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CASE STUDIES

(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.

CLIMATE CHANGE AND MIGRATORY SPECIES

CASE STUDIES

B. Martay[1,4], K. H. Macphie[1,4], H. F. R. Hereward[3,4], K.M. Bowgen[2,3], J. W. Pearce-Higgins[2] & R. A. Robinson[2]
[1] BTO Scotland, Beta Centre, Stirling, FK9 4NF
[2] BTO, The Nunnery, Thetford, Norfolk, IP24 2PU
[3] BTO Cymru, Thoday Building, Bangor, LL57 2UW
[4] Contributed equally to the report as joint first authors

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Case Studies relating to the Impacts of Climate Change

African savanna

Much of sub-Saharan Africa is tropical and subtropical grasslands, savannas and shrubland (Fig. 1; Olson *et al.* 2001). The savanna and grassland habitats are dominated by grasses and are often rich with ungulates and carnivores which prey on these species. Some of these species are migratory, following seasonal patterns in rainfall and productivity. The distribution and abundance of savanna herbivores, and thus carnivores, is generally closely linked to primary productivity, determined by patterns in rainfall (Owen-Smith 2014; Mukhopadhyay *et al.* 2019).

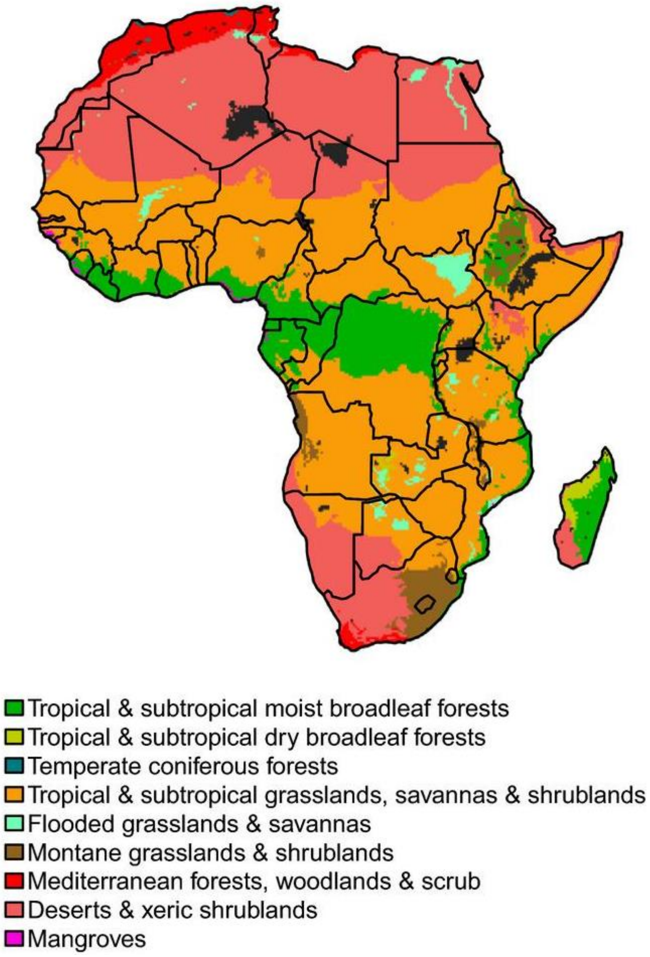


Figure 1. Extent of savanna habitat in Africa (Olson *et al.* 2021)

Migratory savanna species

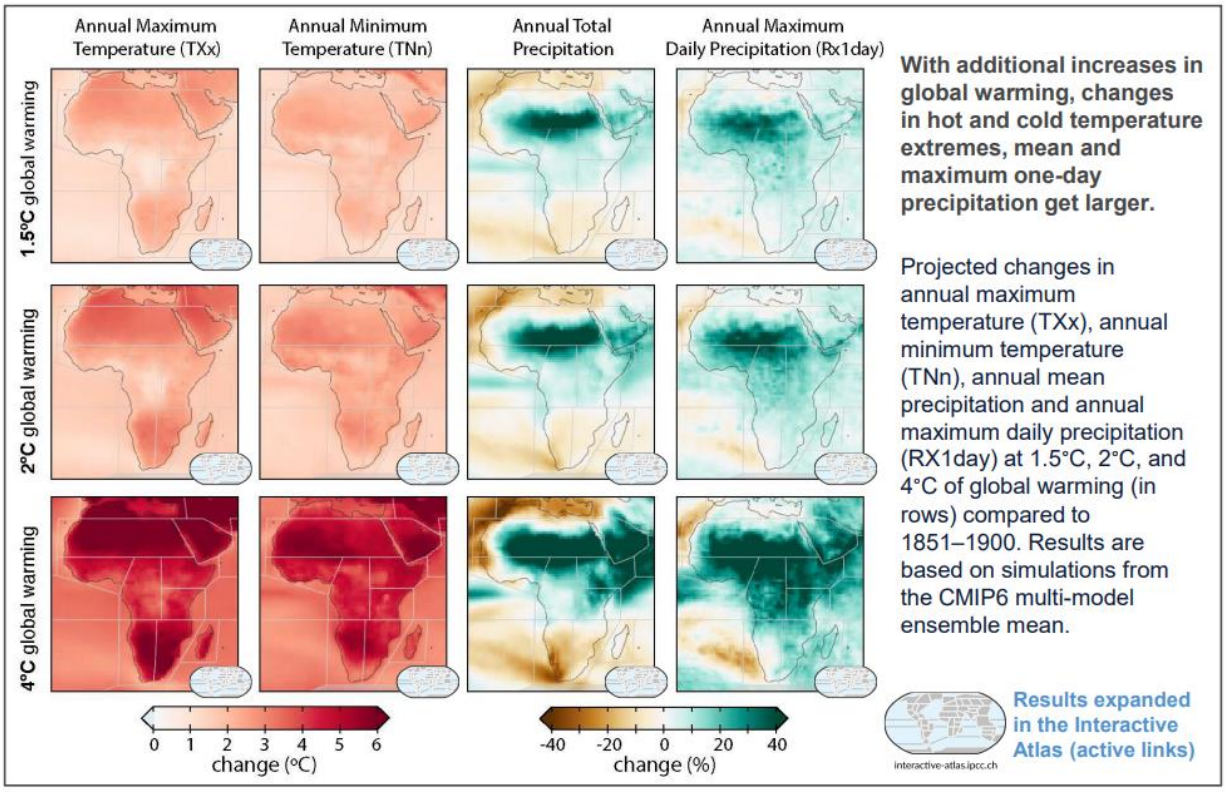
Mammal species listed in the CMS appendices that are found on African savanna habitats include the African Elephant (*Loxodonta africana*), Grevy's Zebra (*Equus grevyi*), Red-fronted Gazelle (*Eudorcas rufifrons*), Giraffe (*Giraffa camelopardalis*), White-eared Kob (*Kobus kob leucotis*), African Wild Dog (*Lycaon pictus*), Cheetah (*Acinonyx jubatus*), Leopard (*Panthera pardus*) and Lion (*Panthera leo*). There are also many migratory birds listed in the CMS appendices, most of which spend all or part of the years on African savanna. These include seven vulture species and many birds of prey such as Brown Snake-eagle (*Circaetus cinereus*) and Eurasian Hobby (*Falco subbuteo*). There are many bird species for which some populations spend their non-breeding seasons on African savanna, including waders such as Jack Snipe (*Lymnocryptes minimus*), Great Snipe (*Gallinago media*), Stone Curlew (*Burhinus oedicnemus*), Curlew Sandpiper (*Calidris ferruginea*) and Collared Pratincole (*Glareola pratincola*); and other birds such as Roller (*Coracias garrulus*) and Bee-eater (*Merops apiaster*).

Predicted Climate Change

Temperatures are predicted to rise across Africa by 1.5-6.5°C by 2100, varying between models and regions (Ziervogel *et al.* 2014; Sylla *et al.* 2016; Luhunga *et al.* 2018; IPCC 2021).

Rainfall predictions are more uncertain (Fig. 2) (Dosio & Panitz 2016; IPCC 2021). Across most of Africa, increases in aridity have been projected (IPCC 2021). Rainfall increases, largely from increases in extreme rainfall events, are predicted over much of the Sahel region, northern Africa and western equatorial Africa, but declines over parts of eastern and southern Africa (Martínez-Freiría *et al.* 2016; Sylla *et al.* 2016; IPCC 2021).

Increasing atmospheric CO_2 levels are also likely to have a direct impact on plant dynamics in African savannas (Conradi *et al.* 2020).



With additional increases in global warming, changes in hot and cold temperature extremes, mean and maximum one-day precipitation get larger.

Projected changes in annual maximum temperature (TXx), annual minimum temperature (TNn), annual mean precipitation and annual maximum daily precipitation (RX1day) at 1.5°C, 2°C, and 4°C of global warming (in rows) compared to 1851–1900. Results are based on simulations from the CMIP6 multi-model ensemble mean.

Results expanded in the Interactive Atlas (active links)

Figure 2. Climate change projections for Africa (IPCC 2021) highlighting not only changes in temperature but, under all scenarios, substantial changes in rainfall pattern.

Rainfall Declines and Drought

Where declines in rainfall and increases in aridity are predicted, there are likely to be declines in many terrestrial mammal populations due to the link between rainfall and primary productivity and thus food availability for herbivores (e.g. ungulates: Bastille-Rousseau *et al.* 2016; Mukhopadhyay *et al.* 2019; Giraffe: Owen-Smith *et al.* 2005; Ogutu *et al.* 2008; Martínez-Freiría *et al.* 2016; Grevy's Zebra: Kigen *et al.* 2013; African Elephants: Boult *et al.* 2019; Dejene *et al.* 2021). For example, rainfall declines, coupled with increasing temperatures are predicted to cause increasing desertification along the southern edges of the Sahara Desert, replacing some savanna habitat north of the Congo basin (Conradi *et al.* 2020). This is likely to lead to increased mortality and local carnivore extinctions (Leopards: Khorozyan *et al.* 2015; Lions: Cooper *et al.* 2021).

In turn, this has the potential for impacts on carnivore populations that prey on such species (Lion: Celesia *et al.* 2010; Leopard: Rodriguez-Recio *et al.* 2022; Sanderson *et al.* 2022). However, for some species, declines in rainfall may be positive, or have little impact. For example, Wild Dog pup survival increases following dry periods (Buettner *et al.* 2007).

Increased levels of drought have also been implicated in a rise in the prevalence of mass mortality events. For example, over 300 African Elephants have recently died in Botswana as a result of biotoxins produced by cyanobacteria in drinking water, triggered by extremes of hot, dry weather (Wang *et al.* 2021). Droughts have also been linked to increases in parasite loads in African Elephants and lions, as more individuals rely on limited water resources (Munson *et al.* 2008; Obanda *et al.* 2011; Titcomb *et al.* 2021). Droughts are also linked to increasing human-wildlife conflicts, for example for African and Asian Elephants, which can lead to increased mortality (Mariki *et al.* 2015; Mukeka *et al.* 2019).

Rainfall Increases and CO_2 Increases

Where rainfall increases, it is predicted that this will lead to shrub encroachment on savannas (Tews & Jeltsch, 2004). Savannas are also predicted to become woodier due to increasing concentrations of atmospheric CO_2, as woody plants will benefit more from this than grasses (Conradi *et al.* 2020). Any declines in large herbivores, particularly African Elephants, will further allow shrub encroachment (Stevens *et al.* 2016).

There is evidence that this shift is already occurring (Conradi *et al.* 2020) and is predicted to threaten many species that rely on grassy habitats (Tews & Jeltsch, 2004). Across southern Africa, bird species associated with open savanna are generally declining, while ones associated with closed, woody savanna are increasing (Sirami *et al.* 2009). An increase in trees may benefit many vulture species, though, which require trees for nesting (Rushworth *et al.* 2018).

Temperature increases

Species are generally adapted to a species-specific temperature range (Grevy's zebra: Kigen *et al.* 2013; African Elephant: Mpakairi *et al.* 2020; Dejene *et al.* 2021). Increasing temperatures may reduce reproductive success in some migratory savanna animals such as Wild Dogs (Woodroffe *et al.* 2017; McNutt *et al.* 2019; Abrahms *et al.* 2022) and decrease populations (e.g. Giraffe: Martínez-Freiría *et al.* 2016).

This is often due to difficulties thermoregulating (African Elephant: Dunkin *et al.* 2013; Pontzer *et al.* 2020; ungulates: Semenzato *et al.* 2021; Wild Dog: Woodroffe *et al.* 2017; Rabaiotti *et al.* 2019). Behavioural adaptations can mitigate some temperature increase, such as foraging earlier and later in the day (Semenzato *et al.* 2021) but this can reduce foraging opportunities. African grassland birds have been found to spend more time keeping cool at higher temperatures, leaving less time for foraging and reducing breeding success (van der Ven *et al.* 2020; Bourne *et al.* 2020; Bladon *et al.* 2019).

Conversely, higher temperatures can improve hunting success for some carnivores, as prey species struggle to thermoregulate when being hunted more than the predator (Wild Dog: Creel *et al.* 2016).

Range shifts

Pole-wards range shifts have been observed and predicted, for example in Cape Vultures (*Gyps coprotheres*) (Phipps *et al.* 2017). Climate change has been linked to range expansions in many Tanzanian savanna bird species, while extinctions were linked more closely to land-use change (Beale *et al.* 2013).

While pole-ward range shifts are generally predicted, the ability of many species to shift their ranges in response to climate change is often unknown. Any mammal range shifts are likely to increase Human-wildlife conflicts and may be prevented by a lack of corridors or suitable habitat. For many migratory mammals, maintaining and creating protected areas and corridors between them is vital for conserving these species under a changing climate (Li *et al.* 2019; Liang *et al.* 2022).

For many species, range shifts and changes in population density are likely to be linked to uncertain patterns in rainfall, and vary between regions. Declines in Lion populations are predicted for southern Africa and West Africa, while predicted to be fairly stable elsewhere (Peterson *et al.* 2014).

Similarly, predictions for changes in African Elephant populations vary between regions and studies. One study predicted only small effects, with a slight improvement in climatic suitability in southern and eastern Africa and reduction in western Africa and northern portions of central Africa (Zacarias & Loyola 2018). Another study predicted a 40% temperature-driven habitat loss in an area in southeast Africa (Mpakairi *et al.* 2020).

Conclusions

As temperatures and atmospheric CO_2 increase across Africa, and rainfall patterns shift, there is likely to be increasing desertification along the boundaries between savanna and desert, and increasing woody encroachment. The area of savanna habitat available is therefore likely to reduce. It is also likely that many savanna animals struggle to thermoregulate in hotter climates and ranges are predicted to move pole-wards. Protected areas and corridors to allow range shifts and migration to follow changes in temperatures and rainfall will be of great importance for conserving many iconic African savanna animals in a changing climate.

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Central Asia & the Tibetan Plateau

Predicted climate change

Central Asia has a range of climatic zones, from temperate and warm continental weather in the north and east, to cold desert and semi-desert climates in south and west. The Tibetan Plateau is generally higher altitude and colder, Tundra habitats. The temperature in Central Asia is likely to increase by up to 6.5 °C by 2100 (Reyer *et al.* 2017), while the Tibetan Plateau is predicted to experience some of the greatest temperature rises globally (Farrington & Li 2016). Most models predict an increase in rainfall in Central Asia but there is some uncertainty in this and declines in rainfall are predicted for drier south west (Reyer *et al.* 2017). On the Tibetan Plateau rainfall is likely to increase, particularly in summer, with some declines in winter (IPCC 2021). Snow-melt is likely to become earlier (Siegfried *et al.* 2012) and glaciers will further retreat (IPCC 2021). Increasing rates of glacial and snow-melt could increase water availability in the short term but decrease it in the medium and long term (Reyer *et al.* 2017). However, where temperatures increase, increasing aridity is likely because of higher rates of evaporation. Human populations are also predicted to increase, which is likely to increase overgrazing, further accelerating grassland degradation (Chen *et al.* 2019).

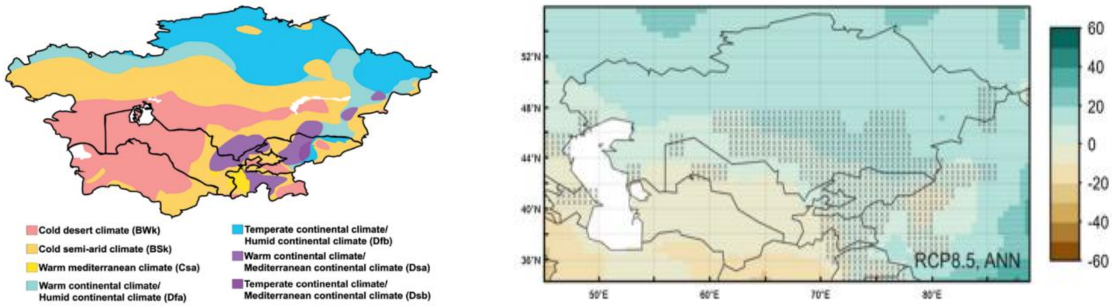

Figure 1. Biomes in Central Asia and projected rainfall change. Predicted percentage change in Central Asian rainfall by 2071-2099 relative to 1951-1980. Hatched areas indicate uncertain regions (Reyer *et al.* 2017).

Impact of climate change on migratory species

Rainfall: For many mammals of Central Asia and the Tibetan Plateau, distribution and migration patterns are driven by availability of food and/or water, generally linked to rainfall which determines primary productivity (ungulates: Luo *et al.* 2015; Goitered Gazelle (*Gazella subgutturosa*): Kaky *et al.* 2023). However, there is much uncertainty and variation in the predicted rainfall changes across Central Asia and the Tibetan Plateau (Luo *et al.* 2015; Reyer *et al.* 2017), adding uncertainty into predictions of climate change impacts.

Temperature: Terrestrial mammal species are generally adapted to a species-specific temperature range (Zhou *et al.* 2022; e.g. Goitered Gazelle: Kaky *et al.* 2023). Increasing temperatures can cause mammal habitats to shift or contract through a range of mechanisms, including reaching thermoregulatory limits (Zhou *et al.* 2022), shifting range of food plants (Qin *et al.* 2020), rising treeline (Forrest *et al.* 2012), retreating glaciers (Luo *et al.* 2015) and increasing aridity (Yadamsuren *et al.* 2019).

Temperature increases are projected to have a greater impact on ungulates of the Tibetan Plateau than other parts of the world. Using three emission scenarios set out in the IPCC (2007), and projections of consequential vegetation changes (Gonzalez *et al.* 2010), the ranges of most ungulates are projected to reduce by 30-50% by 2050, with habitat losses in the south and smaller expansions in the north (Luo *et al.* 2015; Zhang *et al.* 2021).

Rising temperatures are also predicted to cause a large loss of connectivity between increasingly fragmented habitats and across migratory routes which could have large population-level impacts. This has been found for Wild Yak (*Bos mutus*), Kiang (*Equus kiang*), Tibetan Antelope (*Pantholops hodgsonii*), and Tibetan Gazelle (*Procapra picticaudata*) (Liang *et al.* 2021).

There are some instances where warming climates could benefit terrestrial mammals. For example, in colder regions across Asia very severe winters can reduce fecundity and cause mass mortality events for species such as the Saiga Antelope (*Saiga tatarica*) (Coulson *et al.* 2000). Warming on the Tibetan Plateau is particularly rapid in the winter (Farrington & Li 2016) and any lessening in the frequency of extreme winters may be beneficial. However, while average temperatures will increase, an increase in extreme weather events is also predicted, so it is uncertain whether winter mortality will increase or decrease.

Disease: Climate change is likely to increase the incidence of diseases in Central Asian migratory species. In 2015, more than 200,000 Saiga Antelope died in 3 weeks in central Kazakhstan. The deaths were attributed to hemorrhagic septicemia caused by the bacterium *Pasteurella multocida* type B. The outbreak has been linked to unusually warm, humid conditions and instances of this are likely to increase if temperatures continue to rise (Kock *et al.* 2018; Robinson *et al.* 2019).

Other threats to migratory species

Poaching: Poaching is a key threat for some species such as the Saiga Antelope (Singh & Milner-Gulland 2011).

Barriers to migration: Fences for livestock and along borders have a big impact on migratory Asian ungulates (Fox *et al.* 2009; Nandintsetseg *et al.* 2019). The border fences between China and Mongolia prevent migration across the border for a range of species including the Asiatic Wild Ass (*Equus hemionus*) (Xu *et al.* 2022) and Bactrian Camel (*Camelus bactrianus*) (Kaczensky *et al.* 2014).

Other causes of habitat loss: Ungulate habitat across Asia is also threatened by activities and disturbance such as increasing livestock populations, mining and oil drilling (Nandintsetseg *et al.* 2019; Kauffman *et al.* 2021). On the Tibetan plateau Tibetan Antelope, Tibetan Gazelle and Kiang are threatened by activities such as increasing livestock populations, mining and continued hunting (Fox *et al.* 2009). Widespread grassland degradation is predicted across Snow Leopard range, largely attributed to overgrazing (Farrington & Li 2016).

CMS Species of Central Asia & the Tibetan Plateau

CMS species predicted to lose habitat due to increasing temperatures

Much of these species' current range will become climatically unsuitable, but other areas will become suitable. The extent of habitat loss will be partly due to the ability of the species to shift their ranges to track suitable climates (Luo *et al.* 2015).

Snow Leopard (*Uncia uncia*): Montane; Central and South Asia, Tibetan Plateau. Large range declines of around 30% are predicted by 2050, particularly in the south of their range (Farrington & Li 2016). This loss of habitat is partly due to the direct effect of rising temperatures and the rising treeline, and partly due to the range contraction of prey species such as Blue Sheep (*Pseudois nayaur*) (Forrest *et al.* 2012; Aryal *et al.* 2016).

Kiang (*Equus kiang*): Montane & steppe, mainly Tibetan Plateau. Declines due to habitat loss predicted and may become globally endangered (Luo *et al.* 2015).

Wild Yak (*Bos grunniens*): Montane; mainly Tibetan Plateau. Declines predicted by Luo *et al.* (2015).

Goitered (Black-Tailed) Gazelle (*Gazella subgutturosa*): Desert or semi-desert; mainly Central Asia, northern China, Mongolia, Iran & Afghanistan. Declines predicted by Luo *et al.* (2015), Ebrahimi *et al.* (2019) and Zhang *et al.* (2021).

Argali Sheep (*Ovis ammon*): Montane; pockets of subspecies across Central Asia, China and Mongolia. Declines predicted by Luo *et al.* (2015).

Chiru (Tibetan Antelope) (*Pantholops hodgsonii*): Steppe; Tibetan Plateau. Declines predicted by Zhang *et al.* (2021), while possible small range expansion is predicted by Luo *et al.* (2015) if there are no barriers to dispersal.

Tibetan Gazelle (*Procapra picticaudata*): Montane steppe; mainly Tibetan Plateau. Declines predicted by Zhang *et al.* (2021), while possible small range expansion is predicted by Luo *et al.* (2015) if there are no barriers to dispersal.

Urial (*Ovis vignei*): Mountains & steppe; Central Asia, Afghanistan, Pakistan, Iran. Around 60% declines in suitable habitat are predicted in Iran by 2070 (Ebrahimi *et al.* 2019).

CMS species with unknown climate change impacts

Asiatic Wild Ass (Khulan) (*Equus hemionus*): Desert or semi-desert; across the Middle East, Central Asia, Northern China and Mongolia. The impacts of climate change are largely unknown and the observed large declines are attributed to anthropogenic factors such as infrastructure development, grazing livestock and mine exploration (Xu *et al.* 2022).

Bactrian Camel (*Camelus bactrianus*): Desert; four isolated patches in China and Mongolia. Increasing temperatures, reduced river flow and increasing droughts may reduce Bactrian Camel survival and range (Yadamsuren *et al.* 2019). However, they may benefit from reduced predation and competition from less desert-adapted species (Xue *et al.* 2018), so population-level impacts of climate change are difficult to predict.

Saiga Antelope (*Saiga tatarica*): Steppe & woodland; mainly Kazakhstan with smaller populations in Uzbekistan & Russian Federation. Populations are under severe threat from habitat loss, poaching and a lack of protection (Singh *et al.* 2010). Saiga Antelope distribution and migration is closely linked to rainfall, causing seasonal changes in productivity (Singh et al,. 2010). The impacts of climate change are largely unresearched but increasing temperatures and humidity have been linked to recent mass die-off events (Kock *et al.* 2018; Robinson *et al.* 2019), while severe winters can reduce fecundity and cause mass mortality events (Coulson *et al.* 2000).

Mongolian Saiga Antelope (*Saiga tatarica mongolica*): Steppe, woodland, tundra; Mongolia. Populations have declined by around 80% since 2016, linked to a viral infection (peste des petits ruminants virus) found in livestock (Pruvot *et al.* 2020). The impact of climate change on this, and other climate change impacts are largely unknown.

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High Arctic

Predicted change

The Arctic is currently warming twice as fast as the global mean and sea ice extent is rapidly decreasing (Jansen *et al.* 2020). The Arctic has already experienced some of the most rapid rates of warming in recent years and Arctic ecosystems are at particular risk (IPCC 2021). Temperature rises are predicted to be accompanied by further sea-ice loss, glacier retreat, permafrost thaw and increasing rainfall, droughts, fires and storms (Robinson 2022). Many migratory Arctic species will be impacted, particularly marine mammals and Arctic-breeding birds.

Migratory Arctic species

There are many Arctic bird and mammal species listed in the CMS appendices. Many seabirds, shorebirds and waterfowl have breeding ranges that include the Arctic and migrate southwards in the autumn. Examples include the Arctic Tern (*Sterna paradisea*), Whimbrel (*Numenius phaeopus*) and Barnacle Goose (*Branta leucopsis*).

There are also migratory Arctic marine mammals including whale species such as the Narwhal (*Monodon monoceros*) and Beluga (*Delphinapterus leucas*) which generally remain in the Arctic annually, and others such as Blue Whales (*Balaenoptera musculus*) that may migrate to the Arctic as the sea ice contracts in the summer. Other migratory Arctic marine mammals include the Polar Bear (*Ursus maritimus*, see Species Case Study) and pinnipeds such as the Grey Seal (*Halichoerus grypus*).

Climate change impacts

Declines in Arctic sea-ice, combined with rising temperatures and more frequent and severe extreme weather events, will have a major impact on Arctic ecosystems. Key impacts predicted for migratory species are:

A change in the abundance of prey species

Marine mammal and seabird distribution, abundance and breeding success are often closely linked to prey availability (e.g. distribution of Minke (*Balaenoptera acutorostrata*) and Killer (*Orcinus orca*) Whales: Albrecht *et al.* 2021, Vogel *et al.* 2021; seabirds: Gaston *et al.* 2005).

Marine mammals

Krill (Euphausiacea) and other copepods and crustaceans are the key prey for many Arctic baleen whales such as Blue, Bowhead (*Balaena mysticetus*), North Atlantic Right (*Eubalaena glacialis*) and Humpback (*Megaptera novaeangliae*) Whales (Keiper *et al.* 2005; Silber *et al.* 2017). In many areas, sea-ice declines are linked to declines in abundance of krill (Truchon *et al.* 2013).

However, in some areas, sea ice declines may increase primary productivity, increasing both food density and the seasonal availability of food for those that feed on krill (Laidre *et al.* 2008; Simmonds & Isaac 2007; Tulloch *et al.* 2019). This has benefitted some species, for example, Arctic Bowhead Whale population growth and better body condition is better in years with low summer sea ice (Laidre *et al.* 2008; George *et al.* 2015).

In general, the abundance of krill is predicted to decline due to rising temperatures, particularly outside of Arctic regions (Simmonds & Isaac, 2007; Tulloch *et al.* 2019). This is predicted to reduce populations of the baleen whales that migrate into the Arctic, including Blue, Humpback and Fin Whale (*Balaenoptera physalus*) (Learmonth *et al.* 2006; Tulloch *et al.* 2019; Frankel *et al.* 2022).

Seabirds

Arctic Cod (*Arctogadus glacialis*) are often the most abundant fish species and the key prey species for seabirds (Steiner *et al.* 2021). Arctic Cod abundance is generally lower in warmer years (Gaston *et al.* 2005) and many seabirds show reduced breeding success in warmer years. For example, the productivity of southern populations of Brünnich's Guillemots (*Uria lomvia*) is reduced by the impact of warming upon Arctic Cod abundance (Gaston *et al.* 2005). A decline in breeding success in warmer years is also seen in planktivorous birds such as Crested (*Aethia cristatella*) and Parakeet Auklets (*Aethia psittacula*) (Kitaysky & Golubova 2000).

An extreme mass-die off of the Common Guillemot (*Uria aalge*) was observed in the North Pacific in 2016. It was estimated that almost 1 million birds died, and reproduction declined drastically before and after the mass mortality event. It is thought that an extreme marine heatwave, lasting two years, was responsible for reducing phytoplankton, and leading to declines across all trophic levels (Piatt *et al.* 2020).

Shorebirds

Prey availability during the breeding season can also be related to phenology. The mismatch between invertebrate prey emergence and the timing of shorebird breeding is influenced by the timing of snowmelt for some Arctic-nesting shorebirds (Kwon *et al.* 2019). There is some evidence of increasing mismatch between shorebird breeding and invertebrate emergence, linked to declines in chick survival (Lameris *et al.* 2022). In the coldest locations, the increasing mismatch was compensated for by an increase in chick survival, linked to warmer temperatures (Lameris *et al.* 2022).

Change in habitat availability

Marine mammals

Sea ice declines open Arctic waters to migratory species earlier, leading to phenology shifts and range shifts into polar regions by species that are less ice adapted, such as Humpback, Fin, Minke, Killer and Grey (*Eschrichtius robustus*) Whales (Simmonds & Isaac 2007; Laidre *et al.* 2008; Moore & Huntington 2008; van Weelden *et al.* 2021). This earlier migration may lead to increased competition and predation for Arctic species (Laidre *et al.* 2008).

Narwhals (especially), but also Beluga and Bowhead Whales are predicted to be particularly vulnerable to climate change due to increased competition from sub-Arctic species expanding their range northwards and decreasing habitat availability (Learmonth *et al.* 2006; Simmonds & Isaac 2007; Laidre *et al.* 2008; Moore 2008; Chambault *et al.* 2020; van Weelden *et al.* 2021). However, population declines in Arctic whales have not been documented to date (Huntington *et al.* 2017). Arctic Bowhead Whale populations were increasing from 1978-2001 (which could simply reflect recovery from past over-harvesting) and had better body condition in low sea ice years (George *et al.* 2015; Laidre *et al.* 2008).

There was some evidence that changes in Beluga Whale habitat selection can mitigate some effects of sea ice loss (Hauser *et al.* 2018).

Shorebirds

Suitable habitat for breeding may decline for some Arctic-breeding wading birds. Warmer temperatures in Arctic Canada have meant an increase in the amount of woody vegetation (as a result of faster temperature-mediated growth), reducing the area of suitable breeding habitat for Whimbrel (Ballantyne & Nol 2015). However, in Iceland, warmer temperatures are increasing the area of suitable habitat for several species, such as the Black-tailed Godwit (*Limosa limosa*) (Gunnarsson *et al.* 2006). Using six climate change scenarios set out in the IPCC (2013), climatically suitable habitats of 24 Arctic shorebirds were projected to shift and decline by 2070, with 66-83% of species losing the majority of current habitat (Wauchope *et al.* 2017).

Direct impacts of weather events

Shorebirds

Advancing snowmelt and increasing summer temperatures are linked to increased egg production and hatching success in some Arctic-breeding birds such as the Svalbard Barnacle Goose (Layton-Matthews *et al.* 2020), Red-necked Phalaropes (*Phalaropus lobatus*) and Western Sandpiper (*Calidris mauri*) (Weiser *et al.* 2018) and other shorebirds (Meltofte *et al.* 2021).

Extreme weather events are predicted to increase in the Arctic (Robinson 2020). Arctic-breeding seabirds are vulnerable to extreme weather events such as storms, and high egg and chick loss has been observed following storms (Mallory *et al.* 2009). Complete breeding failures were seen in Ivory Gull (*Pagophila eburnea*) colonies following severe storms in Greenland (Yannic *et al.* 2014).

Increasing predation for some species

Advancing snowmelt and increasing summer temperatures are linked to an increase in the abundance of Arctic Foxes (*Vulpes lagopus*), which is likely to decrease fledgling success in ground-nesting birds such as Svalbard Barnacle Geese (Layton-Matthews *et al.* 2020). Ground-nesting birds are also likely to experience more predation from Polar Bears in the short- and medium-term, due the sea-ice declines forcing Polar Bears to shift away from their preferred seal prey (Prop *et al.* 2015),

Sea ice declines may reduce shelter from predation for some marine mammals. Minke Whale declines have been partly linked to sea-ice declines due to lack of shelter from predators (Risch *et al.* 2019).

Increasing human activity

Increases in human activity, particularly shipping, in the Arctic enabled by sea ice loss may increase levels of toxic chemicals, pollution, boat strikes, increase noise pollution (which has been shown to alter migration in Bowhead Whales and other cetaceans), and increase fisheries interactions (entanglement in fishing gear is common). Further exploitation of oil, mineral and other resources is likely to increase as Arctic waters become reliably ice-free (Erokhin & Rovenskaya 2020). Concentrations of persistent organic pollutants (POPs) in samples taken from Polar Bears are increasing due to prolonged fasting periods (due to sea ice decline) and may be causing adverse health effects (Jenssen *et al.* 2015). Conversely, traditional hunting of marine mammals is likely to be reduced because of dangerous sea ice conditions.

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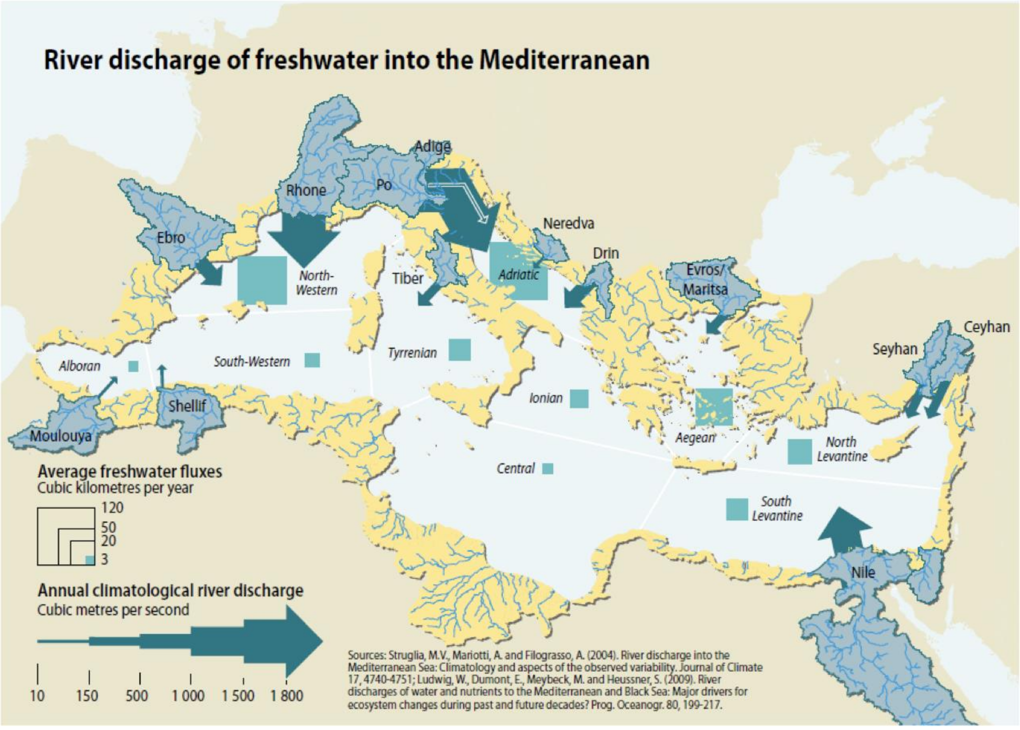
Wetlands around the Mediterranean Sea

The Mediterranean Sea has extensive networks of wetlands – 18.5 million ha (+/- 3.5 million ha) which comprise 1.1-1.5% of the world’s wetlands (including 428 Ramsar sites, as of Oct 2020). In the past century around 50% of the original wetlands have disappeared and many that remain have been degraded. This reduced area now also contains around 23% of artificial wetlands – rice fields, reservoirs, saltpans and oases (Geijzendorffer 2018, Beltrame *et al.* 2012). The principal rivers leading into the Mediterranean Sea are Ebro, Rhone, Po and the Nile with numerous medium and small river catchments between them, particularly to the northern sides (see Fig. 1). River discharges are reducing overall (except the Rhone and Po) as a result of an increased levels of dam construction and water abstraction. The largest wetland areas can be found in Egypt, France, Turkey and Algeria making up to two thirds of the area’s wetlands.



Sources: Struglia, M.V., Mariotti, A. and Filograsso, A. (2004). River discharge into the Mediterranean Sea: Climatology and aspects of the observed variability. Journal of Climate 17, 4740-4751; Ludwig, W., Dumont, E., Meybeck, M. and Heussner, S. (2009). River discharges of water and nutrients to the Mediterranean and Black Sea: Major drivers for ecosystem changes during past and future decades? Prog. Oceanogr. 80, 199-217.

Figure 1. River discharge into the Mediterranean (UNEP/MAP, 2012) highlighting the main wetland areas (https://www.medqsr.org/mediterranean-marine-and-coastal-environment)

Migratory species of Mediterranean wetlands

Birds: Tufted Duck(*) (*Aythya fuligula*), Goldeneye (*Bucephala clangula*), **White-headed duck** (*Oxyura leucocephala*), **Greater Flamingo** (*Phoenicopterus roseus*), **Common Coot** (*Fulica atra*), Black-tailed Godwit (*Limosa limosa*), Dunlin (*Calidris alpina*), Common Snipe (*Gallinago gallinago*), Red-Necked Phalarope (*Phalaropus lobatus*), **Andouin’s Gull** (*Larus audouinii*), **Little Tern** (*Sternula albifrons*), **Common Tern** (*Sterna hirundo*), Arctic Tern (*Sterna paradisaea*), **Sandwich Tern** (*Thalasseus sandvicensis*), **Eurasian Bittern** (*Botaurus stellaris*), **Purple Heron** (*Adrea purpurea*), **Great White Egret** (*Ardea alba*), **Eurasian Spoonbill** (*Platalea leucorodia*), **Western Marsh-Harrier** (*Circus aeruginosus*), **Hen Harrier** (*Circus cyaneus*), Aquatic Warbler (*Acrocephalus paludicola*)

Mammal: **Mediterranean Monk Seal** (*Monachus monachus*), [Dolphin, Porpoise and Whale species interact with wetlands on the peripheries]

Reptiles: **Green Turtle** (*Chelonia mydas*), Leatherback Turtle (*Dermochelys coriacea*), **Loggerhead Turtle** (*Caretta caretta*), Ridley Turtle (*Lepidochelys olivacea*)

Eels: European Eel (*Anguillla anguilla*)

(*) species listed in bold breed in the area, the others are non-breeding visitors

Predicted Climate Change

Some climate change effects have already been seen to impact the Mediterranean Sea and its wetlands – in particular sea level has risen by 22cm over the course of the 20th century (Beltrame *et al.* 2012). In general, the expected risks for the Mediterranean Sea's wetlands are: greater warming than average, an overall decline in rainfall, greater variability in rainfall and temperature, heat waves during summer months and increased frequency of extreme events (e.g. droughts and floods) (IPCC 2021). Land areas within the region have warmed by almost 2˚C in Iberia, southern France and North Africa and rainfall has significantly decreased with a 20% decline in southern European countries around the Mediterranean (Plan Bleu 2008).

Impacts of climate change

Rainfall: Flamingo colonies breed within wetlands but depend on a minimum level of rainfall and given lower precipitation levels with increase climate change this reduces the probability of successful breeding of Greater Flamingos in the Mediterranean, particularly the south (Béchet *et al.* 2012).

Temperature: Cold dwelling species are most likely to be disadvantaged from increasing water levels and given the general assemblages of waterbirds have been seen to be moving more northerly directions, more birds may shift their wintering range to the Mediterranean Basin from sub-Saharan Africa (Beltrame *et al.* 2012).

Nesting grounds for two turtle species (Green and Loggergead) are predicted to be increasing in average temperature, giving rise to potential changes in sex ratios (greater numbers of females, Dissanayake *et al.* 2021). Warming of coastal waters reduces recruitment numbers of the European Eel and also increased earlier colonisation through increased migratory responses (Borges *et al.* 2019). The same paper shows a reduction in survival with only a 4C rise in temperature.

Weather: El Niño events are predicted to become more frequent and intense and increase global temperatures (McPhaden *et al.* 2020). The impacts of El Niño events on Atlantic fish stocks will have a knock-on effect on fish stocks in the Mediterranean, threatening Mediterranean Monk seals (CMS 2005).

Droughts: For species like the Aquatic Warblers that use wetland areas in the Mediterranean for staging on their migrations, droughts will reduce the amount of habitat available and reduce the numbers able to support the populations passing through (Birdlife International 2008).

Flooding and Sea level rise: Coastal erosion and flooding from sea level rise may affect Monk Seals locations for breeding through reduction in suitable areas (CMS 2005) during this part of their, and other species like turtles, life cycles (Dissanayake *et al.* 2021). In periods of excess rainfall and sea level rise, Greater Flamingo's preferred salina sites are predicted to improve in quality for breeding (Béchet & Johnson 2008).

Sea Acidification: Acidification of the ocean, through increasing carbon dioxide emissions slowly changing seawater chemistry, have been shown to hinder migratory responses of European Eels and reducing their ability to follow riverine cues for migration (Borges *et al.* 2019).

Other threats to migratory species

Overharvesting of resources: Overfishing of fish stocks in the Mediterranean is impacting on aquatic species through reduction in resource levels (Bearzi *et al.* 2006, Hynes-Young *et al.* 2010) but also habitat loss can occur through the exploitation of plants, such as those used in medicinal-aromatics (Grigoriadou *et al.* 2020) and reed harvesting in the Camargue (Schmidt et la. 2005) though this has been noted to have some benefits for Eurasian Bitterns through their preferences for first-year reeds (Poulin *et al.* 2009) .

Invasive Species: Non-native plant species are colonising areas of the Mediterranean wetlands and changing the composition of the habitats and in the case of the invasive plant *Myriophyllum aquaticum* providing suitable habitats for young of invasive crayfish species like *Procambarus clarkia* (Lastrucci *et al.* 2017). 24% of the most invasive plant species are those found in wetlands and puts the areas at greater risk of influxes of species affecting the habitats (Zedler & Kercher 2010).

Other causes of habitat loss: Anthropogenic habitat expansion in the coastal zone is putting non-protected wetland sites at threat of loss from development and thus any migratory species that make use of these areas and at risk of loss through sea level rise (Schuerch *et al.* 2023). Furthermore, this compounds sea-level rise to reduce beach and nesting habitat for turtles, among others.

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Extreme Weather Events

While mean conditions are changing, so, importantly, is the variability of climate systems. The frequency and severity of extreme weather events such as storms, cyclones, floods, droughts, wildfires and heatwaves are already occurring, and very likely to increase due to climate change (IPCC 2023). The impact of these events on biodiversity are often severe, but research into their impacts can be limited due to the difficulty in monitoring and predicting where and when extreme events will occur (Ummenhofer & Meehl 2017; Maxwell *et al.* 2019). Here we highlight some examples of the impacts of extreme events on migratory animals that have been documented.

Storms & Cyclones

Storms and cyclones are predicted to increase in frequency and severity over the coming decades. An increase in the intensity of cyclones has already been observed, particularly in the North Atlantic since the 1980s (Figure 1, Murakami *et al.* 2020). The strong winds and heavy rainfall (and resulting floods) that come with storms have been observed to cause large population declines across all taxa and many habitats (Maxwell *et al.* 2019). Coastal ecosystems are particularly vulnerable to storms, which have been observed to cause declines in body condition, survival, breeding success and population size across many coastal and marine species (Maxwell *et al.* 2019).

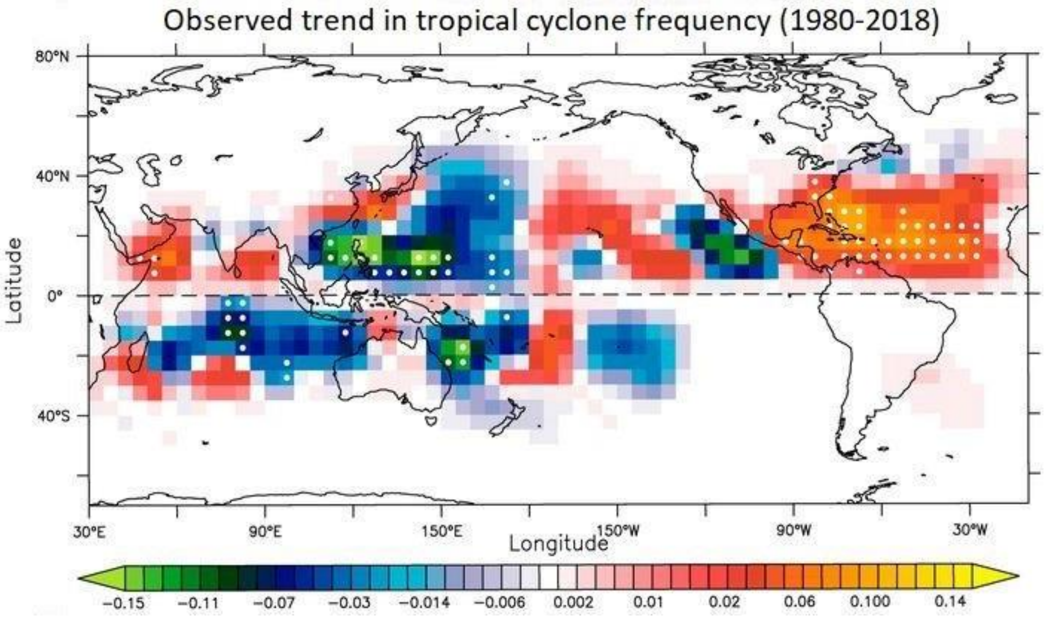

Figure 1 Observed linear trends in tropical cyclone frequency for the period 1980 to 2018 (number per year) (Murakami *et al.* 2020).

Seabirds

Storms have been linked to many mass-mortality events in seabirds (Camphuysen *et al.* 1999). Strong winds have been observed to blow birds away from feeding areas, or severely limit foraging efficiency, such as for Manx Shearwater (*Puffinus puffinus*) (Camphuysen *et al.* 1999; Darby *et al.* 2022). For other species, such as the Shag (*Gulosus aristotelis*) which have poor weather-proofing, large-scale mortality events are linked to strong winter winds (Frederiksen *et al.* 2008). Complete breeding failures were seen in Ivory Gull (*Pagophila eburnea*) colonies following severe storms in Greenland (Yannic *et al.* 2014). Coastal storms can also result in the loss of low-lying coastal nests in species such as of gulls and terns (e.g. Weston & Fraser 2020), or of low-lying exposed cliff nests in others (Newell *et al.* 2015). On an island off New Zealand a landslide caused by heavy rainfall in a storm destroyed over 5% of White-chinned Petrel (*Procellaria aequinoctialis*) burrows and killed over 2% of the population (Elliot & Walker 2022). Avian mass-mortality events have also been observed from severe hail storms (Higgins & Johnson 1978; Narwade *et al.* 2014). In a Black-billed Gull (*Chroicocephalus bulleri*) colony in New Zealand, 95% of individuals were killed in a hail storm (Weston & Fraser 2020). Other examples of increased mortality linked to storm activity include Atlantic Yellow-nosed Albatrosses (*Thalassarche chlororhynchos*) and Magellanic Penguins (*Spheniscus magellanicus*) (Tavares *et al.* 2020).

Marine mammals

Coastal storms, which can scour the seabed and cause freshwater floods, threaten and reduce seagrass productivity which has been linked to high mortality of inshore dolphins and Dugongs (*Dugong dugon*) (Meager & Limpus 2014), and reduced reproductive success and survival in the North Atlantic Right Whale (*Eubalaena glacialis*) (Lanyon & Burgess 2019).

Reptiles

An increasing frequency and intensity of storms will cover or inundate some current marine turtle and Salt-water Crocodile (*Crocodylus porosus*) nesting beaches, leading to loss of habitat and embryo mortality (Fukuda *et al.* 2002; Patrício *et al.* 2021)

Sharks & other Chondrichthyes

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

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

Fish (Actinopterygii)

For some species, the impacts of storms may be severe but short-lived. For example, a population of Pink Salmon (*Oncorhynchus gorbuscha*) declined by 90% after an extreme rainfall event, but had recovered to pre-disturbance levels within two generations (Milner *et al.* 2013; Maxwell *et al.* 2019). There are also examples of beneficial impacts of cyclones for marine species due to increased food availability downstream, such as increasing densities of Striated Surgeonfish (*Ctenochaetus striatus*) after cyclones (Maxwell *et al.* 2019). Invasive estuarine fish species in particular, have been observed to benefit from storm-related floods (Ilarri *et al.* 2022)

Droughts

Rainfall has declined in many regions globally, although predicted patterns in rainfall are more uncertain (Figure 2, Dai 2011). Where rainfall declines, combined with increasing temperatures, droughts will become more frequent and severe (Dai 2011). Droughts can have a large impact on terrestrial and freshwater ecosystems, causing large population declines across many taxa (Maxwell *et al.* 2019).

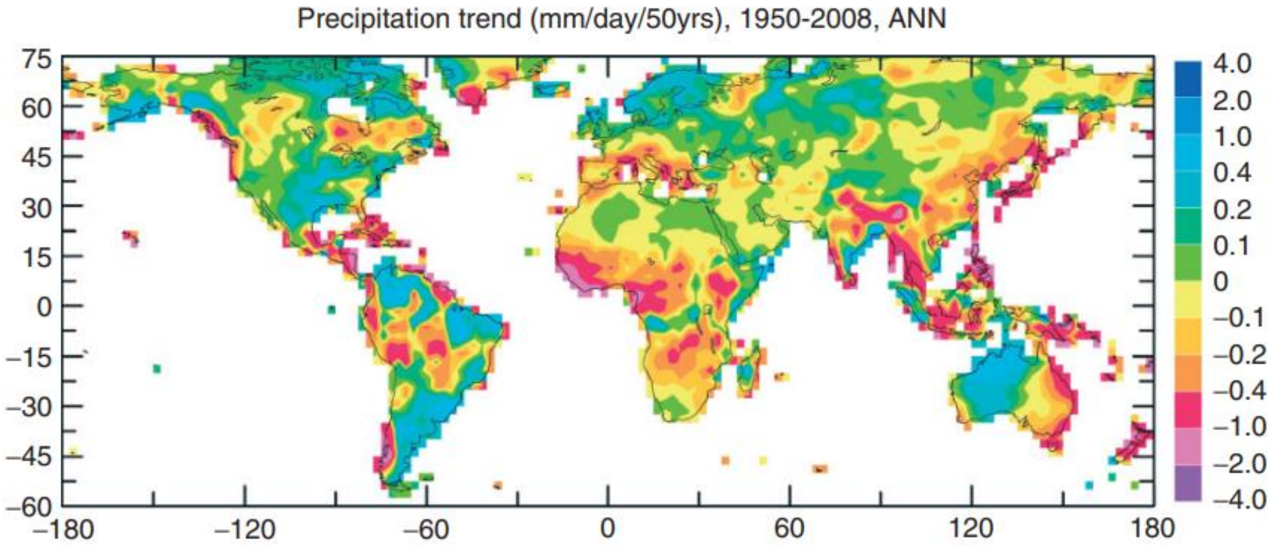

Figure 2 Global trends in rainfall from 1950-2008 (Dai 2011).

Terrestrial mammals

Rainfall declines around the Sahara and the Middle East are likely to lead to increased mortality and local carnivore extinctions such as the Leopard (*Panthera pardus*) (Khorozyan *et al.* 2015) and Lion (*Panthera leo*) (Cooper *et al.* 2021). However, there are examples of carnivore populations, including Jaguar (*Panthera onca*) and Lion populations, being fairly resilient to drought (Burrage *et al.* 2020; Ferreira *et al.* 2021).

Increased levels of drought have been implicated in a rise in the prevalence of mass mortality events. For example, over 300 African Elephants (*Loxodonta africana*) died in Botswana in 2020 as a result of biotoxins produced by cyanobacteria in drinking water, triggered by extremes of hot, dry weather (Wang *et al.* 2021). Droughts have also been linked to increases in parasite loads in African Elephants and Lions, as more individuals rely on limited water resources (Munson *et al.* 2008; Obanda *et al.* 2011; Titcomb *et al.* 2021). Droughts are also linked to increasing human-wildlife conflicts, for example for African and Asian Elephants (*Elephas maximus*), which can lead to increased mortality (Mariki *et al.* 2015; Mukeka *et al.* 2019).

Birds

Droughts have been linked to population declines in many bird species, but appear to be particularly detrimental to migratory species (Albright *et al.* 2010). Droughts in the Sahel region or Africa, where increasing droughts are predicted, may be a major threat to Afro-Palearctic migrants (Vickery *et al.* 2013). In particular, drought in stopover sites along migration routes has been linked to population declines in the Cuckoo (*Cuculus canorus*)

(Hewson *et al.* 2016). Droughts can also change the timing of bird migration: drought at stop-over sites delayed migration to European breeding grounds for Red-backed Shrikes (*Lanius collurio*) and Thrush Nightingales (*Luscinia luscinia*) (Tøttrup *et al.* 2012). The impact of droughts on migratory birds may be due to the association between rainfall and invertebrate abundance (Vickery *et al.* 2013; Anderson *et al.* 2021).

Wildfires

Wildfire frequency and intensity are increasing globally, due to increasing temperatures, high winds and changes in rainfall patterns. This trend is very likely to continue (IPCC 2023). Conversely, an increase in woody plants on African savannas, due to woody plants benefitting more than grasses from increasing atmospheric CO2 concentrations, is likely to reduce wildfire frequency there (Smit & Prins 2015). Wildfires are vital for maintaining some ecosystems but an increase in their frequency and intensity is likely to have a large impact on many terrestrial and freshwater ecosystems.

Birds

Wildfires have been linked to bird community changes as a result of the impact of fire on vegetation dynamics and the resulting habitat loss for some species (Regos *et al.* 2015, 2017). They have also been linked to mass migratory bird die-offs, possibly due to the resulting deterioration in air quality (Yang *et al.* 2021). An increase in the severity of wildfires is likely to be detrimental to old-growth trees, and the species that rely on them such as the Northern Spotted Owl (*Strix occidentalis caurina*) (Rockweit *et al.* 2017). Similarly, an increase in wildfires can favour grasses over woody plants, threatening species that rely on shrubs such as the Greater Sage-grouse (*Centrocercus urophasianus*) (Coates *et al.* 2016). While wildfires are detrimental for many species, management of wildfire regimes in protected areas could be used to slow some climate-change-induced habitat loss for some bird species (Regos *et al.* 2018).

Fish

Heavy rain can wash ash from wildfires into freshwater, altering light and oxygen availability and can lead to mass mortality events in aquatic animals (Gomez Isaza *et al.* 2022).

Conclusions

Extreme events, such as storms and droughts, can cause large population declines in species across all taxa and ecosystems. In some cases, changes in the frequency of extreme events may have a greater impact than changes in mean climatic variables (Frederiksen *et al.* 2008; Guralnick *et al.* 2023). More research is needed to better understand the long-term impacts of extreme events and the consequences of increases in frequency and severity.

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Bactrian Camel *Camelus bactrianus ferus*

Status: Critically endangered species, fewer than 1000 remaining in the wild (Xue *et al.* 2021).

Habitat: Extremely arid environments (Xue *et al.* 2015).

Distribution: Now only found in four isolated patches in China and Mongolia (Adney *et al.* 2019; Xue *et al.* 2021).

Migration: Generally long-distance, from high-altitude pastures in the summer to lowland area near rivers in the winter. This allows them to follow water and food resources and avoid harsh winter conditions (Xue *et al.* 2018).

Trends: Severe losses – their Mongolian distribution has shrunk by about 70% since the last century (Kaczensky *et al.* 2014).

Threats: Increasing human activities such as petroleum and mineral extraction, road and fence construction, poaching, and competition from, hybridization with, and disease transmission from domestic camels (Kaczensky *et al.* 2014; Xue *et al.* 2021).

Figure 1. Bactrian Camel distribution in central Asia

Climate change: Temperature will increase. Rainfall has increased over much of Bactrian Camel range over past decades and is predicted to continue to increase (Chen & Xu, 2005). Although rainfall is increasing, the increasing temperatures and human activities will reduce flow along much of the lowland river system that camels rely on in the winter (Xu *et al.* 2006). Droughts and severe winters are predicted to become more frequent.

Climate change Impacts: Bactrian Camels avoid the hotter parts of their range in the summer months to avoid heat stress and dehydration (Yadamsuren *et al.* 2019), so increasing temperatures may reduce their ranges. Reduced river flow, increasing droughts and severe winters may also increase Bactrian Camel mortality. However, there is very little research into the population-level impacts of climate change. There is some evidence that Bactrian Camel populations may be influenced by predator and competitors: they appear to time their visits to watering holes to reduce predation risk from wolves, and have been observed chasing competitors away from watering holes (Xue *et al.* 2018). As Bactrian

Camels are better adapted to harsh conditions than predators such as wolves and competitors such as Goitered Gazelle, climate change could be beneficial to Bactrian Camel, but more research is required.

Conservation: The impacts of climate change on Bactrian Camels is uncertain, but there is strong evidence that increasing human activities have severely reduced Bactrian Camel populations and could threaten their survival in the future. Conservation actions to protect their habitats is vital to their conservation. Conservation could be aided by reducing barriers to their migration, such as roads and the border fence between China and Mongolia (Kaczensky *et al.* 2014).

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Green Sturgeon *Acipenser medirostris*

Status: Endangered (Moser, 2022)

Trends: Largely unknown probably declining, especially in their southern range (Moser *et al.* 2022).

Migration & Distribution: They spend most of their life in coastal north Pacific waters (Beamesderfer *et al.* 2007). They typically migrate to freshwater rivers from Mexico to Alaska for spawning.

Threats: Key threats are loss of spawning habitat (particularly to dams), overfishing and bycatch, and entrapment in water diversions (Adams *et al.* 2007).

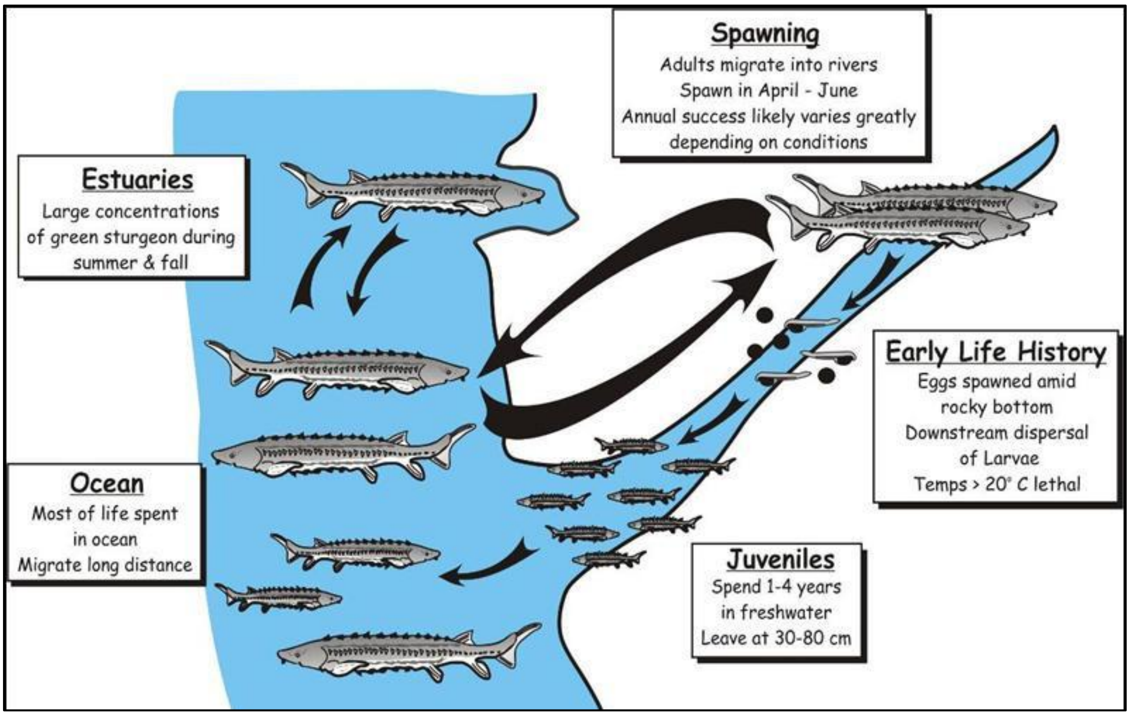

Figure 1. Life-cycle of the Green Sturgeon (from Beamesderfer *et al.* 2007)

Climate change: The impact of climate change on these migratory fish is complex and largely unknown. Warming generally has a negative impact on fish populations (Huang *et al.* 2021; Levangie *et al.* 2022).

Increasing temperature: Green Sturgeon hatching success declines in temperatures above 18°C, above which many embryos develop abnormally (van Eenennaam *et al.* 2006). This has led to reduced populations for many migratory fish (Goto *et al.* 2018), particularly at the warm edges of their ranges (Lassalle *et al.* 2010).

Prey availability for Green Sturgeon is predicted to decline as temperatures increase (Vaz *et al.* 2015; Zarri & Palkovacs, 2019). High temperatures also increase metabolism, which increases food requirements and lowers body condition particularly when food availability is low (Poletto *et al.* 2018).

Changes in river flow: It is uncertain how rainfall patterns along western North America will change (Mearns *et al.* 2013), but the frequency and severity of droughts and floods are likely to increase. Increasing temperatures will also contribute to a reduction of flow which is associated with declines in sturgeon reproductive success (Scarnecchia *et al.* 2019). Higher than usual flow rates can also be negative, scouring stream beds, damaging spawning grounds and can flush young fish out of rivers prematurely (Limburg *et al.* 2016). Green Sturgeon prey decreased at higher flow rates (Zarri & Palkovacs, 2019).

Changes in salinity: Climate change is likely to bring changes in the salinity of estuaries and rivers, namely declines in salinity in winter and increases in summer (Sardella & Kultz, 2014). Green Sturgeon can acclimate to salinity changes, but it does cause cellular stress, which could amplify the negative impacts of reduced food availability (Sardella & Kultz, 2014; Vaz *et al.* 2015).

Changes in ocean acidity and ocean currents: are known to have complex impacts marine fish (Limburg & Waldman, 2009), but their impact on Green Sturgeon is unknown (Hannan & Rummer, 2018).

Adaptations and conservation: Green Sturgeon return to their natal spawning grounds, which will reduce their ability to shift ranges polewards or to areas of more favourable flow (Huff *et al.* 2012). Successful conservation actions that have stabilised or increased populations in other sturgeon species include efforts to restore freshwater and tidal wetlands, increase floodplain connectivity, the removal of dams and translocations (Limburg *et al.* 2016).

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Loggerhead Turtle *Caretta caretta*

Status: Globally Vulnerable (Casale & Tucker, 2017). They are locally Endangered in the North Pacific Ocean, Mediterranean Sea, Northeast Atlantic Ocean, North Indian Ocean and South Pacific Ocean.

Threats: The key threats to Loggerhead turtles are bycatch in fishing gear, primarily in longlines and gillnets; and human development on their nesting beaches (Fuentes *et al.* 2013). The impact of climate change on a population-level is poorly understood but likely to be increasing, key research questions to better understand this are posed by Patrício *et al.* (2021).

Trends: Trend varies between population, but most have declined in the last few decades (by up to 90%), although nesting trends in some have been more stable recently (NOAA Fisheries 2021).

Migration & Distribution: Long-distance migration between nesting beaches and feeding grounds. For example, many Loggerhead Turtles hatched in the western Atlantic migrate to feeding grounds in the eastern Atlantic or the Mediterranean

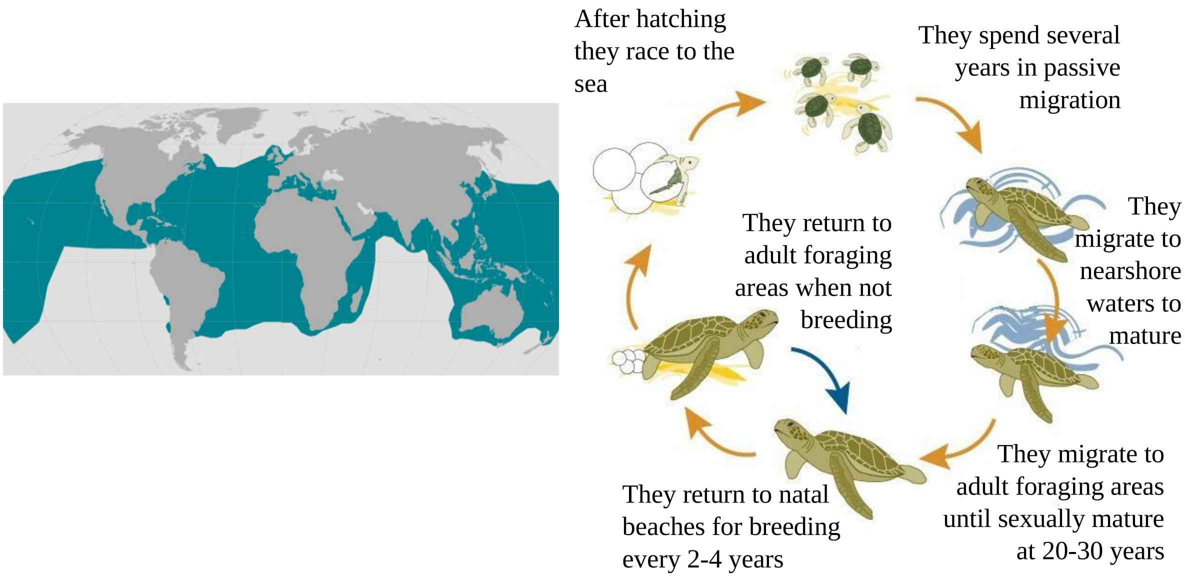

Figure 1. Distribution and life-cycle of the Loggerhead Turtle (from NOAA Fisheries 2021)

Sea level rise & increasing storms: will lead to the loss of many Loggerhead Turtle nesting beaches (Poloczanska *et al.* 2009; Patrício *et al.* 2021). It is predicted that around 60% of current Mediterranean nesting sites will disappear by 2100 (Dimitriadis *et al.* 2022), and over 80% of Atlantic USA sites (Fuentes *et al.* 2020).

Increasing temperatures: are increasing the female:male sex ratio as turtles have temperature-dependent sex determination (Patrício *et al.* 2021). This is currently positive for most populations (Perez *et al.* 2016). In the future, extremely limited male populations could lead to population declines through reduced fertilisation or limited genetic diversity (Hays *et al.* 2014).

Increasing temperatures: may reduce subsequent Loggerhead Turtle nesting activity and clutch size, possibly due to reduced food availability (Chaloupka *et al.* 2008; Mazaris *et al.*

2008). Conversely, other studies have found temperature rises lead to increased rate of egg production (Marn *et al.* 2017).

Range shifts have been observed and will be the key to Loggerhead Turtle adaptation to climate change, as they shift their distribution poleward in response to warmer temperatures (Perez *et al.* 2016; Girard *et al.* 2021). The major threat that will prevent range shifts will be is human coastal development and the availability of potentially suitable nesting beaches in potentially suitable new areas (Perez *et al.* 2016; Fuentes *et al.* 2020). Range shifts are not predicted to be adequate to prevent a reduction in Loggerhead Turtle ranges (Hazen *et al.* 2013; Fuentes *et al.* 2020).

Phenology shifts in nesting have been observed (Mazaris *et al.* 2008) and may help to prevent extreme sex ratios, if this means that the turtle eggs develop at lower temperatures because of being earlier in the season (Laloë *et al.* 2016).

Human interventions could include shading beaches e.g. by tree planting (Mitchell & Janzen 2010), preventing coastal development on emerging nest beaches (Girard *et al.* 2021), protection of beaches with adjoining sand-dunes that allow landward shifts in nesting (Katselidis *et al.* 2014) and translocation of eggs (Hawkes *et al.* 2007).

Reduction of other threats is also important, such as protecting their current nesting beaches and using fishing methods that reduce the likelihood of turtle bycatch (Poloczanska *et al.* 2009)

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Polar Bear *Ursus maritimus*

Status: Vulnerable (Wiig *et al.* 2015).

Distribution: Arctic and near-Arctic Greenland and Canada (Derocher 2010).

Migration: Polar Bears migrate seasonally to follow prey. They generally migrate in autumn to sea ice edges where they mainly hunt seals. In the spring, Polar Bears typically migrate to follow the remaining ice, then on to land for the summer months where they hunt for other prey such as birds or eggs.

Threats: The reduction in sea ice caused by climate change is considered to be the key threat to Polar Bears (Atwood *et al.* 2015). Another threat is high levels of persistent organic pollutants in Polar Bears, from industrial waste and pesticides, which can reduce reproductive success (Jenssen *et al.* 2015).

Trends: Most populations are declining and many sub-populations are likely to go extinct over the next few decades (Castro de la Guardia *et al.* 2013; Bromaghin *et al.* 2021). Models based on IPCC climate projections predict almost complete extinction by 2100 (Hunter *et al.* 2010; Molnár *et al.* 2020).

Figure 1. Distribution of the Polar Bear (from Derocher 2010)

Temperature increase: The Arctic is currently warming twice as fast as the global mean and sea ice extent is rapidly decreasing (Jansen *et al.* 2020; IPCC 2021). Polar Bears rely on sea ice to hunt for their main prey, seals. As sea ice contracts, hunting habitat for Polar Bears declines, which reduces population sizes (Stirling & Parkinson 2006; Bromaghin *et al.* 2021), survival (Molnár *et al.* 2010; 2020), body condition (Derocher *et al.* 2004; Stirling & Parkinson 2006) and reproductive success (Peacock *et al.* 2011). Their main prey, seals, rely on sea ice for breeding, so Polar Bear populations will also be impacted by likely declines in seal populations (Tynan & DeMaster 1997).

Declines in food availability will increase the tissue concentrations of dangerous pollutants if this leads to periods of prolonged fasting, which may have population-level impacts (Jenssen *et al.* 2015; Nuijten *et al.* 2016), while increasing time on land increases pathogen exposure (Pilfold *et al.* 2021).

Adaptations: Polar Bears may be able to adapt foraging behaviour to new prey species. Polar Bear diet is shifting to include more non-pinniped species such as ground-nesting birds (Prop *et al.* 2015), whales (Rode *et al.* 2022), fish and blueberries (Dyck & Kebreab 2009). However, these food sources are not likely to be sufficient to make up for the reduced availability of seal prey (Petherick *et al.* 2021; Rode *et al.* 2022).

Polar Bears are changing their migration patterns, often migrating further or spending more time on land (Pilfold *et al.* 2017), but both strategies reduce survival, particularly for cubs (Cherry *et al.* 2013; Miller *et al.* 2022).

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Red Knot *Calidris canutus*

Status: Near threatened (ICUN Red List, BirdLife International 2018)

Habitat: Breeds in middle and high Arctic tundra (close to water, usually near coast), principally winters on the coasts on tidal mudflats and sandflats. Migration stopover sites normally coastal and rarely inland (Van Gils and Wiersma 1996).

Biology: Small wader, breeding populations in the Arctic split into 6 subspecies with one of the longest migrations in the world (up to 15,000 km). Forages on intertidal invertebrates in the non-breeding season and importantly takes advantage of productive stopover sites such as those with Horseshoe Crabs *Limulus polyphemus* (for eggs, Van Gils & Wiersma 1996).

Distribution: Breeding range is very large from Alaska (USA) via Greenland (Denmark) across to northern Russia. Wintering range consists of Atlantic and Pacific coasts of North and South America, north-western Europe, west coast of Africa, southern Asia and around Australasia (Van Gills & Wiersma 1996).

Trends: Many subspecies have decreased strongly over both the short and long term, often due to anthropogenic loss of stopover sites and food resources (van Roomen 2014, Andres *et al.* 2012, WSFWS 2014). Only the *islandica* subpopulation has seen increases (Birdlife International 2015) but even that had a decreasing trend between 2003-2012 while their long-term trends are more variable and fluctuating.

Threats: Risks on breeding grounds from climate change affecting food resources and increasing chance of phenological mismatch. Increasing risk of contraction of their breeding habitats northwards. Habitat and food declines at stopover sites also big issue, especially in the East-Asian Australasian flyway due to anthropogenic habitat loss but also at the East Atlantic flyway's Delaware Bay stopover site from overfishing of Horseshoe Crabs.

Migration: Nearly always long distance, migration routes run from Arctic regions mostly along coastlines south towards lower temperate and tropical latitudes and for certain sub-species, the southern hemisphere. Each subspecies takes a different flyway including Pacific, West Atlantic, Icelandic, East Atlantic, East Asian-Australasian flyways (Conklin *et al.* 2022). Stopover sites are seen on almost all flyways.

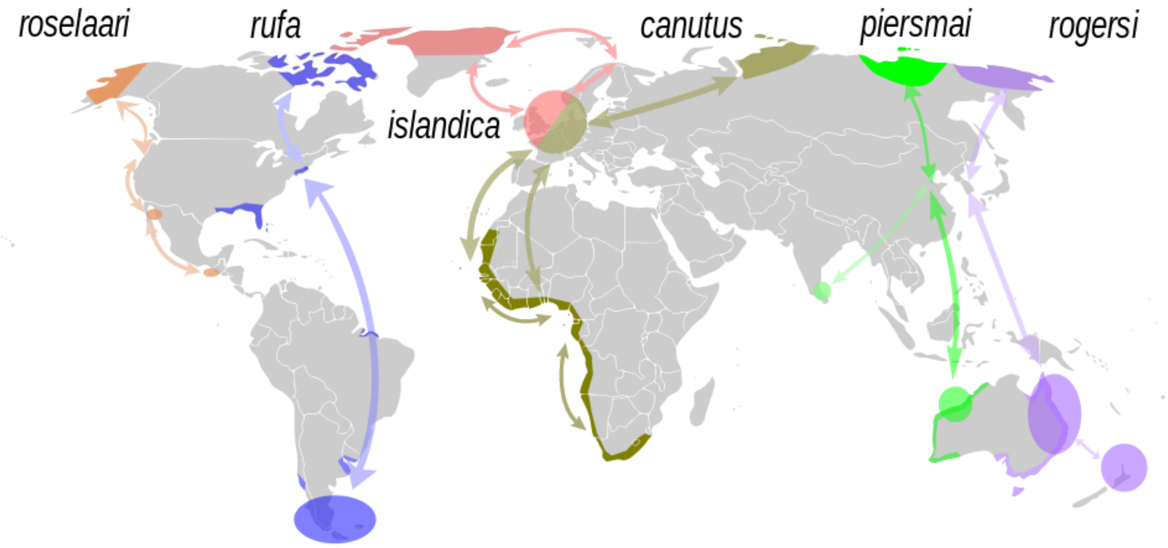

Figure 1. Migratory destinations of the six subspecies of Red Knot (source: https://www.theredknotsproject.org/the-flyways2)

Climate Change impacts: Contraction of suitable breeding habitat for Arctic waders has been observed though northward shift in the occurrence of tundra, predators and competitors (Anderson *et al.* 2023, Piersma & Baker 2000).

Rainfall: (increase, extreme) Wader species decline in abundance at wintering sites under the impacts of increasing cumulative rainfall (Kelly 2001).

Temperature: (increase, change to mean) Chick growth rate is related to timing of peak arthropod abundance and whilst no mismatch is evident yet between hatching dates and invertebrate peaks, their vulnerability to this has been proven for warming climates (Lameris *et al.* 2022) and the peak abundances of tundra arthropods preferred by waders are moving earlier (Tulp & Schekkerman 2007). Climate warming has also been identified as having an impact on body size in Red Knot, smaller offspring in warming breeding grounds affecting wintering ground foraging due to shorter bill sizes (van Gils *et al.* 2016).

Snow: (delay in snowmelt) Late snowmelt reduces the total available breeding period and thus decreases the opportunity for re-laying after failures – reduced breeding success as a consequence of late breeding season (Meltofte *et al.* 2008).

Wind/storms: (increasing frequency, severity of weather conditions) Severe weather can lock up foraging areas under ice and drive prey items (invertebrates) deeper into the sediments making it harder to forage and increasing mortality in many waders (Clark 2007).

Sea level rise: Coastlines at stopover and non-breeding sites are predicted to change and thus birds will find themselves pushed for foraging with less exposure time to access intertidal invertebrates, for Red Knot the loss of area at Delaware Bay is of particular worry (Galbraith *et al.* 2014).

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Siberian Crane *Leucogeranus leucogeranus*

Status: Critically Endangered (Birdlife International 2018)

Habitat: The species is found in wetlands throughout the year, preferring wide areas of shallow fresh water that are infrequently visited by people. Breeding sites consist of marshland, tidal marshes and other wetland depressions. Non-breeding habitat includes stopover areas of large, isolated wetlands and wintering areas of seasonal lakes of the Yangtze Basin plus steppes near water and swamps. In India and Iran they use artificial water areas and flooded fields (Archibald *et al.* 2020).

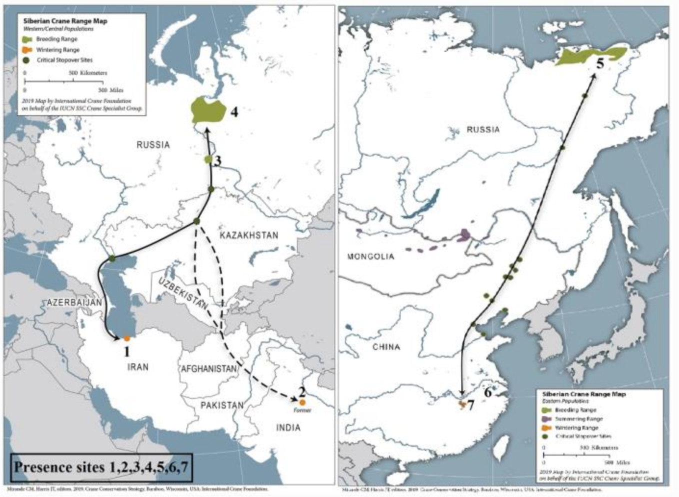
Biology: A large, long-lived migratory crane that has an omnivorous diet throughout the year. It breeds in Arctic Russia in territorial pairs at low densities (1 per 625km^2) before travelling southwards on migration to non-breeding sites (Birdlife International 2018).

Distribution: Breeds in Arctic Russia (Yakutia and West Siberia) with two regional populations (west and east). In the non-breeding season birds are found at or near Poyang Lake, China where almost the entire population stays plus occasionally Keoladeo, India and Caspian Sea, Iran (Birdlife International 2018, Archibald *et al.* 2020).

Trends: Severe declines seen within a short period of time, over just three generations (Birdlife International 2018).

Threats: Key threats of wetland loss at non-breeding and stopover sites through diversion of water for anthropogenic reasons (human use, agriculture, oilfield development) and disturbance. Of particular importance is the effects of the Three Gorges Dam, China, which lowered water levels in the Yangtze River causing Poyang Lake to drain more rapidly and increased droughts. New proposed dams will flood non-breeding foraging areas (Birdlife International 2018, Archibald *et al.* 2020). Hunting, pesticide use and pollution are also causing issues for the species (Archibald *et al.* 2020).

Migration: Migratory routes follow a network of wetlands south to the east and west sides of the species range. The species generally starts migration at the end of September arriving on non-breeding grounds in October (west) and November (east). Spring migration starts in late March to early April (Archibald *et al.* 2020).



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Distribution Map of the Siberian Crane *Grus leucogeranus* and breeding range and wintering range as presence sites of West and East Asia used in this study (2019 Map by International Crane Foundation on behalf of the IUCN SSC Crane Specialist Group)

Figure 1. Migratory routes of the Siberian Crane (Ansari 2022)

Climate Change Impacts: Loss of breeding habitat through loss of permafrost which causes expansion of lakes and reduction in shoreline and island breeding areas and degradation of food resources (Ansari 2022, Hou *et al.* 2020, van Impe 2013).

Rainfall: (drought, increase, decrease, flooding, extreme) Lack of rainfall through projected warming will reduce the areas of low-lying wetland for the species to nest in (Pshennikov 2010). Given the large areas each pair defend this restricts the breeding area significantly (Birdlife International 2018). Drought conditions at the non-breeding sites also restricts suitable habitat and will impact the areas suitable for birds (Pshennikov 2010).

Temperature: (increase cold/hot, reduction in cold/hot, change to mean) A loss of permafrost due to increasing temperatures will reduce the areas of breeding habitat (Ansari 2022) and encourage growth of vegetation that will restrict sight-lines that the Siberian Crane's look for in breeding sites as an anti-predator/disturbance mechanism (Birdlife International 2018). Some areas of previously unsuitable habitat may become suitable in Northern and Eastern Russia and China, but the positive impacts of these are considered limited in the face of issues in other parts of the flyways (Ansari 2022).

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Wandering Albatross *Diomedea exulans* s.l.

Status: Vulnerable. Four subspecies: Tristan - Critically Endangered; Antipodean – Endanged; Amsterdam – Endangered; Snowy – Vulnerable (Birdlife International 2018, Carboneras 1992)

Habitat: In the breeding season the species nests in open and patch vegetation near ridges or hillocks. When non-breeding the species in in flight above marine waters (Carboneras 1992).

Biology: One of the largest seabirds, with the longest wingspan of any living bird, with a circumpolar distribution and range in the Antarctic Ocean. Forages on marine prey – mainly fish and cephalopods and lays a single egg once every two years and normally don't breed until they are 10-12 years old (Tickell 2000).

Distribution: Breeds on South Georgia, Prince Edward Island, Crozet Islands, Kerguelen Islands and Macquarie Island. Non-breeding birds are found north of the 50˚ South on subantarctic and subtropical waters (Birdlife International 2018).

Trends: The species is currently in decline with a -1.8% decline per year for the past 20 years, over 4% per year since 1997 (Poncet *et al.* 2006). Specific colonies have declines up to 30% over the long term (Poncet *et al.* 2006).

Threats: Anthropogenic threats from fisheries, such as longline tuna fisheries are a big risk to the species, particularly to juvenile birds and females who tend to range further north than adults, particular adult males (Weimerskirch *et al.* 1997). Introduced species into locations with breeding colonies are also causing breeding failures through predation e.g. by cats and House mice (Barbraud *et al.* 2021, Dilley *et al.* 2016).

Migration: Post breeding, most birds take a general circumpolar movement over the Antarctic Ocean. Most birds have been recorded between 30˚S and 50˚S with some going further up into oceans to the north but all staying south of the equator (Birdlife International 2018, Carboneras 1992).

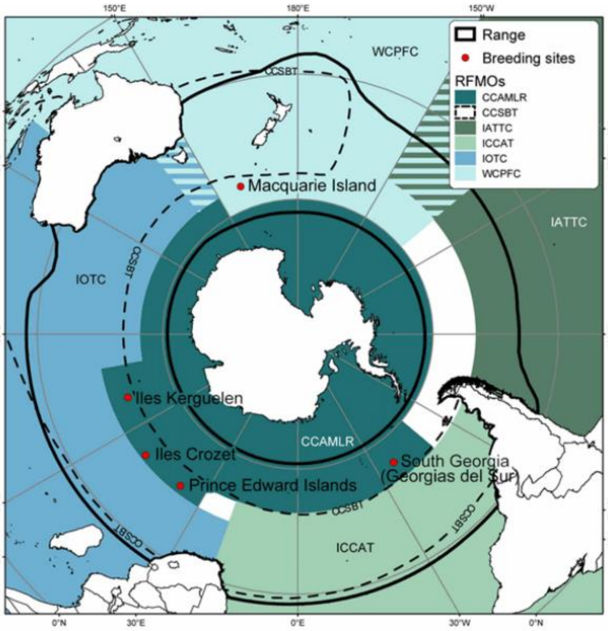

Figure 1. Distribution range of the Wandering Albatross (Ansari 2022)

Climate Change impacts: There is a southward shift in distribution of several species including the Wandering Albatross linked to changing climate and changes in food abundance but is difficult to fully assess (Péron *et al.* 2010). These shifts are projected to mean greater overlap with fisheries activities increasing the risk of indirect mortality if fisheries are not well managed (Krüger *et al.* 2018). Wandering Albatross are predicted to have the highest range reductions making this type of impact more significant.

Temperature: (increase, change to mean) Higher sea surface temperatures negatively affect early-life survival of Wandering Albatrosses, but positively relate to recruitment rates (Fay *et al.* 2015). However, population dynamics of long-lived species tend to be more sensitive to survival rates, so the former effect may be stronger.

Wind/storms: (increasing frequency, severity of weather conditions) Stronger winds in the non-breeding season are affecting population recovery potential in several albatross species, including Wandering, in a combined environmental and anthropogenic effect. In the breeding season, the probability of breeding was reduced by stronger wind conditions (Pardo *et al.* 2017). In co-occurring albatross species (*T. chrysostoma*) El Niño events caused lower food availability (krill abundance declined) in the breeding season, resulting in reduced productivity, and these events are increasing with climate change (Pardo *et al.* 2017).

Sea level rise: Relying on low lying islands for breeding puts the majority of breeding locations of the Tristan albatross subspecies at risk for habitat loss due to predicted sea level rise (Carboneras 1992).

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Whale Shark *Rhincodon typus*

Status: Endangered (Pierce & Norman, 2016).

Biology: The Whale Shark the largest fish species and filter feeds mainly on macro-zooplankton such as shrimps, krill, fish larva and copepods (Rohner *et al.* 2013).

Distribution: Largely in tropical and warm temperate water between 30° N and 30° S and generally in waters between 23 and 35° C (Sequeira *et al.* 2013). Roughly 75% of Whale Sharks occur in the Indo-Pacific and 25% in the Atlantic (Pierce & Norman, 2016).

Trends: Whale Shark populations have roughly halved in the past 50 years (Pierce & Norman, 2016).

Threats: Whale Sharks are probably most threatened by shipping, fishing and fisheries bycatch (Pierce & Norman, 2016, Reynolds *et al.* 2022). Whale Shark abundance is strongly linked to food availability (Grose *et al.* 2020) but there is little research on changes in food availability.

Migration: There is still little known about Whale Shark migration, but movement is often long-distance and probably driven by food availability (Fig. 1; Sequeira *et al.* 2013; Davies, 2014; Grose *et al.* 2020). Probably Whale shark aggregations coincide with seasonal multi-species fish spawning events (Heyman *et al.* 2001).

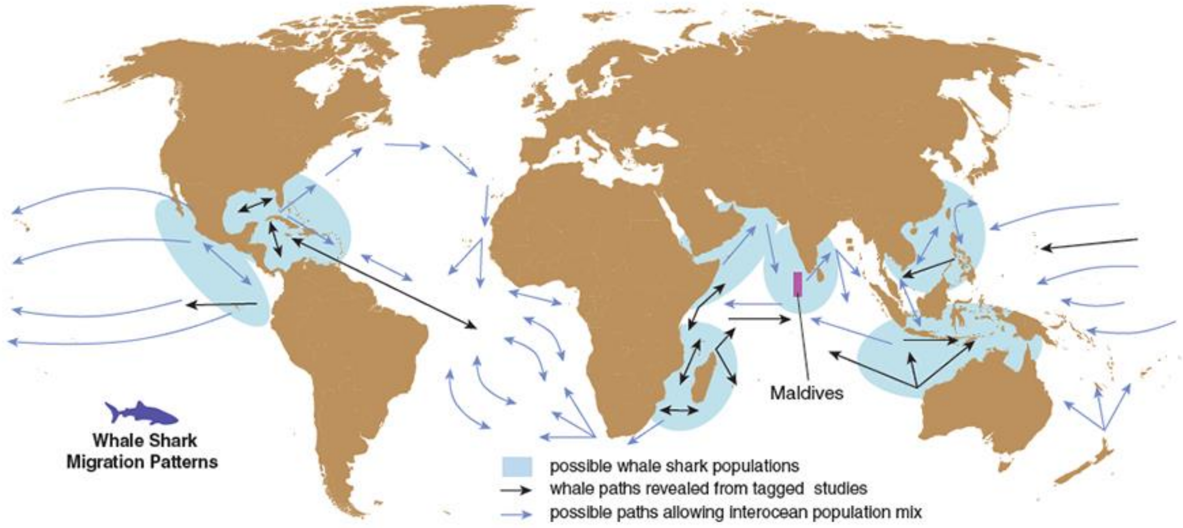

Figure 1. Migration routes of Whale Shark (Davies 2014)

Increasing temperatures are linked to pole-wards range shifts as Whale Sharks are generally adapted a limited temperature range (Sequeira *et al.* 2013). Pole-wards range shifts are likely to increase over coming decades.

Ocean acidification can reduce growth of zooplankton, which is predicted to lead to population declines for Whale Sharks (Reynolds *et al.* 2022).

Warm water holds less oxygen. Deoxygenation is likely to reduce the distribution and abundance of large sharks such as Whale Sharks in warmer waters (Schlaff *et al.* 2014) although more research is required to understand the population-level impact of this.

Increasing storms may damage inshore habitats that juvenile Whale Shark rely on, especially as nursery area (Field *et al.* 2009; Brame *et al.* 2019).

Impacts from **increasing oceanic weather events such as El Niño and La Niña** are likely to be region-specific. Whale Sharks in the southwest Pacific increased during La Niña conditions (Sleeman *et al.* 2010; Adams *et al.* 2016; Osgood *et al.* 2021).

Sea level rise may be beneficial for Whale Sharks, enabling them to increase their range (Vignaud *et al.* 2014).

Climate change impacts on food availability: The greatest impact of climate change is likely to be as a result of the impact of climate change on food availability. There is limited research on the impact of climate change on global Whale Shark food availability, but declines are most likely (Sequeira *et al.* 2013; Grose *et al.* 2020).

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Willow Warbler *Phylloscopus trochilus*

Status: Least Concern (Birdlife International 2018)

Habitat: Wide range of mixed scrub and tundra habitats for breeding season across boreal and temperature forest regions. In the non-breeding grounds in Africa, south of the Sahara, a range of wooded open country and wetland habitats, as well as arable land and rural gardens (Birdlife International 2018, Clement 2015).

Biology: Abundant small highly migratory warbler that eats insects and spiders plus some fruit and berries. Forages alone and in small groups, mainly in the tree canopy but also at lower levels. Nests close to the ground usually in low vegetation (Clement 2015).

Distribution: Breeding range stretches from western edges of northern Europe (Ireland) eastwards to the far-eastern ranges of Russia, north into the boreal region and as far south as central Europe and northern Kazakhstan. The southern half of Africa, south of the Sahara hosts the non-breeding population – from Senegal eastwards to Kenya and down to the bottom of South Africa (Birdlife International 2018).

Trends: Appears to be expanding northwards in NW Siberia, but 38% decline across Europe in the last 40 years (Birdlife International 2018).

Threats: Drought conditions on non-breeding grounds and anthropogenic changes to habitat affect the species (Thingstad *et al.* 2015). Habitat loss from forestry management is thought to have caused declines in some areas (Stostad & Menéndez 2014), as has declining habitat quality, through impacts on invertebrate populations (Peach *et al.* 1995).

Migration: Long, mainly nocturnal migration (up to 12,000 km) covering 100+ km daily (Clement 2015). All populations spend the non-breeding season south of the Sahara with only small numbers in East and North of Sahara. Several migration routes either through SW Europe or Central or South East Europe flyways.

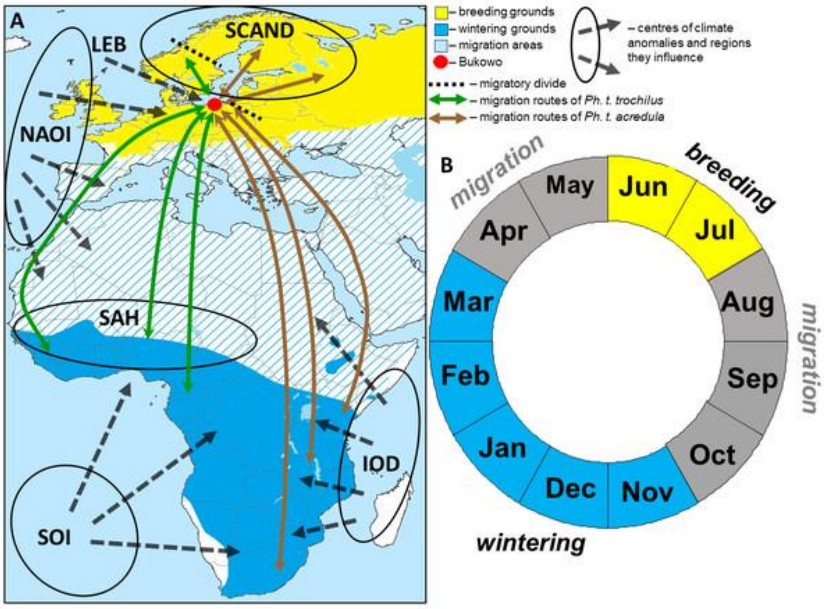

Figure 1. Breeding and non-breeding distribution of Willow Warbler, with location hypothesized climatic influences (from Remisiewicz & Underhill 2020)

Climate Change impacts: Willow Warbler arrival dates on the breeding grounds advanced by greater than 5 days over a 36 year period in a relationship with changes to climate indices (Remisiewicz & Underhill 2020). Climate change at non-breeding grounds and stopover sites have been found to be drivers of change in arrival times for migrants including Willow Warblers to Europe, this can be positive in terms of enabling earlier breeding (Remisiewicz & Underhill 2022).

Rainfall: (drought, increase, decrease, flooding, extreme) Drought conditions in the Sahel affected Willow Warbler populations on their northward migrations and they have had a slow recovery (Thingstad *et al.* 2015). In springs of dry years, Sahel index, Willow Warbler suffered twice the normal mortality than in wet years (Zwarts *et al.* 2009).

Similarly, on the breeding grounds, Willow Warbler populations are declining most in the drier, southern parts of their range, possibly as a result of reduced insect abundances, (Morrison *et al.* 2016). These may be exacerbated by land management practices that reduce the amount of surface standing water through drainage or urbanisation.

Heavy summer rainfall can wash away invertebrates from vegetation and cause limitation on feeding opportunities for species such as Willow Warblers which do better in drier summers; in wetter breeding seasons there are higher incidences of nestling mortality (Leech *et al.* 2004).

Temperature: (increase cold/hot, reduction in cold/hot, change to mean) High local spring temperatures (Sokolov *et al.* 1998) and higher local mean annual temperatures (Hüppop & Hüppop 2003) have been found to be associated with earlier arrivals of Willow Warblers in northern Europe. Nesting Willow Warblers have lower fledging success during hot and dry regional weather conditions in the chick brooding period (Morrison 2011).

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Case Studies relating to Migratory Species and Their Role in Ecosystems

Cetaceans aid ocean nutrient transfer and Carbon capture

Ecosystem service(s) provided by the focal species: carbon capture, nutrient transfer, food, tourism.

The deep sea

The deep sea (broadly where the influence of light as an energy source diminishes) incorporates a vast area of the ocean (from the pelagic zone to vents and seeps covering) and supports a wide range of habitats and associated species, all of which contribute to a variety of ecosystem services. These include Regulation and Maintenance through, carbon capture from carcass fall and decay, and methane oxidation by microbes, as well as nutrient cycling and regeneration, which aids surface productivity and subsequent Provisioning via fishing. Deep sea fishing is the most recent Provisioning service from this habitat, which is becoming more important as a source of human food (Roberts *et al*. 2002). There is also the Cultural aspect of the mystery and intrigue that the deep sea, and the species' it supports, elicits (Thurber *et al*. 2014).

Whales

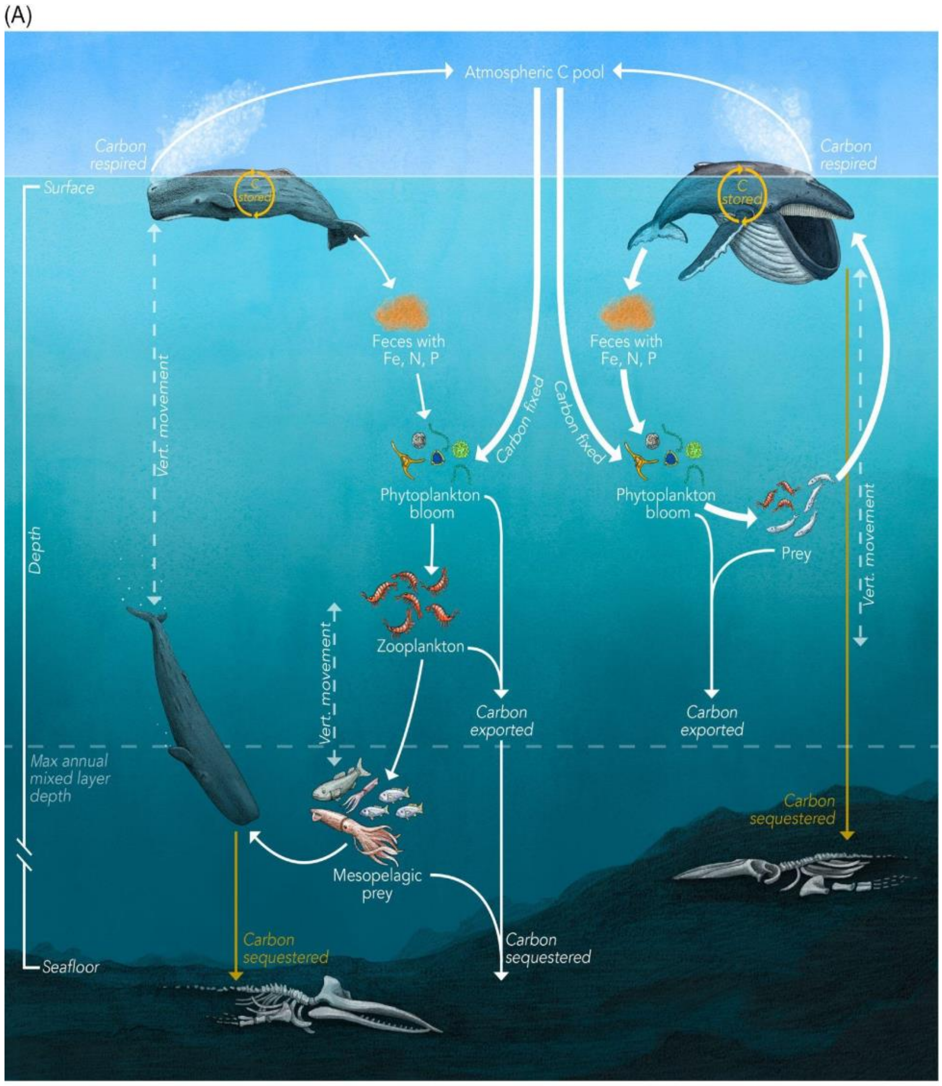
Whales are among the larger and longest-lived inhabitants of the deep sea and are found globally across the oceans. They face a wide range of threats, including fishing, pollution and disturbance from human activities (which includes climate change mitigation through large-scale marine renewable developments) (Lascelles *et al*. 2014). Two of the longest living animals globally are baleen whales (Blue *Balaenoptera musculus* and Fin *B. physalus* whales; both listed on CMS Appendix I); adult individuals weigh in excess of 200 or 45 tonnes respectively and both are thought to have a lifespan of 80-90 years. Blue Whales are listed on CMS Appendix I and are Endangered on the IUCN RedList, while Fin Whales are listed on CMS Appendix I and II and are Vulnerable. Three other species are dominant across the Southern Ocean - Humpback Whale (~40 tonnes and live ~40-45 years; *Megaptera novaeangliae*; CMS Appendix I; Least Concern), Southern Right Whale (~60 tonnes and live ~80 years; *Eubalaena australis*; CMS Appendix I; Least Concern) and Antarctic minke whale (~5 tonnes and live ~50 years; *Balaenoptera bonaerensis*; CMS Appendix II; Near Threatened).

Climate change nature-based solution(s)

The continued restoration of great whale populations to near-historic levels has the potential to make a significant contribution to carbon sequestration. As whales are long-lived, they store a lot of Carbon in their bodies. When they die, their carcass falls to the ocean floor where it decomposes and the Carbon is locked into the substrate. This has the potential to contribute an estimated 0.062 megatonnes of carbon per year (Pearson *et al*. 2023; Schmitz *et al*. 2023). Whales also move nutrients vertically from their foraging zone in the water column to the surface when they breathe and release nutrients via excrement which then descends through the water column (termed "whale pump"; estimated to contribute 0.4-22.0 megatonnes of carbon per year (Pearson *et al*. 2023). This provides nutrients for a large number of other species in the water column and ocean floor, including deep-sea biodiversity (Butman, Carlton & Palumbi 1995). They also transfer nutrients across the oceans from their nutrient rich breeding grounds to nutrient poor non-breeding grounds via migration (Pearson *et al*. 2023).

Conservation benefits

Pearson *et al*. (2023) outline various knowledge gaps that need filling to fully understand the potential direct and in-direct benefits whales give to alleviate climate change. However, the current research shows whales are a positive nature-based solution to climate change. Therefore, the conservation of these cetacean species would not only aid in climate change mitigation but the conservation of these species would benefit the rest of the ecosystem that rely on whales for nutrients as well as being an additional benefit to humans for provisioning and opportunities for tourism (Butman, Carlton & Palumbi 1995; Malinauskaite *et al*. 2022a, 2022b; Pearson *et al*. 2023; Schmitz *et al*. 2023).



Trends in Ecology & Evolution

Figure 1. The importance of whales for carbon capture. From Pearson *et al*. 2023

Dugong grazing aids seagrass bed genetic diversity

Ecosystem service(s) provided by the focal species (indirectly): carbon capture, resilience against storms and cyclones.

Seagrass beds

Seagrasses (from four families in the order Alismatales) are flowering plants found globally along clear coastlines and estuaries across the world's oceans (Al-Asif *et al*. 2022). They can propagate sexually and vegetatively (Short *et al*. 2007). Seagrass beds are mainly threatened by anthropogenic impacts, for example, eutrophication from run-off, an imbalance in ocean salinity (flooding or drought), turbidity in the water, various climate change induced impacts (e.g. sea-level rise, plastics, ocean acidification), although the natural threat of overgrazing is also an important factor (Al-Asif *et al*. 2022). Seagrass beds are the primary producers which support a large number of animals, including CMS Appendix species: Dugongs and Turtles, alongside other marine species (Short *et al*. 2007; Al-Asif *et al*. 2022; e.g. terns, gulls, Berr *et al*. 2023). Within the Coral Triangle (encompassing countries: Indonesia, Malaysia, Papua New Guinea, Philippines, Solomon Islands and Timor-Leste), seagrass beds cover around 58,550 km^2, about half of which is within Indonesia. The combined seagrass bed plant biomass and soil has been estimated to currently hold 368 Megatonnes of Carbon (Alongi *et al*. 2015; Al-Asif *et al*. 2022), although, a more recent study from Southeast Asia suggests that the level of carbon stored might be much lower (5.85-6.80 Megatonnes of Carbon per year) (Stankovic *et al.* 2021). This discrepancy in the level of carbon stored is likely due to habitat loss, due to the various reasons already outlined above (Al-Asif *et al*. 2022).

Dugong

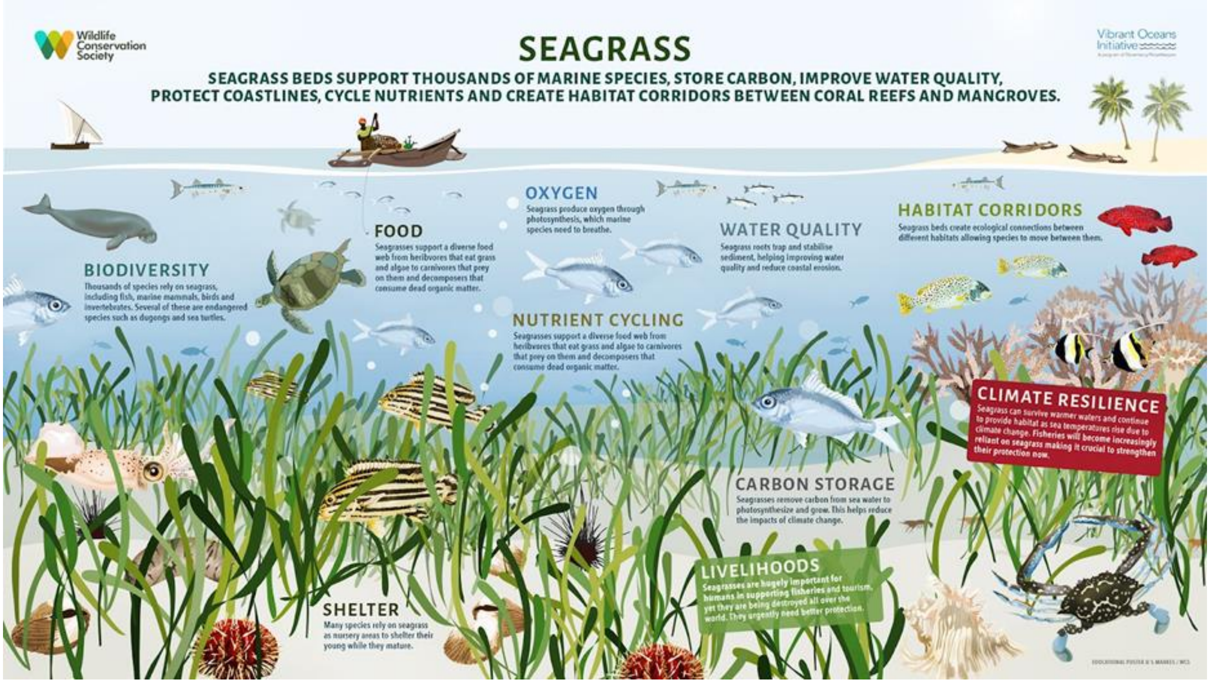
Dugongs (*Dugong dugon*) are one of the many groups of species that rely on seagrass for food (Al-Asif *et al*. 2022). Dugongs are found around the coastlines of the countries bordering the Indian Ocean and countries bordering the western side of the Pacific Ocean, where there are seagrass beds. They are on the CMS Appendix II list and are Vulnerable on the IUCN Red List. Various threats impact the Dugong populations and these include shipping lane interactions and being caught for food or as bycatch. However, climate change induced flooding and storm events are also likely to impact their populations and associated habitats. Dugongs are one of the groups of species that help maintain the natural balance of seagrass beds (Al-Asif *et al*. 2022). However, high-intensity grazing can cause a decline in seagrass bed associated biodiversity and increase the time seagrass beds take to recover (Aragones & Marsh 2000).

Climate change nature-based solution(s)

Seagrass beds are an important sink for carbon storage. Dugongs are one of the large bodied herbivores that, under moderate levels of grazing, help maintain them (Al-Asif *et al*. 2022). Areas of seagrass with Dugong grazing had higher levels of clonal richness and therefore genetic diversity. This occurs because grazing Dugongs dig up the rhizomes as well as consuming the leaves, creating a meandering furrow in the seabed, typically as wide as their muzzle (Preen 1995) which provides an open area of ground available for seagrass recruitment (McMahon *et al*. 2017). When combining the grazing pressure from the Dugong with other external pressures (e.g. cyclone intensity), the projected population decline of the Dugong (due to the threats mentioned above) and the climate change induced increased intensity of cyclones, the colonial richness and therefore genetic diversity will decline, reducing seagrass beds resilience to this and other environmental perturbations (McMahon *et al*. 2017).

Conservation benefits

Dugongs are a large bodied herbivore, as such they exert top-down pressure on the ecosystem they inhabit (Aragones & Marsh 2000; McMahon *et al*. 2017). Through appropriate conservation management of the Dugong populations (e.g. protected areas), this is likely to aid in the conservation of seagrass beds and the associated species that also rely on seagrass for food and shelter (e.g. terns, gulls, Berr *et al*. 2023; turtles, Aragones & Marsh 2000), or on the habitat heterogeneity created by the grazing behaviour. Not only are there these carbon storage and other species conservation benefits, Dugongs are important Culturally as a source of tourism and as a probable source for ancient stories of mermaids (Al-Asif *et al*. 2022).



BIODIVERSITY
Thousands of species rely on seagrass, including fish, marine mammals, birds and invertebrates. Several of these are endangered species such as dugongs and sea turtles.

FOOD
Seagrasses support a diverse food web from heribvores that eat grass and algae to carnivores that prey on them and decomposers that consume dead organic matter.

OXYGEN
Seagrass produce oxygen through photosynthesis, which marine species need to breathe.

WATER QUALITY
Seagrass roots trap and stabilise sediment, helping improving water quality and reduce coastal erosion.

HABITAT CORRIDORS
Seagrass beds create ecological connections between different habitats allowing species to move between them.

NUTRIENT CYCLING
Seagrasses support a diverse food web from heribvores that eat grass and algae to carnivores that prey on them and decomposers that consume dead organic matter.

CLIMATE RESILIENCE
Seagrass can survive warmer waters and continue to provide habitat as sea temperatures rise due to climate change. Fisheries will become increasingly reliant on seagrass making it crucial to strengthen their protection now.

CARBON STORAGE
Seagrasses remove carbon from sea water to photosynthesize and grow. This helps reduce the impacts of climate change.

LIVELIHOODS
Seagrasses are hugely important for humans in supporting fisheries and tourism, yet they are being destroyed all over the world. They urgently need better protection.

SHELTER
Many species rely on seagrass as nursery areas to shelter their young while they mature.

Figure 1. A generic representation of the seagrass bed ecosystem and nature-based solutions. Source: WCS Tanzania

Seabird ornithogenic nutrients aid coral growth

Ecosystem service(s) provided by the focal species: nutrient transfer, ecosystem resilience to coastal erosion and storm surges (indirect).

Coral reefs

Coral reefs are found in much of the world's tropical coastal waters and they contribute to a wide range of ecosystem services. These are detailed in Woodhead *et al*. (2019) but include Regulation and Maintenance services (coastal protection, water quality and biogeochemical cycling), Provisioning (food, materials for building) and Cultural (biotechnology inspiration, tourism, recreation, cultural values). However, coral reefs are threatened by multiple drivers including climate change, fishing pressure, coastal construction, anthropogenic nutrient-rich runoff and sediment and invasive non-native species (Riegl *et al.* 2009; Hughes *et al*. 2017). Coral grows through the symbiotic relationship it has with 'zooxanthellae' where the coral host excretes inorganic nutrients which is taken up by the 'zooxanthellae', used to support photosynthesis. This in turn is converted back into organic compounds which are then used by the coral. 'Zooxanthellae' can also take up inorganic nutrients from the surrounding seawater (Savage 2019). This symbiotic relationship is negatively impacted by higher water temperatures because the symbiont 'zooxanthellae' are damaged and consequently expelled. If the 'zooxanthellae' do not return quickly, the coral typically dies, termed 'coral bleaching' (Riegl *et al*. 2009).

Seabirds

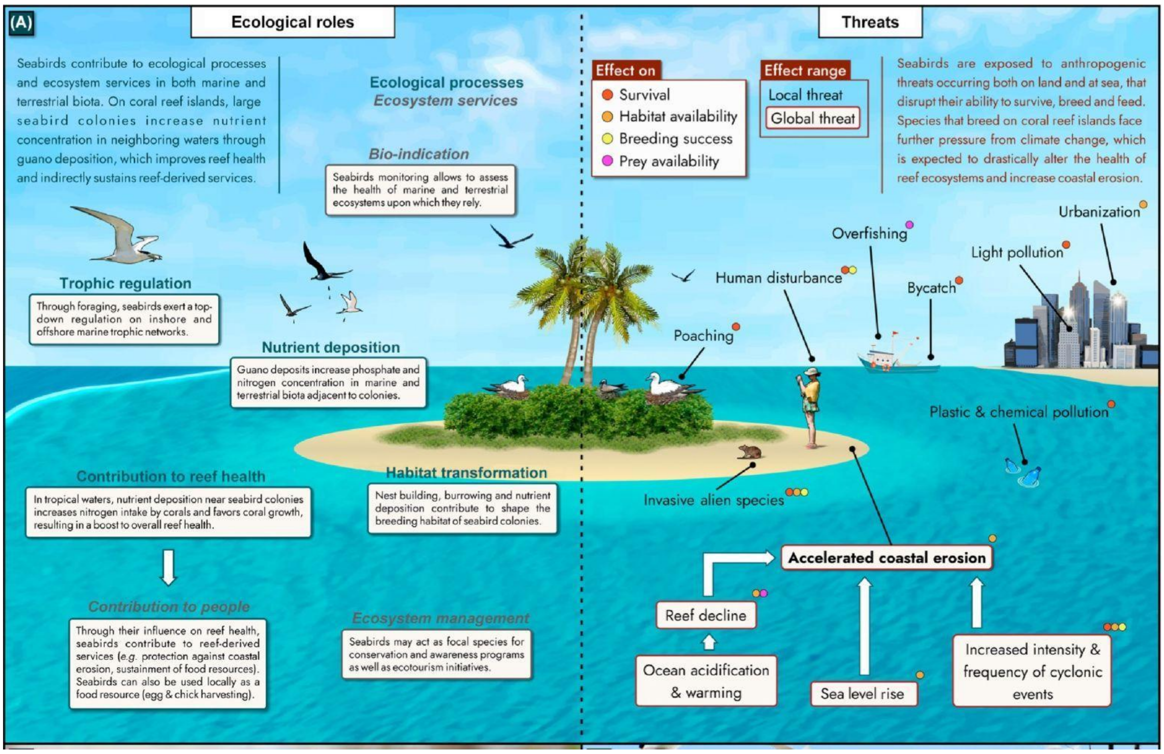
Seabirds bridge the gap between the marine and terrestrial environments because they spend the non-breeding season at sea, and only return to their breeding grounds (often cliffs and islands) to breed (Dias *et al*. 2019). The top three threats to seabird survival are regarded as fisheries by-catch, invasive non-native species and climate change (Dias *et al*. 2019). Berr *et al*. (2013) summarise both the services and threats to seabirds. Many seabirds are on various of the CMS Appendix I and/or II lists including some in the review by Berr *et al*. (2023) which incorporate seabird breeding locations across the Indian and Pacific Oceans (IUCN Red List categories ranged from about a third being Vulnerable or higher; Berr *et al*. 2023). Seabirds contribute to ecosystem services in a variety of ways, including, predation by seabirds maintains a trophic cascade, aiding in nutrient cycling both terrestrially and in the marine ecosystems (McKechnie 2006; Berr *et al*. 2023). Here we concentrate on the role seabirds have in aiding coral growth across the Indian and Pacific Oceans including the Red-footed booby (*Sula sula*), Great Frigatebird (*Fregata minor*), and the Brown Booby (*Sula leucogaster plotus*); none of which are on the CMS Appendix I or II lists and all of which are Least Concern on the IUCN Red List (Lorrain *et al*. 2017, Savage 2019), and the Roseate Tern (*Sterna dougallii*; CMS Appendix II listed; Least Concern) (Graham *et al*. 2018). Migratory island and cliff-nesting seabirds may perform similar nutrient cycling functions, for example with respect to shallow coastal seas (rather than specifically coral reefs), but do not appear to have been subject to the same level of study.

Climate change nature-based solution(s)

As mentioned above, coral growth relies upon the symbiotic relationship with 'zooxanthellae' as well as nutrients in the surrounding water (Savage 2019) and many seabirds nest along coastal and island edges leaving ornithogenic nutrients (guano and other bird related detritus) on land as well as the nearby sea (Dias *et al*. 2019). The process of assessing the impact these nutrients have on the surrounding landscape has been assessed at various different levels. One example analysed the Nitrogen isotope content of a species of coral (*Pocillopora damicornis*) near large seabird colonies in the Pacific Ocean. They found that the coral nearest the seabird colonies had the highest level of Nitrogen-15 isotope (which is associated with seabird guano) compared to coral samples from further away, demonstrating that ornithogenic nutrients contribute to coral reef growth (Lorrain *et al*. 2017). Another example from Fiji further emphases this, where Red-Footed Booby's nest adjacent to coral reefs. Savage (2019) assessed the proportions of Nitrogen isotopes in the dominant reef-building coral (*Acropora formosa*) and found that the closer to the shore, the faster the coral grew. In fact, when transplanted coral fragments were switched between far and near to shore, the ones closest to the seabird colony grew four times faster. A final example from the Chagos Archipelago, Indian Ocean, has identified that the plants on islands and algae and coral reefs around islands where rats have not been introduced have a higher Nitrogen-15 isotope (which is associated with seabird guano) compared to islands with invasive rats (the nitrogen input by seabirds was estimated to be 190 $kg.ha^{-1}.year^{-1}$ on rat free islands compared to $0.8kg.ha^{-1}.year^{-1}$ on rat infested ones). There are mixed conclusions on the vulnerability Nitrogen enriched corals may have to coral bleaching, some suggesting the coral becomes more vulnerable, some suggesting increased coral resilience (Lorrain *et al*. 2017). Lorrain *et al*. (2017) suggest further studies are needed to establish the impact of nitrogen, especially specifically from seabird guano. Nevertheless, this shows that invasive rats disrupt island nutrient flows and by undertaking eradication programmes on islands it is possible to reinstate seabird populations and the wider benefits they provide through their ornithogenic nutrients (Graham *et al*. 2018).

Conservation benefits

These studies have shown that seabirds provide various ecosystem services which, in turn, enables the surrounding habitats and other species to retain their ecological functions and associated ecosystem services - especially beneficial for climate change nature-based solutions. Therefore, by conserving seabirds it is possible to also protect other species and habitats. Various conservation management tools are already in use within the marine and coastal environments. Savage (2019) suggests that while many studies have focused on protected areas to connect reefs, there is also a need to incorporate catchment-to-reef connectivity to take into account both the anthropogenic threats but also the ecosystem function benefits. The studies presented here also identify the benefits of eradication programmes for invasive non-native species with benefits not only for the seabirds but on the many plants and animals that rely on the nutrients they provide (Lorrain *et al*. 2017; Graham *et al*. 2018; Savage 2019). This has positive impacts on the surrounding coastal habitats - exemplified here by healthy coral reefs which provide many ecosystem services including climate change related nature-based solutions.



Seabirds contribute to ecological processes and ecosystem services in both marine and terrestrial biota. On coral reef islands, large seabird colonies increase nutrient concentration in neighboring waters through guano deposition, which improves reef health and indirectly sustains reef-derived services.

Seabirds monitoring allows to assess the health of marine and terrestrial ecosystems upon which they rely.

Through foraging, seabirds exert a top-down regulation on inshore and offshore marine trophic networks.

Guano deposits increase phosphate and nitrogen concentration in marine and terrestrial biota adjacent to colonies.

In tropical waters, nutrient deposition near seabird colonies increases nitrogen intake by corals and favors coral growth, resulting in a boost to overall reef health.

Nest building, burrowing and nutrient deposition contribute to shape the breeding habitat of seabird colonies.

Through their influence on reef health, seabirds contribute to reef-derived services (*e.g.* protection against coastal erosion, sustainment of food resources). Seabirds can also be used locally as a food resource (egg & chick harvesting).

Seabirds may act as focal species for conservation and awareness programs as well as ecotourism initiatives.

Seabirds are exposed to anthropogenic threats occurring both on land and at sea, that disrupt their ability to survive, breed and feed. Species that breed on coral reef islands face further pressure from climate change, which is expected to drastically alter the health of reef ecosystems and increase coastal erosion.

Figure 1. Seabirds and their ecological roles. From Berr *et al*. 2023.

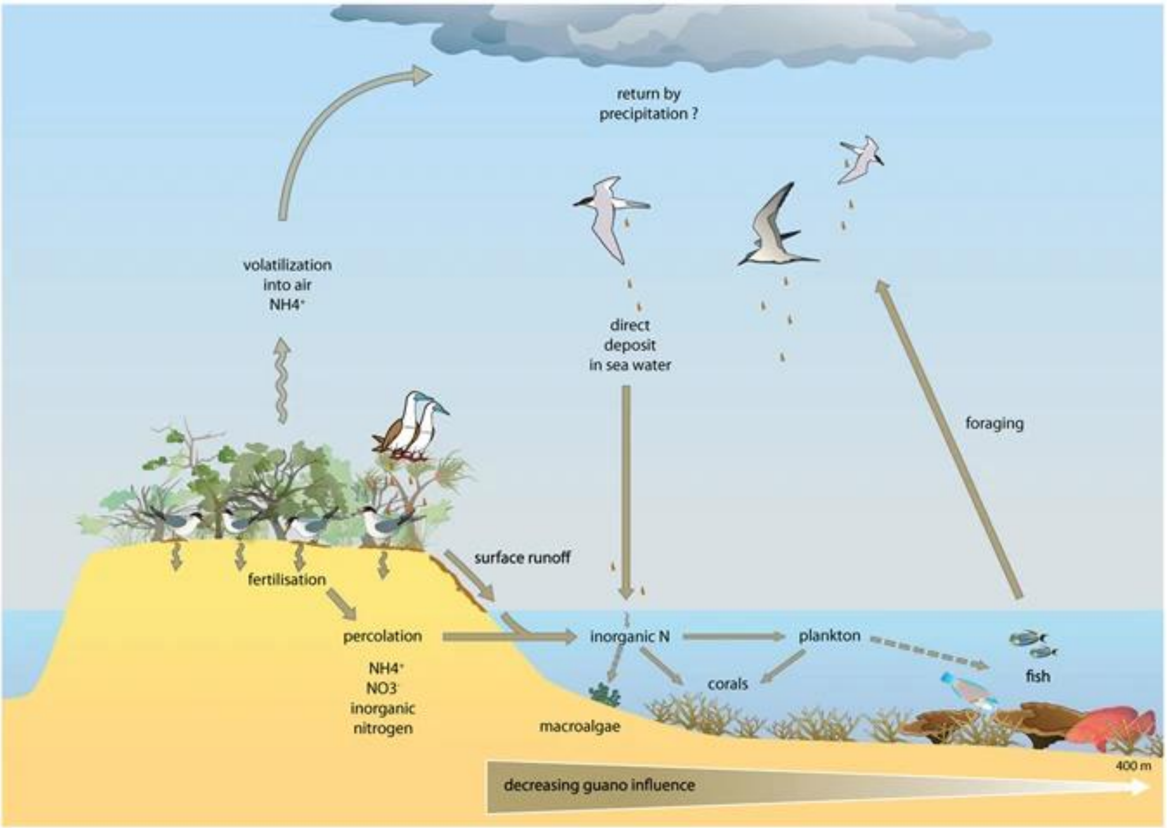


Figure 2. Seabirds and the role their guano has in the surrounding ecosystem in providing Nitrogen. Lorrain *et al*. 2017.

Bats foraging techniques aid plant survival and propagation

Ecosystem service(s) provided by the focal species: pollination, seed dispersal, pest control and soil nutrients (via guano).

Bats

Bats are found globally in a wide variety of habitats (e.g. rainforests, tropical dry forests, both of which contribute their own ecosystem services). Many are listed on the CMS Appendix II list (with one on the Appendix I list: Mexican (or Brazilian) Free-tailed Bat *Tadarida brasiliensis*; Least Concern on the IUCN Red List). Over a third of bats are listed as Threatened or Data Deficient on the IUCN Red List and the broad threats to bats are habitat loss, roost damage and human consumption (Ramírez-Fráncel *et al*. 2021).

Climate change nature-based solution(s)

Bats are one of the groups of species that provide ecosystem services that are directly relevant to plant growth and survival which in turn are important as climate change nature-based solutions (Ramírez-Fráncel *et al*. 2021). Many of the bats reviewed by Ramírez-Fráncel *et al*. (2021) are listed on one or both of the CMS Appendices, and provide at least one of the following ecosystem services: pollination, seed dispersal, pest control and fertiliser via guano (Frafjord 2007; Krauel, Westbrook & McCracken 2015; Burke, Frey & Stoner 2021; Ramírez-Fráncel *et al*. 2021; Manning & Ando 2022). The two examples below come from species not necessarily on the CMS Appendices lists but are likely to be representative of similar behaviours and subsequent services to that of CMS listed bat species.

Megabats (or flying foxes) are predominantly frugivores (includes one CMS Appendix II species - Straw-coloured Fruit Bat, *Eidolon helvum*; Near Threatened). These species target fruiting trees, consuming both the fruit as well as blossoms, pollen, leaves and insects. 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 due to direct human destruction, but may also play a key role in facilitating changes in the distribution of fruiting trees in response to climate change.

Three nectivorous bats (Mexican Long-tongued *Choeronycteris mexicana* and Mexican Lesser Long-nosed *L. yerbabuenae* Bats, both Near Threatened, and Mexican Long-nosed Bat *Leptonycteris nivalis* Endangered; none on CMS Appendices) migrate through Chihuahuan and Sonoran Deserts crossing between the US and Mexico. They are important pollinators and seed dispersers of columnar cacti and agave (*Agave* spp.) which are found in tropical dry forests. However, 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 *et al.* 2021). Burke *et al.* (2021) suggest that an increase in land protection (through habitat conservation and responsible plant population management) will be important for both the plant and bat survival.

Some maladaptation is already being recorded due to possible migration changes. For example, Krauel *et al.* (2015), who identify that the Mexican Free-tailed Bat (*Tadarida brasiliensis*; CMS Appendix I; Least Concern) predates upon three agricultural pest species of noctuid moth (corn earworm *Helicoverpa zea*, fall armyworm *Spodoptera frugiperda*, and cabbage looper *Trichoplusia ni*). However, for species whose migration timings are dictated by weather patterns, the bat pest control benefits may change due to climate change (Krauel *et al.* 2015). Therefore, given bats make important contributions to various nature-based solutions/ecosystem services and the often negative associations to pathogen transfer, improved monitoring and research will be important to better aid their conservation (Ramírez-Fráncel *et al*. 2021).

Conservation benefits

These examples of bat services highlight that by increasing the conservation of bats this will also aid: in the regeneration of forests (and so aid in the continued carbon capture forests provide and the habitat for associated species; Frafjord 2007); in the pollination and seed dispersal of plants to retain their genetic diversity (important in the increasingly fragmented habitats); and if conservation initiatives include the establishment of protected areas to connect habitats, this will benefit the other species that also rely on the habitats (Burke *et al.* 2021).

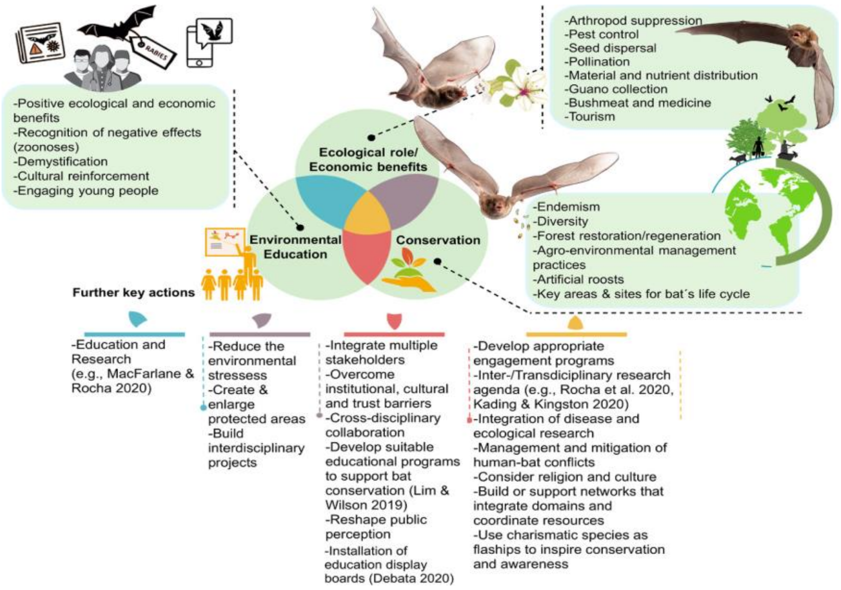


Figure 1. Bats as ecosystem service providers, highlighting the key services provided by bats in the areas of environmental education, ecological role/economic benefits and conservation. Key actions for further research and action are given. From Ramírez-Fráncel *et al*. (2021).

Elephants as ecosystem engineers for the African savanna

Ecosystem service(s) provided by the focal species: carbon capture, tourism.

The African Savanna Elephant

The African Savanna Elephant *Loxodonta africana* is found in African savanna habitats (which includes forest, shrubland, grassland) as well as inland wetland habitats. They are herbivorous grazers and their foraging technique, size and behaviours often causes treefall (Sandhage-Hofmann *et al*. 2021). The African Savanna Elephant is listed as a CMS Appendix II species and Endangered on the IUCN Red List. There are various threats to it, which include human-induced habitat loss, hunting and development, and climate change impacts including fire and drought (Wittemyer *et al*. 2014; Fritz 2017).

Climate change nature-based solution(s)

African Savanna Elephants are considered ecosystem engineers for the role they play in maintaining a balance between trees and grasses in African savanna habitats (Fritz 2017). However, this balance is complex and elephants can provide services and disservices for climate change related nature-based solutions, nevertheless they are one of the main focus megafauna species for conservation efforts in Africa (Sandhage-Hofmann *et al*. 2021). Successful conservation efforts (e.g. protected areas, controlling poaching, community engagement to reduce human-elephant conflict, living fences using bees) have meant that in some parks, elephant densities have increased (Sandhage-Hofmann *et al*. 2021), leading to a decline in tree density (Baxter & Getz 2005). This promotes open habitats (important for some savanna species and for tourism) and counters the anticipated impact of increasing Carbon Dioxide concentrations to promote the growth of woody plants (Conradi *et al*. 2020). However, any reduction in tree cover due to increases in Elephant densities is likely to decrease above-ground carbon storage. A recent study has compared these carbon storage pros and cons for low, medium and high numbers of Elephants. Sandhage-Hofmann et al. (2021) found that the loss of trees (where Elephant densities were high) meant a loss of carbon storage by 6.4 $t.ha^{-1}$. However, the soil organic Carbon content from a combination of the knocked over tree decomposition and Elephant dung increased soil Carbon by 4.7 $t.ha^{-1}$. This means there was a net loss of Carbon as Elephant densities increased, due to treefall (of ≤1.4 t C ha-1). In some locations, management of excessively high Elephant densities may be required to maintain appropriate tree cover and store carbon.

Conservation benefits

Overall, these studies highlight that while increasing Elephant densities may reduce Carbon storage, they do provide some nature-based solutions for climate change adaptation by counteracting an increase in woody vegetation caused by increasing Carbon Dioxide concentrations and maintaining areas of open savanna (Sandhage-Hofmann *et al*. 2021). Therefore, continued conservation actions to maintain or increase Elephant densities, such as protection against poaching (Wittemyer *et al*. 2014), will aid in maintaining savanna ecosystems, provide habitat for other African savanna species and retain the iconic wildlife that much of African tourism depends upon (Smit & Prins 2005).

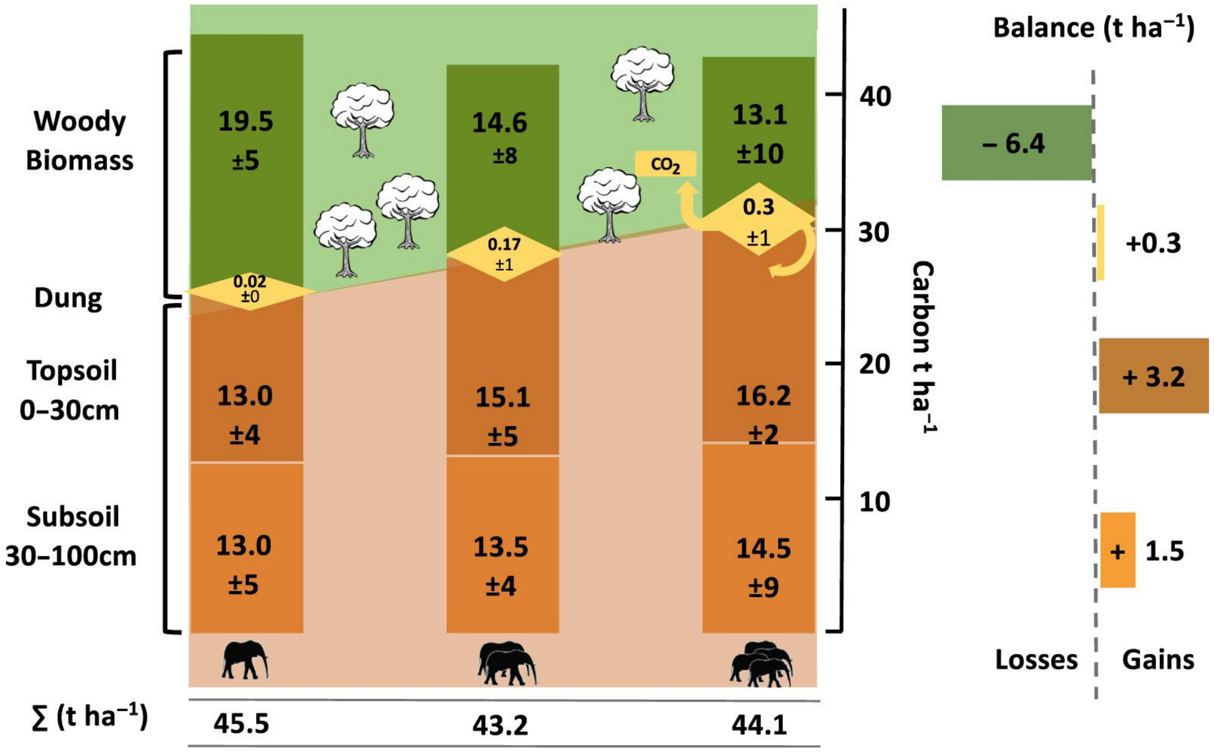


Figure 1. Elephant services and disservices in low, medium and high numbers. Where higher numbers decreased the woody biomass, but increased the amount of carbon stored in the soil. From Sandhage-Hofmann *et al*. (2021).

Saiga antelope aid in grassland biodiversity recovery

Ecosystem service(s) provided by the focal species: increases biodiversity, ecosystem resilience to fire (grazing regime).

Steppes and Semi-Desert of Central Asia

The steppes and semi-desert habitats of Central Asia incorporate a wide variety of different natural and anthropogenic habitats which support a wide variety of species (See Central Asia case study, Part 1). The management of livestock grazing areas has polarised in recent years compared to during Soviet Union times. Steppe and semi-desert grasslands are now being either intensely grazed or not grazed at all (Kamp *et al*. 2016). These grasslands provide a variety of ecosystem services including: carbon storage in grassland and soil, established grassland reduces soil erosion and increases water retention, tourism and recreation (Zhao, Liu & Wu 2020).

Saiga Antelope

The Saiga Antelope (*Saiga tatarica* and *S. borealis mongolica*) is found across the steppe grasslands and semi-arid deserts of Central and Eastern Asia, where they are herbivorous grazers. They are listed as a CMS Appendix II species and as Critically Endangered on the IUCN Red List. They are threatened by various human induced impacts (livestock, disease transmission, transportation corridors, hunting and fire) as well as the impact of climate change induced droughts and temperature extremes (Singh *et al*. 2010; Kamp *et al*. 2016; Khanyari *et al*. 2022).

Climate change nature-based solution(s)

Large bodied herbivores are important ecosystem engineers in grassland systems due to their grazing behaviour which creates a mosaic of habitats utilised by other animals and populated by different plants (Kamp *et al*. 2016). This is particularly true of long-distance migrant herbivores, like the Saiga Antelope (Akçakaya *et al*. 2018) which help maintain natural steppe vegetation communities, compared to more species-poor livestock grazed grasslands that are also at greater risk of wildfire (Brinkert *et al*. 2016).

Conservation Actions

These studies highlight the importance of continued grazing to restore the grassland biodiversity (Kamp *et al*. 2016) and reduce the risk of fire (Brinkert *et al*. 2016). Several studies suggest that the implementation of dynamic/‘moving’ protected areas would aid the protection of Saiga Antelope to enable it to retain its ecological function as a dominant grazer on the Central Asian Steppes (Singh *et al*. 2010; Bull *et al*. 2013). Furthermore, not only would the Saiga Antelope grazing benefit the plant communities but it would also aid other species that rely on these grasslands year round or as migrants passing through (e.g. migrating waterbirds on the Central Asia flyway which utilise the Steppes and semi-deserts freshwater lakes; Kamp *et al*. 2016).

Further research on the impact to associated plant and animal biodiversity of this patchy grazing style where some areas are intensely grazed and some are not grazed at all will be important to better understand and subsequently suggest the most appropriate conservation management techniques to implement (commented in Kamp *et al*. 2016).

Vultures Aid in Reducing Disease Transmission

Ecosystem service(s) provided by the focal species: pest and disease control, nutrient cycling, culture.

Disease spread

Zoonotic diseases are diseases that are naturally transmitted between animals and humans (FAO/WHO, 1959). In a changing world, especially with climate change, the impact these diseases and novel diseases have on wildlife and also human-wildlife interactions will be important to monitor. This is because the conditions vectors and pathogens need are likely to alter due to climate change (Rupasinghe, Chomel & Martínez-López 2022). There are some well known species that carry diseases which are of concern for humans - for example rats (*Rattus* sp.) carry *Leptospirosis* spp. bacteria and the bubonic plague (still prevalent in rural parts of Africa and India), and stray dogs (*Canis lupus familiaris*), amongst other canine specific diseases, carry rabies (Pain et al. 2003; Markandya *et al*. 2008). These mammals have adapted well to urban and agricultural environments, taking advantage of the homogenic landscapes and available food, which increases the possibility of wildlife-human interactions (Donázar *et al*. 2016). However, other species are known to be biological controls of these species which aid in reducing the human infection rates; for example, Vultures (Markandya et al. 2008; Donázar *et al*. 2016).

Vultures

Vulture species are divided into 'Old World' found across Africa, Europe and Asia and 'New World' found across North and South America. They are particularly important in providing Regulation of carrion through their scavenger foraging behaviour, which aids in disease and pest regulation as well as nutrient cycling for the soils (Markandya *et al*. 2008; Whelan, Wenny & Marquis 2008; Donázar *et al*. 2016; Van Den Heever *et al*. 2021). They are also important Culturally (as natural heritage and providing symbolic value; Markandya *et al*. 2008). The collapse of Asian vulture populations in the late 1990s due to poisoning from the veterinary drug diclofenac (Markandya *et al*. 2008), has identified their importance for pest and disease control. Long-billed Vulture (*Gyps indicus*), Slender-billed Vulture (*Gyps tenuirostris*), and Oriental White-backed Vulture (*Gyps bengalensis*), formerly widespread across forest, shrubland and grassland habitats of south and southeast Asia, as well as in urban areas, are all now listed on the CMS Appendices I and II and are Critically Endangered on the IUCN RedList.

Climate change nature-based solution(s)

Vultures are a group of species that aid in pest and disease control (amongst other services) which is beneficial for human survival (Markandya *et al*. 2008; Whelan, Wenny & Marquis 2008; Donázar *et al*. 2016). This ecological service was particularly noticed after the vulture populations in India crashed due to diclofenac poisoning, which left a large amount of carrion uneaten. With the increase in available carrion, the stray dog populations increased, leading to a higher likelihood of a stray dog-human interaction. This increased the number of humans bitten and, as stray dogs carry rabies, subsequent disease related deaths. Similarly, the rat population increased with the removal of pressure from predation, likely increasing crop consumption and the possibility of more rat-human contacts to transmit diseases (Markandya *et al*. 2008). Whilst this example comes from South and Southeast Asia, similar concerns of disease transfer from rats and stray dogs in response to declining vulture populations are apparent in Africa (Van Den Heever *et al*. 2021).

Conservation Actions

These studies highlight the importance of conserving Vultures (New World and Old World species), not only for the cultural importance in many countries, but as their scavenging naturally aids in retaining pest and disease control, whilst also contributing to nutrient cycling through decomposing carcases. These all benefit the other wildlife using the ecosystems as well as humans (Markandya *et al*. 2008; Whelan, Wenny & Marquis 2008; Donázar *et al*. 2016). This is particularly true for humans who live/work within the human-wildlife-livestock interface and are particularly vulnerable to economic instability (Van Den Heever *et al*. 2021).

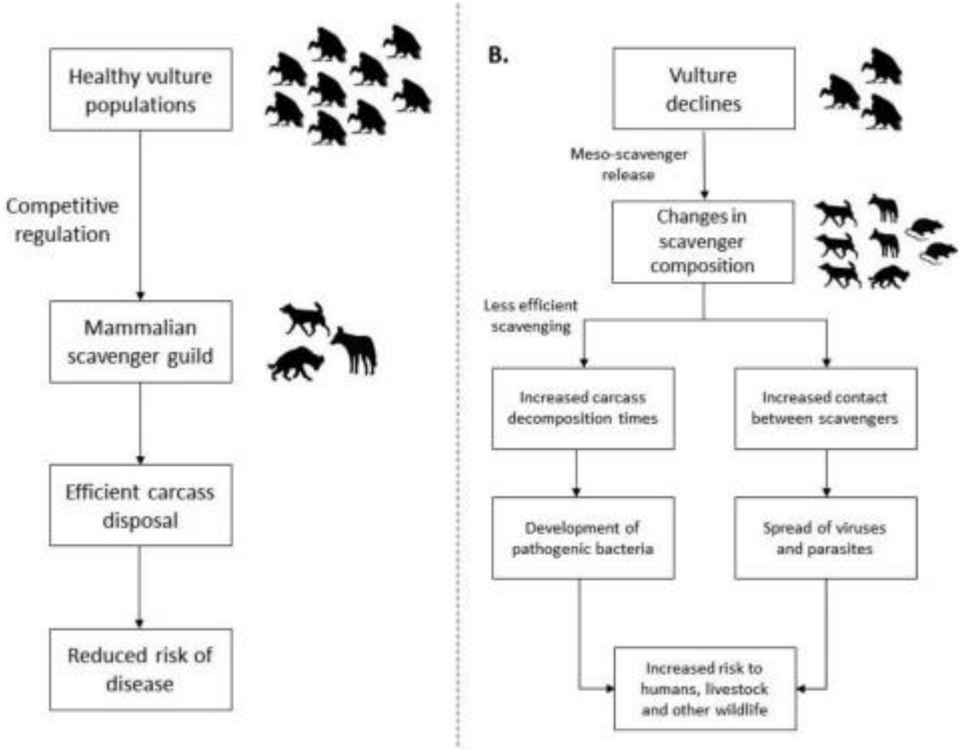


Figure 1. Demonstrating the importance of Vultures as scavengers who competitively regulate and control the mammalian scavenger guild. A) under a healthy vulture population, B) under a reduced vulture population, releasing the mammalian scavenger guild and leading to the increased risk of humans, livestock and other wildlife to viruses, parasites and pathogenic bacteria. From van den Heever *et al*. 2021.