prevent the spread of disease to humans (specifically in this case rabies) due to their scavenging behaviours. This is because vultures and stray dogs compete for the same carcasses, when vulture populations decreased due to poisoning from the veterinary drug diclofenac, stray dog populations increased which increased the source of rabies with knock on effects to humans (Markandya *et al*. 2008). Other studies have found similar results in other countries/continents where vultures are found (e.g. Africa; van den Heever *et al.* 2021).

4.5 Mammalia: Terrestrial mammals

Terrestrial mammals predominantly influence Regulation and Maintenance ecosystem services through carbon storage. This is predominantly through the dropping of dung, which is decomposed and the resulting carbon stored in the soil. Examples of this include: Wild Yak and Saiga Antelope dung in alpine grasslands (Brinkert *et al*. 2016; Zhang *et al*. 2016), and Reindeer/Caribou dung in grasslands (Beard *et al*. 2019). However, other terrestrial mammals also aid in carbon storage indirectly through compacting snow which reduces the carbon released from permafrost (e.g. American Bison in the Arctic where ~500 Gt of carbon is stored in permafrost; Schmitz *et al*. 2023) and through causing an area to be protected, for example woodland which is important for carbon storage (e.g. Boreal Woodland Caribou; Johnson *et al*. 2022).

Additional services terrestrial mammals provide include:

- soil maintenance, regulating vegetation dynamics, nutrient cycling, seed dispersal and erosion control (e.g. African Savanna Elephants as ecosystem engineers, Fritz 2017).
- fire management of grassland savanna (Common Wildebeest,grazing; Dobson 2009; Holdo *et al*. 2009; Rouet-Leduc *et al*. 2021; Saiga Antelope, Brinkert *et al*. 2016; Akçakaya *et al*. 2018).
- maintaining grassland biodiversity via grazing (Bison, Gilgert & Zack 2010; Johnson *et al*. 2012; and Saiga Antelope, Brinkert *et al*. 2016).
- habitat modification via wallowing in wetlands, which are beneficial for many migratory birds and other resident species e.g. Prairie Dogs (American Bison; Gilgert & Zack 2010; Johnson *et al*. 2012).
- food, as a Provisioning service (van Moorter *et al*. 2020).

These are often charismatic, large megafauna and so also often feature within Cultural ecosystem services for tourism (Fritz 2017).

Some studies have already identified climate change related trophic mismatches; these will be important to be taken into account when considering nature-based solution(s) the species may contribute to. One study highlights that if there is a delayed migration of grazing Caribou it allows more time for Greenland vegetation to grow which provides a stronger carbon sink (Beard *et al*. 2019). Another highlights that the earlier immersion of elderberries (*Sambucus racemosa*) means that Grizzly Bears are eating less Salmon which reduces the amount of nutrients from salmon carcases (discarded by the bears) going in the surrounding riparian habitat (Beard *et al*. 2019). Furthermore, another study highlighted a population decline in some long-distance seed-dispersers which has a knock on effect on the associated plant distributions, however the same study also noted the positive role of introduced species as substitute dispersers (Fricke *et al*. 2022). Finally, Wildebeest and other African migratory ungulates are important for nutrient cycling and carbon storage as they graze across their migration routes (Dobson 2009). However, when ungulate populations have previously declined due to disease, this increased the amount of standing grasses to burn in wildfires, therefore releasing carbon dioxide rather than the savanna being a sink (Holdo *et al*. 2009; Rouet-Leduc *et al*. 2021; Schmitz *et al*. 2023). Maintaining a functioning migratory population of ungulates will be important in retaining this aid in reducing wildfires and improving ecosystem resilience (See African savanna case study for examples of conservation efforts).

4.6 Mammalia: Migratory bats

Bats contribute to Regulation and Maintenance ecosystem services through pollination and seed dispersal (which aids in reducing genetic isolation of plants) and pest control within agricultural landscapes (Frafjord 2007; Krauel, Westbrook & McCracken 2015; Lopez-Hoffman *et al*. 2017; Burke, Frey & Stoner 2021; Ramírez-Fráncel *et al*. 2021; Manning & Ando 2022). For example one study of Megabats (or Flying Foxes), which are predominantly frugivores (includes one CMS Appendix II species - Straw-coloured Fruit Bat; Near Threatened), identified they are particularly important for regeneration of rainforest habitat both on mainland and islands (Frafjord 2007). This is important given the reduction in rainforest habitat. Another example study of three nectivorous bats (not currently listed on CMS Appendices), which migrate between the US and Mexico, identified they are important pollinators and seed dispersers of columnar cacti and agave (*Agave* spp.). These plants are found in tropical dry forests, however, the distribution of this habitat is increasingly becoming patchy and so the continued pollination and seed dispersal by the bats will be imperative for these plant species to retain genetic diversity whilst also there being enough food available for the bats to survive (Burke, Frey & Stoner 2021). Burke, Frey & Stoner (2021) suggest that an increase in land protection (through habitat conservation and responsible plant population management) will be important for the survival of both the plants and bats. A further example, demonstrates that alongside plant isolation due to climate change, many are needing to expand their range polwards as a range shift response to climate change (Hansson, Dragusch & Shulmeister 2021) and various different species groups aid in this, including a group of bats (the Neotropical leaf-nosed bats; Phyllostomidae; not currently listed on CMS Appendices). They are frugivores and so distribute tree seeds enabling forest expansion (Ramírez-Fráncel *et al*. 2021).

Both seed dispersal and pollination are important because plants, especially isolated plants, rely on animals for pollination and seed dispersal (Kremen *et al*. 2007). However, the ability for these and other animals to perform these services has been impacted by different factors such as the loss of biodiversity, anthropogenic impacts of habitat loss/increased habitat patchiness (Fricke *et al*. 2022) and climate change induced range shift changes to higher elevations and latitudes (Hansson, Dragusch & Shulmeister 2021). For isolated plants this is an increasing concern in light of maladaptation due to climate change induced phenological mismatches of migration timings by pollinators/seed dispersers (Bedford *et al*. 2013).

4.7 Mammalia: Marine mammals

Whales (and likely smaller cetaceans too) contribute to Regulation and Maintenance ecosystem services predominantly through carbon capture by carcass fall. All bodies retain carbon, the longer lived, and larger, the animal, the more carbon that is stored. As whales are both large and long-lived, their carcass falling to the ocean floor locks a substantial amount of Carbon into the ocean floor substrate when they die (Pearson *et al*. 2023; Schmitz *et al*. 2023). Whales also aid in marine nutrient cycling through being 'pumps' circulating nutrients between ocean floors and surface waters (Schmitz *et al*. 2023) as well as globally due to their long migratory journeys (Pearson *et al*. 2023). Whales are also important Culturally (Butman, Carlton & Palumbi 1995; Malinauskaite *et al*. 2022a, 2022b; Pearson *et al*. 2023; Schmitz *et al*. 2023). See the Cetacean case study for more details.

Alongside whales providing ecosystem services, other marine mammals do so also. It has been suggested that the moderate levels of Dugongs grazing help seagrass retain genetic diversity, because during grazing they create furrows allowing space for seed recruitment. As seagrass is important for carbon capture, Dugongs therefore indirectly aid Regulation and Maintenance through carbon capture (Preen 1995; McMahon *et al*. 2017). Tropical and temperate coastal ecosystems (e.g. coral reefs, kelp forests and seagrass beds; Figure 5) are important for carbon storage (e.g. primary production of kelp forests in the Atlantic can exceed 1 kg Carbon.m^{-2}.yr^{-1}. So for Scotland with an area of ~8000 km^2 this would equate to 8 million tons of Carbon stored per year; Smale *et al*. 2013). In addition, a further nature-based solution to support the potential for climate change adaptation that these ecosystems provide is reducing coastal erosion and protecting the coast, especially from extreme climate change induced weather events (Gallagher *et al*. 2022; Schmitz *et al*. 2023).

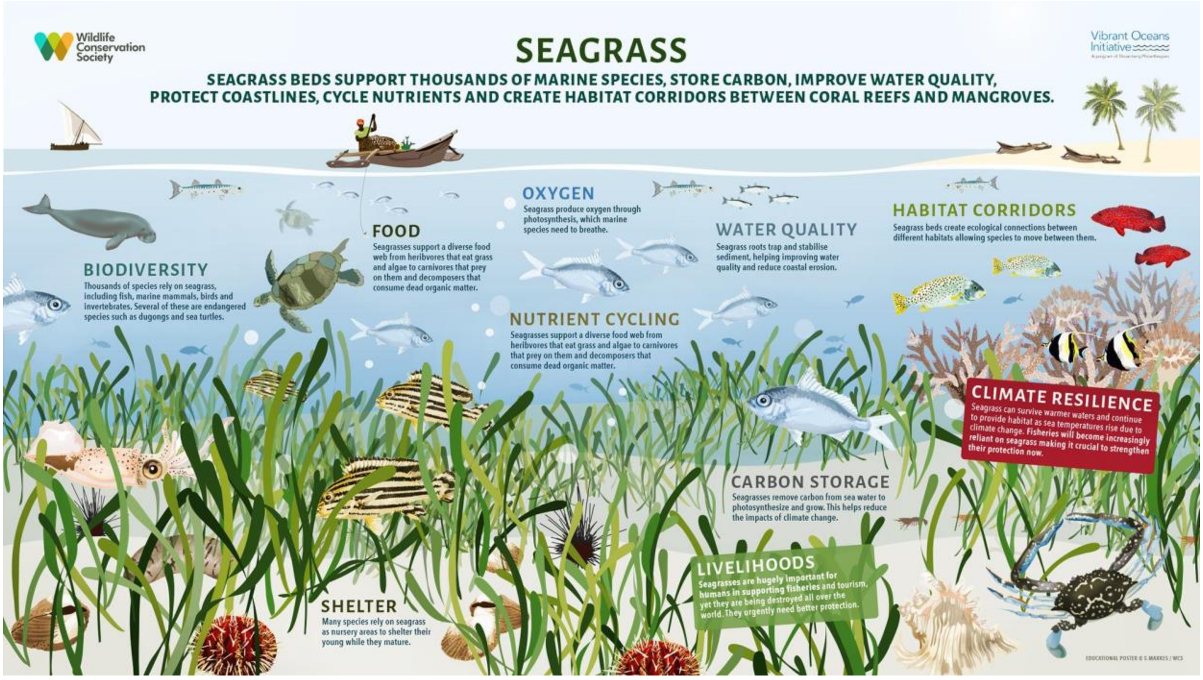


Figure 5. Seagrass bed ecosystem and nature-based solutions. WCS Tanzania

4.8 Bony fish (Actinopterygii)

Within both freshwater river systems and in the ocean, bony fish provide all three types of ecosystem services - through Regulation and Maintenance (nutrient transfer between ocean and freshwater systems), Provisioning (via food) and Culturally (recreation) (Wilcove 2008; Kovach *et al*. 2013; Beard *et al*. 2019; Steiner *et al*. 2019; Hare *et al*. 2021; Almeida *et al*. 2023).

4.9 Sharks and rays (Chondrichthyes)

Sharks provide important regulation and maintenance ecosystem services in the form of carbon capture and reducing coastal erosion through ensuring top-down trophic cascades (Gallagher *et al*. 2022). For example, the presence of migratory Tiger Sharks, which are apex predators with a strong habitat association with seagrass beds (*Thalassia testidinum* and *Syringodium filiforme*), around seagrass beds keeps grazers moving around, which aids in avoiding overgrazing. Thus maintaining the natural balance of the seagrass bed ecosystem as a carbon store (Atwood *et al*. 2015). Tiger Sharks are found globally and adults undertake long migrations. In the Bahamas, continued conservation of the Tiger Shark alongside their associated habitat (through e.g. Marine Protected Areas) will likely aid in the carbon storage in the seagrass and therefore ecosystem resilience of coastal communities (Gallagher *et al*. 2022; Schmitz *et al*. 2023). Although Tiger Sharks are not currently listed on CMS, marine predators (including sharks) are important in protecting carbon stored in marine vegetation, and further research into the full impact apex predators can have on the carbon cycle will be important (Atwood *et al*. 2015).

4.10 Insects

Only one insect species is currently listed in the CMS Appendices. This is the Monarch Butterfly, which is important Culturally for tourism and also providing symbolic value and natural heritage (Lopez-Hoffman *et al*. 2017; Lemelin & Jaramillo-López, 2020). Nevertheless, other butterfly species are also long-distance migrants and Hawkes *et al*. (2022) comment they are likely to provide Regulation and Maintenance services in the form of pollination across their migration (e.g. Painted Lady Butterfly). Furthermore, many other insects are migratory and these also provide Regulation and Maintenance ecosystem services (Satterfield *et al*. 2020). Specifically, trans-boundary insect migrants aid in pollination and pest control (e.g. Hoverflies; Tzilivakis *et al*. 2015; Doyle *et al*. 2020; Jia *et al*. 2022; Satterfield *et al*. 2020) as well as Cultural services through providing inspiration (e.g. butterflies, Lopez-Hoffman *et al*. 2017; Lemelin & Jaramillo-López, 2020). Pollination and pest control are important because plants, especially isolated plants, rely on animals for these services (Kremen *et al*. 2007). However, the ability for these and animals to perform these services has been impacted by different factors such as the loss of biodiversity, anthropogenic impacts of habitat loss/increased habitat patchiness (Fricke *et al*. 2022) and climate change induced range shift changes to higher elevations and latitudes (Hansson, Dragusch & Shulmeister 2021). For isolated plants this is an increasing concern in light of maladaptation due to climate change induced phenological mismatches of migration timings by pollinators/seed dispersers (Bedford *et al*. 2013). Therefore, insects and their associated services will be important to consider in light of their population declines due to the use of neonicotinoids and other insecticides (Siviter & Muth 2020).

5 Conclusions and Recommendations

The aim of this relatively rapid review was to highlight the role migratory species could have as nature-based solutions in reducing the impact of climate change. We have identified examples in the published literature where migratory species are integral to various ecosystem functions and where their conservation may support nature-based solutions to climate change mitigation. In some cases, resulting conservation actions will not only protect and enhance the main species of interest but also associated species' and surrounding habitats. This highlights the importance of understanding, and where needed restoring the functional role of, the target species within the ecosystem.

From a climate change perspective, the most frequently identified ecosystem functions fulfilled by migratory species were Regulation and Maintenance ecosystem services (covering: carbon capture, pollination, seed dispersal and pest control). We also noted that migratory species were important for a wider range of other services within Culture (covering: tourism, recreational activities, symbolic value and natural heritage) and Provisioning (predominantly food) categories, as well as other functions such as ecosystem engineers (e.g. elephants - Fritz 2017, burrow nesting seabirds - McKechnie 2006). Of these services, pollination, seed dispersal and pest control were particularly provided by migratory bird, bat and insect species groups, which indirectly benefit plants (to support their reproduction and responses to climate change, to retain their genetic diversity and therefore to promote carbon storage). Larger migratory species - other terrestrial mammals, marine mammals and sharks were highlighted as particularly important in aiding direct carbon capture and other climate change related Regulation and Maintenance services.

The strongest evidence that the conservation of migratory species can support nature-based solutions to climate change mitigation come from published research on carbon capture by a substantial number of different species – especially the larger, megafauna. These included, large terrestrial grazers – Caribou, Bison, Yak, African Elephant; large marine mammals – Whales, Dugongs; bony fish, tiger sharks and cliff or island nesting seabirds (Table 2). These studies show that conserving these migratory species not only aids in increasing carbon capture, but along with associated measures of achieving this, protecting areas (terrestrial and marine) and enacting habitat restoration (e.g. invasive predator removal at seabird breeding grounds), improves the surrounding ecosystems and maintains biodiversity.

Furthermore, we identified that migratory species not only aid in carbon capture but can also contribute towards climate change adaptation, particularly in response to climatic hazards (e.g. flooding, sea-level rise, frequent and intense droughts, heatwaves and wildfires) by enhancing ecosystem resilience. However, there were fewer examples of this, which highlights the need for further work to review and identify such studies (that may have been deemed outside the scope of our literature search) and further empirical research. In addition, we identified examples of species which aid in retaining genetic diversity of particularly isolated plants through pest control, pollination and seed dispersal via frugivorous and insectivorous bats and birds and pollinating insects (e.g. hoverflies, butterflies). However, the magnitude of benefit of this for adaptation, and the specific role of migratory species in this area, is uncertain, and we suggest further assessments of CMS species of note within the birds, bats, and insect categories for this.

The role of migratory species conservation aiding in solutions to ameliorate the impacts of extreme weather events were identified, highlighting the importance of intertidal and near-coastal habitats (e.g. coral reefs and seagrass beds). By conserving particular migratory species, these habitats are also conserved – retaining and boosting their ecosystem resilience to these climate change hazards as well as providing habitat for a wide range of other species that depend on them (e.g. Tiger Sharks as apex predators maintain trophic cascades, Gallagher *et al*. 2022; Dugongs as grazers of seagrass, McMahon *et al*. 2017; breeding Seabirds on cliffs and islands, Savage 2019; Berr *et al*. 2023). Providing and maintaining protected areas will likely be important for this to continue (e.g. Tiger Sharks and seagrass beds, Gallagher *et al*. 2022). These principles likely also apply with respect to other habitats and climate change related hazards, such as flood management, wildfires and snow melt, but we found relatively few studies documenting these. Again, we suggest targeted searches for specific climate change hazards of interest, to identify any further species and or knowledge gaps for future research, will also be important.

The studies identified in this review demonstrate that migratory species not only form significant components of many ecosystems, but also facilitate significant transfers of energy and resources across their migration routes (Bauer & Hoye 2014). However, despite the growing understanding of how species providing ecosystem services can help with nature-based solutions to human challenges such as climate change (e.g. Díaz *et al*. 2006; Schmitz *et al*. 2023), specific studies about the importance of migratory species are not common. We suggest further work is required to develop additional case-studies of these examples on a wider number of migratory species (especially those listed on CMS Appendices I and II) to better understand the climate change mitigation and adaptation services these species can provide, noting the much weaker evidence-base for the latter (Part 2). This will be particularly key for the smaller/less charismatic fauna (e.g. insects, bats, birds) for which there are fewer specific studies linking respective species/species groups ecological function(s) to ecosystem services. In particular, there is a pressing need for stronger research in the global south, as this study's review revealed fewer species studied in this area, given the projected large scale of climate impacts in the global south and the lack of resources and capacity to mitigate/adapt to them.

As has already been detailed in Part 2, some conservation management tools already exist to aid in identifying the potential role(s) humans can play in providing appropriate ecosystem management to support these ecosystem services and functions (e.g. Díaz *et al*. 2006; Schmitz *et al*. 2023). In fact, in a recent study, Schmitz *et al*. (2023) argue that restoring specific wild animals to their natural functional roles through conservation (e.g. restoration and protection) can aid in climate change mitigation (e.g. through carbon storage). Identifying other examples requires quantifying the impacts of the transfers of energy and resources migratory species make (see the cetacean case study). For many of the studies in this review (although not whales!), these transfers of energy and resources directly or indirectly relate to change in vegetation biomass. It will therefore be important to consider the human land and coastal use of ecosystems that overlap with migratory species (Morecroft *et al*. 2019) and associated management options in light of ecosystem services they provide (Mitchell, Bennett & Gonzalez 2013). Finally, another aspect studies have identified is the importance of including interdisciplinary, local and stakeholder discussions to aid in unifying ways forward for species management and conservation (e.g. Ramírez-Fráncel *et al*. 2021; Malinauskaite *et al*. 2022a, b).

Biodiversity is strongly impacted by climate change drivers in addition to more long-standing threats (Part 1). Climate change adaptation will therefore become an increasing consideration of species' conservation in a changing climate (Part 2). At the same time, there is a pressing need to consider how best to manage natural systems to support climate change mitigation and limited greenhouse gas concentrations in the atmosphere, and also for reasons of ecosystem-based adaptation or nature-based solutions to climate change (Morecroft *et al*. 2019). These measures have the potential to be synergistic or conflicting with adaptation for migratory species, hence the need for careful consideration of how best to respond to climate change. Our intention in publishing this review is to highlight examples where the conservation of migratory species may also contribute to wider benefits for people and ecosystems, to help decision-makers begin to consider these issues in a cross-cutting and holistic way. However, we recognise that this was a relatively rapid review, and would therefore recommend that further in-depth assessments of the literature, and particularly to engage with species and regional experts from around the world to undertake a more comprehensive assessment of such activities. Many of these may not appear in the scientific literature (and so would not have been picked up), to identify a wider range of examples where the conservation of migratory species may support or conflict with management for climate change mitigation and nature-based solutions to climate change for people in order that best practice and learning around overcoming the inevitable challenges may be shared widely. Given the high uncertainty associated with the effectiveness of adaptation (e.g.

Pearce-Higgins *et al*. 2022), we would also recommend the need to ensure that management interventions are properly monitored and evaluated, and the results made available, to inform wider decision-making.

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NB: * = paper identified in the main review process. ** = paper identified in Supplementary search.

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7 Supplementary Materials

7.1 Methods - Strategic literature databases

Preliminary search on 14/04/2023 in Web of Science comprising of the Web of Science Core Collection, BIOSIS Citation Index, MEDLINE(r), Zoological Record, KCI_Korean Journal Database and SciELO citation Index databases; 1991-2023 inclusive, using the basic search bar searching in ‘topic’.

The main search on 18/04/2023 and 19/04/2023 in Web of Science comprising of the Web of Science Core Collection, BIOSIS Citation Index, MEDLINE(r), Zoological Record, KCI_Korean Journal Database and SciELO citation Index; 1962-2023 inclusive, using the basic search bar searching in ‘topic’.

7.2 Methods - Detailed search terms

Table S1. Detailing the searches used to filter the "migrat*" search, to identify any remaining papers specific to the CMS list. List of search terms was based on the Part One search terms.

Date(s) searched	Additional search terms to extract additional, by species, papers
18/04/2023	(duck OR goose OR swan)
18/04/2023	(albatross OR petrel OR shearwater OR procellariiformes)
18/04/2023	(accipiter OR eagle OR aviceda OR buzzard OR falco OR kite OR circus OR osprey)
18/04/2023	(owl)
18/04/2023	("microcarbo pygmaeus" OR "phalacrocorax nigrogularis" OR "fregata andrewsi")
18/04/2023	(diver OR loon)
18/04/2023	(flamingo)
18/04/2023	("podiceps auritus" OR"podiceps grisegena")
18/04/2023	(gull OR tern)
18/04/2023	(egret OR heron OR bittern OR ibis OR pelican)
18/04/2023	(sporophila OR seedeater OR tyrant OR bobolink)
18/04/2023	(warbler)
18/04/2023	("Afro-palearctic migrant")
18/04/2023	(muscicapidae OR sylviidae OR turdidae OR motacillidae)
18/04/2023	(bustard)

18/04/2023	(“spheniscus demersus” OR “spheniscus humboldti”)
18/04/2023	(corncrake OR crake OR crane OR flufftail)
18/04/2023	(stork)
18/04/2023	(vulture OR condor)
18/04/2023	(wader OR shorebird OR Charadriidae OR Scolopacidae OR Laridae OR Haematopodidae OR Burhinidae OR Ibidorhynchidae OR Recurvirostridae OR Pluvianellidae OR Dromadidae OR Glareolidae OR Laridae OR Alcidae)
19/04/2023	(mammal OR cetacea* OR carnivor* OR seal OR lion OR manatee OR dugong)
19/04/2023	(turtle)
19/04/2023	(sturgeon OR actinopterygii OR shovelnose)
19/04/2023	(shark OR ray OR chondrichthyes OR sawfish)
19/04/2023	(bat*)
19/04/2023	(ungulate OR gazelle OR antelope)
19/04/2023	(gorilla OR chimpanzee)
19/04/2023	(“Ursus maritimus” OR “Ursus arctos isabellinus”)
19/04/2023	(Elephant) NOT (Seal)
19/04/2023	(Lontra)
19/04/2023	(“Lycaon pictus” OR “Acinonyx jubatus” OR “Panthera onca” OR “Panthera pardus” OR “Panthera leo” OR “Uncia uncia”)
19/04/2023	(“Danaus plexippus” OR Moth OR (Butterfly NOT fish))

7.3 Methods – Ecosystem services provided by group

Table S2. Supplementary table summarising the broad Ecosystem Service(s) categories and specific services from the 73 studies identified in the results section (Part 3. Section 3).

Species group	Habitat	Species	Service	Specifics	Refs
Aves combined	-	Birds	Cultural	Tourism. Symbolic value. Natural heritage	Sekercioglu 2002
		Birds	Disservices/ maladaptations		Kerbes *et al*. 1990; Manny *et al*. 1994; Post *et al*. 1998; Bedford *et al*. 2013; Buij *et al*. 2017; Beard *et al*. 2019; Fricke *et al*. 2022
	-	Birds	Regulation and maintenance	Seed dispersal	Fricke *et al*. 2022
	-	Birds	Regulation and maintenance	Pollination	Anderson, Kelly and Ladley 2016
	Woodland	Corvids	Regulation and maintenance	Seed dispersal	Pesendorfer *et al*. 2016
	Grassland	Frugivores	Regulation and maintenance	Pest control. Pollination	Bedford *et al*. 2013
	Woodland	Frugivores	Regulation and maintenance	Seed dispersal	Rodríguez-Pérez *et al*. 2017
	Grassland-Forest	Hummingbirds	Regulation and maintenance	Pollination	Leimberger *et al*. 2022
	Agriculture	Insectivores	Regulation and maintenance	Pest control	Kleemann *et al*. 2020; Jedlicka *et al*. 2021
	Oak Savanna	Insectivores	Regulation and maintenance	Pest control	Wood and Pidgeon 2015

	Woodland	Nutcrackers	Regulation and maintenance	Seed dispersal	Holtmeier 2012
	Coastal	Seabirds	Regulation and maintenance	Soil nutrients. Carbon capture.	McKechnie 2006; Lorrain *et al*. 2017; Graham *et al*. 2018; Savage 2019; Berr *et al*. 2023
	Grassland	Waterbirds	Regulation and maintenance	Pest control. Carbon capture. Healthy soils. Seed dispersal	Buij *et al*. 2017; Beard *et al*. 2019; Menon 2021; Valkó *et al*. 2022; Lovas-Kiss *et al*. 2023
	Agriculture	White-eyes and sunbirds	Regulation and maintenance	Pollination	Wester & Claßen-Bockhoff 2006; Fang, Chen & Huang 2012
	Agriculture	Vultures	Regulation and maintenance. Cultural	Disease control. Pest control. Cultural	Markandya *et al*. 2008; Donázar *et al*. 2016; Van Den Heever *et al*. 2021
	-	Birds	Regulation and maintenance. Cultural. Provisioning	Broad range	Whelan, Wenny & Marquis 2008; Whelan; Şekercioğlu and Wenny 2015
Mammalia: Terrestrial mammals	-	Mammals	Disservices/ maladaptations		Fricke *et al*. 2022
	Grassland	American Bison	Regulation and maintenance	Carbon capture. Habitat modification (Grazing - biodiversity. Wallowing - flooding)	Gilgert & Zack 2010; Johnson *et al*. 2012; Schmitz *et al*. 2023

	-	Mammals	Regulation and maintenance	Seed dispersal	Fricke *et al*. 2022
	Grassland	Mammals	Regulation and maintenance	Fire management	Rouet-Leduc *et al*. 2021
	Grassland	Reindeer/Caribou	Regulation and maintenance	Carbon capture	Beard *et al*. 2019; Johnson *et al*. 2022
	Grassland	Saiga Antelope	Regulation and maintenance	Carbon capture. Fire management. Habitat modification (grazing - biodiversity)	Brinkert *et al*. 2016; Akçakaya *et al*. 2018
	Grassland	Wild Yak	Regulation and maintenance	Carbon capture	Zhang *et al*. 2016
	Grassland	African Savanna Elephant	Regulation and maintenance. Cultural	Soil maintenance. Nutrient cycling. Seed dispersal. Erosion control	Wittemyer *et al*. 2014; Smit and Prins 2015; Fritz, 2017; Sandhage-Hofmann *et al*. 2021
	Grassland	Common Wildebeest	Regulation and maintenance. Cultural. Provisioning	Fire management. Nutrient cycling	Dobson 2009; Holdo *et al*. 2009; Conradi *et al*. 2020; Van Moorter *et al*. 2020
Mammalia: Migratory bats	Mountains	Bats	Regulation and maintenance	Pollination. Seed dispersal.	Burke, Frey and Stoner 2021
	Forest	Bats	Regulation and maintenance	Pollination. Seed dispersal.	Frafijord 2007
	Agriculture	Bats	Regulation and maintenance	Pest control	Krauel, Westbrook & McCracken 2015; Manning and Ando 2022

	Globally	Bats	Regulation and maintenance	Pollination. Seed dispersal. Pest control. Fertiliser via guano	Ramírez-Fráncel *et al*. 2022
Mammalia: Marine mammals	Coastal	Dugongs	Regulation and maintenance	Carbon capture. Coastal resilience to storms	Preen 1995; McMahon *et al*. 2017
	Ocean	Whales	Regulation and maintenance. Cultural. Provisioning	Carbon capture. Food. Tourism.	Butman, Carlton & Palumbi 1995; Malinauskaite *et al*. 2022a, 2022b; Pearson *et al*. 2023; Schmitz *et al*. 2023
Migratory bony fish (Actinogopteryii)	Ocean	Fish	Provisioning. Cultural	Food. Fishing as recreation	Steiner *et al*. 2019
	Rivers	Fish	Regulation and maintenance	Nutrients	Wilcove 2008; Beard *et al*. 2019
	Rivers	Fish	Regulation and maintenance. Cultural. Provisioning	Nutrients. Food. Fishing as recreation	Kovach *et al*. 2013; Hare *et al*. 2021; Almeida *et al*. 2023
Sharks and rays (Chondrichthyes)	Coastal	Sharks	Regulation and maintenance	Carbon capture	Atwood *et al*. 2015; Gallagher *et al*. 2022
Insects	Forest	Butterflies	Cultural	Tourism. Symbolic value. Natural heritage	Lemelin & Jaramillo-López 2020
	Forest	Butterflies	Cultural	Symbolic value	Lopez-Hoffman *et al*. 2017
	Forest	Butterflies	Regulation and maintenance	Pollination	Hawkes *et al*. 2022
	Flowers; Agriculture	Hoverflies	Regulation and maintenance	Pollination. Pest control.	Tzilivakis *et al*. 2015; Doyle *et*

					al. 2020; Jia *et al*. 2022
	Agriculture	Insects	Regulation and maintenance	Pest control	Siviter and Muth 2020
	-	Insects	Regulation and maintenance	Pollination. Pest control.	Satterfield *et al*. 2020

7.4 Species names

Table S3. List of species considered in articles within the literature review. Species marked with * are migratory, but not CMS-listed. Where species are included in the CMS appendices (App's) I or II (or both), and the 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 (Frafjord 2007; Pesendorfer *et al*. 2016; Doyle *et al*. 2020; Kleemann *et al*. 2020; Jedlicka *et al*. 2021; Ramírez-Fráncel *et al*. 2021; Al-Asif *et al*. 2022; Hawkes *et al*. 2022; Leimberger *et al*. 2022; Almeida *et al*. 2023; Berr *et al*. 2023; Pearson *et al*. 2023).

Common name	Scientific name	Appendices	Instruments
Aves			
Red-winged Blackbird*	*Agelaius phoeniceus*		
Bobolink	*Dolichonyx oryzivorus*	II	CMS, Southern South American Grassland Birds 2018
Baltimore Oriole*	*Icterus galbula*		
Orchard Oriole*	*Icterus spurius*		
Brown-headed Cowbird*	*Molothrus ater*		
Southern Double-collared Sunbird*	*Nectarinia chalybea*		
Northern Nutcracker*	*Nucifraga caryocatactes*		
Tennessee Warbler*	*Oreothlypis peregrina*		
Common Grackle*	*Quiscalus quiscula*		
Yellow-rumped Warbler*	*Setophaga coronata*		
Palm Warbler*	*Setophaga palmarum*		
Western Meadowlark*	*Sturnella neglecta*		
Redwing*	*Turdus iliacus*		

Blackbird*	*Turdus merula*		
Song Thrush*	*Turdus philomelos*		
Fieldfare*	*Turdus pilaris*		
Ring-ouzel*	*Turdus torquatus*		
Mistle Thrush*	*Turdus viscivorus*		
Yellow-headed Blackbird*	*Xanthocephalus xanthocephalus*		
Mountain white-eye*	*Zosterops japonicus*		
Orange River White-eye*	*Zosterops pallidus*		
Aves: Seabirds			
Great Frigatebird	*Fregata minor*		
Roseate Tern	*Sterna dougallii*	II	CMS, AEWA
Brown Booby	*Sula leucogaster plotus*		
Red-footed booby	*Sula sula*		
Aves: Waterbirds			
Asian Openbill Stork*	*Anastomus oscitans*		
Pink-footed Goose	*Anser brachyrhynchus*	II	CMS, AEWA
Brant Geese*	*Branta bernicla nigricans*		
Black-headed Ibis*	*Threskiornis melanocephalus*		
Aves: Raptors			
Oriental White-backed Vulture	*Gyps bengalensis*	I&II	Birds of Prey (Raptors) (2015), CMS
Long-billed Vulture	*Gyps indicus*	I&II	Birds of Prey (Raptors) (2015), CMS
Slender-billed Vulture	*Gyps tenuirostris*	I&II	Birds of Prey (Raptors) (2015),

			CMS
Mammalia: Terrestrial mammals			
Bison*	*Bison bison*		
Yak	*Bos grunniens/ Bos mutus*	I	CMS, Central Asian Mammals Initiative
African savanna ungulates (including wildebeest*)	*Connochaetes taurinus*		
Prairie Dogs*	*Cynomys ludovicianus*		
African Savanna Elephants	*Loxodonta africana*	II	CMS, 1979: West African Elephants
Caribou*	*Rangifer tarandus*		
Saiga Antelope	*Saiga borealis mongolica*	II	Saiga Antelope (2006), CMS
Saiga Antelope	*Saiga tatarica*	II	Central Asian Mammals Initiative, Saiga Antelope
Grizzly Bears	*Ursus arctos middendorffi*		
Mammalia: Migratory Bats			
Mexican Long-tongued *	*Choeronycteris mexicana*		
Straw-coloured Fruit Bat	*Eidolon helvum*	II	CMS
Mexican Long-nosed Bat*	*Leptonycteris nivalis*		
Mexican Lesser long-nosed Bat*	*Leptonycteris yerbabuenae*		
Brazilian or Mexican Free-tailed Bat	*Tadarida brasiliensis*	I	CMS
Mammalia: Marine mammals			

Antarctic minke whale	*Balaenoptera bonaerensis*	II	CMS, Pacific Islands Cetaceans
Blue Whale	*Balaenoptera musculus*	I	CMS, ACCOBAMS, Pacific Islands Cetaceans
Fin Whale	*Balaenoptera physalus*	I&II	ACCOBAMS, CMS, Pacific Islands Cetaceans
Dugongs	*Dugong dugon*	II	CMS, Dugong
Southern Right Whale	*Eubalaena australis*	I	CMS, Pacific Islands Cetaceans
Humpback Whale	*Megaptera novaeangliae*	I	CMS, ACCOBAMS, Pacific Islands Cetaceans
Bony fish (Actinogopteryii)			
Alewife*	*Alosa aestivalis*		
Blueback Herring*	*Alosa pseudoharengus*		
Salmon	*Oncorhynchus nerka*		
Salmonids*	*Oncorhynchus and Salvelinus* spp.		
Sharks, rays (Chondrichthyes)			
Tiger Sharks*	*Galeocerdo cuvier*		
Insects			
Monarch Butterfly	*Danaus plexippus*	II	CMS
Marmalade Hoverfly*	*Episyrphus balteatus*		
Painted Lady Butterfly*	*Vanessa cardui*		