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**MIGRATORY SPECIES AND HEALTH:
A REVIEW OF MIGRATION AND WILDLIFE DISEASE DYNAMICS, AND THE HEALTH OF MIGRATORY SPECIES, WITHIN THE CONTEXT OF ONE HEALTH AND ECOSYSTEM APPROACHES TO HEALTH**

(Submitted by the Secretariat)

Summary:

This document has been prepared by the University of Edinburgh for the CMS Secretariat. It is in a draft form, it should not be cited. The report is subject to review by the Scientific Council to help inform the final version.

Migratory Species and Health:

A Review of Migration and Wildlife Disease Dynamics, and the Health of Migratory Species, within the Context of One Health and Ecosystem Approaches to Health

DRAFT FINAL DOCUMENT: VERSION 1

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Cover photo: [*Placeholder*]

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Executive Summary

[*Placeholder: summary text, plus summary 'integrated approach to health' graphic (graphical abstract)*]

1 INTRODUCTION

1.1 CMS and wildlife health

CMS has an extant resolution on wildlife disease and migratory species that was adopted at COP12 in 2017 (UNEP/CMS/Resolution 12.6 Wildlife Disease and Migratory Species), and has played an important role in responding to poisoning and avian influenza in migratory species.

Other than this Resolution and those specific disease activities, a review of CMS Resolutions and documentation relating to Memoranda of Understanding (MOUs), working groups, task forces and action plans, finds relatively few mentions of the terms ‘health’ and ‘disease’. Although a good numbergood number of these documents discuss ‘hazards’ to species, they mainly discuss non-infectious threats, with little or no focus on disease, overall health, or disease surveillance. Recognising the increasing anthropogenic pressures on wildlife and thus the increasing disease threats that arise from these, it is worth noting that some of the older action plans may not necessarily reflect some more recent or emerging threats. The paucity of good wildlife disease surveillance systems compounds our poor understanding of disease threats to species.

With increasing awareness of the importance of wildlife disease it is recognised that there is scope for increased CMS focus on this topic.

Wildlife disease was not prominent on the COP13 agenda, however, the COVID-19 pandemic has since led to renewed interest in One Health with CMS contributing toto UNEP’s Preventing the Next Pandemic report (UNEP, 2020). Following COP13, the CMS Scientific Council decided to undertake action regarding the health of migratory species, and consequently proposed establishment of aa new working group, alongside this review.

1.2 Project aims and objectives

1.2.1 Aim

This programme of work aimed to conduct a review of the health of migratory species for the United Nations Environment Programme’s Convention on Migratory Species (UNEP CMS) based on the terms of reference set out in UNEP/CMS/ScS-SC5/Doc.6.4.1.

1.2.2 Objectives

As per these terms of reference, the overall objective was to inform the work of the proposed CMS Working Group on Migratory Species and Health (UNEP/CMS/ScC-SC5/Outcome 11) to assist them in their:

- Development and prioritization of a work programme;
- Contribution to initiatives such as the One Health High-Level Expert Group (involving UNEP, WHO, FAO and OIE) and other relevant initiatives.

1.2.3 Requested outputs

The report was to include the following outputs (taken from the terms of reference):

1. A brief review of the context of the issue of wildlife health and conservation, the interdependence of health across the sectors, and the need for One Health and ecosystem approaches.

2. A review at a high level of the key health issues affecting migratory species, including key specific known issues for CMS-listed species. To be provided in text and a tabular form for terrestrial, aquatic and avian taxa.

3. A review of disease dynamics in relation to migration, highlighting potential consequences of migration disruption for zoonotic risks.

1.3 Main subject areas

The report therefore comprises the following main sections:

A '**One Health and ecosystem health**' section summarising the context of health in relation to conservation; the interdependence of health across the sectors; and the need for One Health and ecosystem approaches to health and its management.

A '**key health issues for migratory species**' section reviewing key health issues affecting migratory species, at a high level, with an emphasis on known issues for CMS-listed species.

A '**migration and disease dynamics**' section, which discusses disease in relation to migration and the potential impacts of migration and its disruption on the health of wildlife, domestic animals and humans (i.e. zoonotic risks).

2 ONE HEALTH AND ECOSYSTEM HEALTH

In this section, we review the concept of One Health and how ecosystem and wildlife health are integral and connected to this approach. We also highlight opportunities for health management to be more holistic across sectors.

2.1 Definitions

2.1.1 Health dimensions

Wildlife health

For this review, we define wildlife health '*as the physical, physiological, behavioural, and social wellbeing of wild-living animals measured at an individual, population and wider ecosystem level, and their resilience to change*' (Meredith et al., 2022).

[*Placeholder: wildlife health figure*]

From this perspective, 'health' in individuals and wider populations infers that their basic needs are met, and they are able to adapt to environmental change. This means that individuals and populations are resilient to associated social changes and able perform to their usual functions, both for themselves and for what we expect of a 'healthy' functioning population (Stephen, 2014). It relates closely to the concept of ecosystem health discussed below.

Ecosystem health

"A healthy ecosystem is defined as being 'stable and sustainable'; maintaining its organisation and autonomy over time and its resilience to stress" (Rapport et al., 1998).

The concept recognises that ecosystem health is interconnected to the health of others and that our actions on ecosystems can significantly affect the health of their inhabitants and their ability to adapt to change.

One Health

"*One Health is an integrated, unifying approach that aims to sustainably balance and optimize the health of people, animals, and ecosystems. It recognizes the health of humans, domestic and wild animals, plants, and the wider environment (including ecosystems) are closely linked and interdependent" (*OHHLEP, 2022).

This is the most used and accepted term describing a collaborative and interdisciplinary approach to managing large-scale health issues affecting humans, animals (livestock and wildlife) and the environment. One Health approaches are intended to achieve better health equity across all these sectors, emphasising that for human health problems spanning these sectors, optimal management requires attention to the animal and environmental factors linked to disease problems.

Health promotion and harm reduction is a concept that has been used in the human health sector for decades and has been proposed as a potential approach to be used for One Health. In health promotion, the aim is to support public health by encouraging and safe-guarding health and capacity to cope by linking public and private sectors to work together. It focuses of getting communities and individuals to collaborate and promote their own health. It focuses on environmental and social actions, rather than on individual behaviours. In harm reduction, it tackles public health issues by decreasing the impact of the harmful issue, without removing it completely. For example, this practical approach has been used to combat drug addiction to make it safer by addressing the 'drivers' of this harm (social, personal issues) whilst providing safer solutions for those affected. In these ways, like One Health, it tackles difficult problems by using many sectors (interdisciplinary approach) to reduce harm to health by using pragmatic and effective solutions. By involving communities and actively involving them in collective action, health promotion and harm reduction strategies could amplify One Health approaches to address global One Health challenges while ensuring the preservation and health of wildlife populations (Gallagher *et al,* 2021).

Other health dimensions

A healthy wildlife population is a genetically diverse one. Small population sizes are more at risk of detrimental changes at a genetic level, such as inbreeding, harmful genetic mutations and a reduction in genetic variation. This can reduce their resilience to change, and can increase their susceptibility to infectious disease, thus increasing the risk of extinction for some populations (Frankham *et al*., 2012).

Indigenous concepts of health have historically been overlooked, however, people who have grown up surrounded by, and learning from, nature have a unique perspective and understanding of how ecosystems function. They can perceive subtle changes as early indicators of significant health issues, for example, hunters can identify their prey losing condition, which may be an early indicator for local population stressors and declines (Kutz and Tomaselli, 2019). The health of the environment is a key feature of many indigenous cultures and beliefs, which are commonly consistent with the ethos of One Health. They are also custodians of some of the most natural and biodiverse ecosystems remaining in the world (Riley *et al*., 2021).

2.1.2 Health conditions

What is disease?

Disease can be defined as '*any impairment that interferes with or modifies the performance of [an organism's] normal functions, including responses to environmental factors such as nutrition; toxicants and climate; infectious agents; inherent or congenital defects, or combinations of these factors*' (Wobeser, 1981).

From this definition, it is important to appreciate that not all disease is caused by infectious agents, but also by non-infectious conditions which can also impair health and function.

Animals can be 'infected' by an agent (e.g., bacteria), however, if the bacteria's presence has little to no negative impact on that animal, it is not impairing their normal functions, thus the animal in question is **not** exhibiting signs of disease. This could mean they are subclinically or silently infected. Other animals in the same species may demonstrate signs of infection, and thus have clinical disease. On the other hand, an infection in one species which causes no harm, could cause severe disease or death in another species, especially if it is an agent they have not encountered before.

It is also important to note that if an animal is infected, doesn't always mean they are contagious – they are only contagious if the agent can be transmitted from contact from an infected animal, their bodily fluids or from a surface or contaminated environment.

Disease also does not always lead to death of individuals: it may make them ill or impair their normal physiological or behavioural functions; or it may lead to ongoing health issues; but animals can recover from disease and may be more resistant to challenge in the future, e.g. through development of immunity. See Table 1, below for descriptions of some common related terms, including 'infection' and 'zoonosis'.

Table 1. Common terminology (adapted from Wobeser., 2006; Thrusfield *et al*., 2018)

Terminology	Description
Infection	The presence in an individual of an agent that can cause disease. An individual can be 'infected' with an agent, but may or may not suffer from disease as a consequence of the infection
Infectious (agent)	An agent which can cause infection in an individual (see Table 2 below)
Disease (clinical)	Impairment of normal functions due to the presence of an infectious agent or other impairment
Contagious	An agent which can cause infection and can also be transmitted from contact with an infected individual, their bodily fluids, or contaminated environments/surfaces.
Communicable disease	A term used in human health describing a contagious disease (see above)
Subclinical or 'silent' infections	An infection by an agent causing little or no outward symptoms of disease in the individual. There may be little to no observable negative impact on the individual
Non-infectious disease	Health impairments that are not infectious. This includes genetic diseases; disease resulting from physical extremes (heat, cold); trauma, degenerative (e.g., age-related) diseases; nutritional diseases or deficiencies; and diseases due to chemicals (human-related or natural toxins), heavy metals or other toxic substances
Zoonosis (or zoonotic disease)	Diseases than can be transmitted between animals and humans
Endemic	The continual and 'normal' presence of infectious agent, and or disease levels within a population and/or area

What causes disease?

As discussed, not all disease is caused by infectious agents: in many cases, non-infectious conditions are responsible for the disruption of normal functions. These conditions in animals can be natural in origin or originate from human activities. Table 2 lists infectious agents and non-infectious conditions as categorised for the purpose of this review.

Table 2. Infectious agent and non-infectious conditions of disease (adapted from Beckmann et al., 2022).

Infectious agents	**Non-infectious causes**
Viruses	Toxins, pollution, eutrophication
Bacteria	Physiological response to climate (e.g. hyperthermia)
Fungi and yeasts	Undernourishment (e.g. starvation), nutritional disease or deficiency
Protozoa	Stress or disturbance from people (e.g. noise or light pollution)
Endoparasites (worms)	Unintentional trauma from humans (e.g. vehicle collision, entanglement, bycatch); trauma from intentional injury, predation or competition[1]
Ectoparasites (fleas, ticks, mites, etc)	Ingestion of foreign objects (e.g. plastic)
Other e.g. transmissible tumour (as relevant)	Environmental injury (e.g. electrocution, drowning, burn injury)
Prions	Other conditions, including developmental, genetic, or behavioural issues

[1]Trauma from intentional injury, predation or competition is included for completeness here, but is categorised separately, under ‘other problems’ (specifically ‘persecution’ and ‘ecological problems’) in Section 3 of this review.

However, it is worth noting that health concerns in wildlife are not just from infectious and non-infectious disease (Stephen, 2022). There are many other threats affecting wildlife health which often stem from deep-rooted socio-political issues such as the increasing drive for economic wealth, agricultural expansion, urbanisation and political conflict to name a few (Manfredo *et al.*, 2020).

[Placeholder: *importance of wildlife health – figure*]

2.2 Wildlife health, biodiversity conservation and spillover

2.2.1 Conservation status of migratory species

Many migratory species are declining [*Placeholder: more on their conservation status?*], due to a multitude of factors, many of which are commonly driven by human activity. Most of these ‘drivers’ (described later in this section) are contributing to the decline of not only migratory species, but wildlife species worldwide. These declines and their drivers are explored further in another UNEP CMS report, currently in preparation. [*Placeholder: more background on conservation threats*?]

2.2.2 Wildlife health and conservation

Taking into account the above definitions of wildlife health and disease and given that a low level of disease is to be expected in any wildlife population, diseases of concern to wildlife conservation are those to which the population in question is unable to respond or is non-resilient to over time (Hanisch *et al*., 2012; UFWS., 2020; Bacon *et al*., 2023). In this review we use the term 'threat' to denote such significant disease conditions, for which there may evidence of a negative impact at the population level.

As above, disease in wildlife populations can be a natural occurrence and a mechanism for natural regulation of the number of individuals of a particular species within an ecosystem. However, when populations are declining as a result of other stressors such as habitat encroachment, pollution or persecution, then disease in an at-risk population can cause a decline of such severity that the population is unable to rebound. This can lead to local extinction events (Aguirre & Tabor., 2008).

Disease-induced declines in wild animal populations can then further negatively impact ecosystems. Many migratory species provide ecosystem benefits. For example, grazing ungulates in large herds provide essential nutrients to grasses and plants via their excretions. Their feeding or foraging behaviours can regulate plant growth, sustaining the overall biodiversity of plant and animal species in the ecosystem they inhabit (Kauffman *et al*., 2020). Thus, disease outbreaks in wildlife can sometimes have wider ecosystem impacts.

Case example

Population reduction of prairie dogs (*Cynomys spp.*) by infection with *Yersinia pestis* (sylvatic plague) leads to changes in grassland plant species and altered nitrogen content in soil. Mountain plovers (*Charadrius montanus*) nest on the ground of prairie dog burrows, so when prairie dog numbers decline from *Y.pestis* infection, mountain plover populations often concurrently decline (Eads & Biggins, 2015).

2.2.3 Wildlife health and 'spillover'

Wildlife disease outbreaks can occur within wildlife populations and/or between different wildlife species. Their infectious agents can also potentially 'spillover' to, and cause disease in, domestic animals (including livestock) and people (Acevedo-Whitehouse & Duffus., 2009). 'New' emerging infectious diseases are more likely to come from wildlife via spillover events as a result of increasing pressure from human activities. However, direct zoonotic disease transmission from wildlife to people is rare. The vast majority of zoonotic disease transmission derives from domesticated animals (companion animals and livestock), for example through the consumption of livestock products as foodborne zoonoses (Grace *et al.,* 2012). Where transmission to people from wildlife does occur, it is mostly through indirect transmission i.e., via an intermediate ('vector') species such as the mosquito (e.g. West Nile virus) (Kock & Caceres-Escobar., 2022).

Spillover depicts when an agent is transmitted from a maintenance host population (reservoir) or community (see Table 3 below) to non-maintenance hosts, i.e. the infection is not self-sustaining (Nugent, 2011; Fenton & Pederson., 2005). This cross-species agent transmission can lead to transient spillover infections into new host species including other wildlife species, domestic animals or humans. Should the infectious agent be able to adapt to the new host species then genuine disease emergence may occur. The likelihood of this occurring can vary, as discussed further in section 4.2.1 below. The intricate and complicated interactions between the infectious agent, host animal(s) and the environment can greatly influence the outcome from exposure (Keesing and Ostfeld., 2021).

Livestock and other domestic animals are often the source of disease for wildlife, either through spillover, or through disease transmission where domestic animals are the reservoir host.. This is a significant concern for many wildlife species and can have severe consequences. For example, in 2016-2017 mass mortalities numbering thousands of Mongolian saiga antelope (*Saiga tatarica mongolica)* likely occurred following the introduction peste des petits ruminants virus (PPRV) from small ruminant livestock (sheep and goats) (Pruvot *et al.*, 2020). Deaths also occurred in other wildlife species including the Siberian ibex (*Capra sibirica*) and goitered gazelle (*Gazella subgutturosa*). The virus is thought to have been introduced from movements of sheep and goats using the same lands as saiga, and significantly reduced the saigas' population size (Pruvot *et al.*, 2020).

Case example

The strain of H5N1 highly pathogenic avian influenza (HPAI), which since 2020 has significantly affected wild bird populations globally, originated in domestic geese in China in 1996. The virus was largely maintained in poultry in Asia until a large spillover event to wildlife occurred at Lake Qinghai, China, in 2005. Early high mortality of wild birds was followed by years of episodic outbreaks. Changes in the virus and pathways to new hosts such as seabird breeding colonies has led to serious conservation concerns and calls for better protection of wildlife from livestock diseases (Kuiken & Cromie, 2022).

Types of host

To understand how diseases are transmitted to and between populations and species, one needs to have a basic understanding of the different types of 'host'. This is a tricky subject area with many conflicting (and confusing) definitions.

Table 3. Different host types regarding agent transmission, adapted from (Caron *et al*., 2015; Thrusfield *et al*., 2018; Fenton & Pederson., 2005).

Host type	Description
Target host/population	The host or population of interest
Maintenance host population	The agent/pathogen remains and circulates within the population despite the lack of transmission from other hosts
Maintenance host community	Multiple connecting populations (or environments) where the agent/pathogen is perpetually sustained.
Reservoir host/population	As maintenance host community where agent persistence is permanent. These can be hosts which have a high probability of agent transmission to within species and between other species.
Bridge host	A host that can transmit an agent to others, but is not a maintenance host i.e. it is unable to maintain the agent/pathogen. They are the connecting link between the target host and the maintenance hosts.
Amplifier host	A host which rapidly increases the amount of infectious agent in the population, usually due to changes in population dynamics (e.g. and can act as a source of infection to others over a short period and amplify the numbers infected).

Bridge hosts are particularly relevant to migratory species as they can transmit an infectious agent over a large distance to an entirely new population (as in HPAI). [*Placeholder: expand*]

2.3 Conservation threats as drivers of disease

There is great overlap between the conservation threats to endangered or vulnerable species and the drivers of disease emergence. The main drivers contributing to the decline and extinction of wildlife species are also drivers of disease outbreaks (Machalaba *et al*., 2020). Disease then further exacerbates the threats to conservation status.

For example, habitat loss and encroachment from human activities, such as agriculture and development, puts pressure on populations by reducing their available inhabitable areas or degrading habitat quality. These changes can predispose them to disease outbreaks in a number of ways, such as leading to closer contact with domesticated animals (livestock) and humans, increasing the likelihood of disease transmission from livestock to wildlife, or vice versa (Kock & Caceres-Escobar., 2022). [*Placeholder: draw/separate this aspect out further.*] Table 4 outlines the drivers of threats to wildlife conservation and disease emergence. We use these categories of driver in our review (Section 3, below).

Thus, the presence of infectious and non-infectious diseases in wildlife, and their severity, can be indicators of the health of the ecosystem they inhabit, and wildlife can act as sentinels (warning systems) for the health status of ecosystems. Actions to improve the health of wildlife, and their ecosystems, by reducing pressures through more sustainable human actions can additionally improve the health of humans and livestock. Interdisciplinary approaches are required to develop solutions to these difficult and complex issues (Meredith *et al*., 2022).

Table 4. Drivers of conservation threats, which also act as drivers of disease emergence (adapted from IUCN, 2023).

Driver	Description
Agriculture or aquaculture	Agricultural expansion or intensification, including an increased livestock-wildlife interface
Other habitat loss, degradation, or disturbance	Human related settlement; changing land use; roads or other infrastructure; alteration, destruction, or disturbance of habitats from other human activities (including energy production and extractive industries); transportation and service corridors; noise disturbance; war and conflict; recreation. Can lead to increased proximity to human settlements or non-farmed domestic or feral species (e.g. dogs/cats).
Overexploitation (harvesting or persecution)	Deliberate or unintentional consumptive overuse of wild resources by hunting, collection, fishing, harvesting resources
Invasive species	Invasive alien species, other problematic species or genes[1]
Pollution	Introduction of exotic and/or excess or toxic materials or energy to the environment. Includes chemical and plastic pollution; agricultural, forestry, industrial run-offs/effluents, domestic wastewater, solid waste
Climate change or severe weather events	Threats from long-term climatic changes, which may be linked to global warming and other severe climatic/weather events. Includes droughts, temperature extremes, storms, and flooding
Other	Catastrophic geological events

[1]The IUCN and CMS definition includes invasive diseases from these species, but we consider these separately for the purpose of this review.

Figure 1. Infectious and non-infectious threats to the health of wildlife, and the drivers of these threats

2.5 Holistic health approaches: challenges and opportunities

2.5.1 Limitations of current approaches

It is important to recognise the weaknesses in how society currently views wildlife health, with a predominant focus on ill-health/disease and emergency responses to outbreaks. These then dominate the funding and expenditure in health. Whilst this focus is no doubt important, it distorts the health equation, and does not address what 'determines' health (or ill-health). That failure can result in unnecessary burdens of disease for humans, domestic and wild animals. Moreover, animal health is often viewed as a responsibility of agriculture ministries with too little engagement in health from environmental sections of government.

For wildlife health, this is often viewed through the prism of how it immediately affects humans and our interests. Responses to disease outbreaks in which wildlife play a role have generally been reactionary, rather than preventative. This can quickly lead to negative outcomes. A recent example has been the COVID-19 pandemic. Wildlife was quickly blamed as the source of the virus with some reports of bats being targeted as part of fear-based responses. Similarly, H5N1 HPAI spilling into wild birds led to both killing of wild birds and destruction of nests and some wetland habitats in the early days of disease. These responses fail to both understand the root causes and realise the interconnectedness of health in animals, the ecosystem, and people. Using rational, preventative approaches – such as improving planning of farming activities or biosecurity practices in farms and markets or improving agricultural practices to reduce stressors on wildlife – can allow people to live more sustainably alongside wildlife and with fewer negative outcomes (Machalaba *et al*., 2020). Reactive management may not only be detrimental in the long term but is also economically costly – and much more so than preventative approaches (Dobson *et al.*, 2020).

The One Health approach has come under criticism for frequently remaining too anthropocentric, focusing most of its attention on improving the health of humans and reducing the risks facing humans, with little regard to the health and wellbeing of non-human animals (Stephen *et al*., 2023). As above, this can lead to great costs to animal populations, such as when culling or containment is used as a method of disease control. It also puts a great emphasis on wildlife being the cause of disease outbreaks and risk to humans, rather than understanding how all these systems are interlinked, and that human actions are a frequent underlying causal factor. To improve this, new frameworks are being proposed to make One Health more holistic and less human orientated, such as the framework recently proposed by Stephen *et al*. (2022): a health '*equity informed one health framework*'.

Added to the above are multiple logistical difficulties that negatively impact responses to wildlife disease problems. For example, many countries have inadequate surveillance and diagnostic facilities, or lack of capacity for appropriate investigative approaches and storage of samples. Moreover, countries which appear to be hotspots for emerging diseases (zoonotic and otherwise), are often those with weakest health infrastructures and investigative systems (Watsa *et al*., 2020). Compounding this are the regulations in transporting samples from threatened (CITES-listed) species which can delay sample analysis and thus responses to disease outbreaks (Machalaba *et al.*, 2020). Voluntary reporting systems for wildlife disease or mortality incidents are frequently inadequate and ineffective, and collaborative efforts worldwide are required to improve this situation.

2.5.2 Importance of biodiversity

There have been many debates over the years about the role biodiversity plays in emerging diseases, particularly zoonotic ones. Initially, areas with high biodiversity were thought to be hotspots and sources for zoonotic infectious agents, however, other research has identified potentially a reduction in transmission of these agents in areas of high biodiversity. These opposing views have been highly debated among experts, with the conclusions still not 100% definitive.

What is known, is that changes in biodiversity can alter the contact rates and mechanisms between species which can influence disease transmission. Reduction in biodiversity can also make ecological niches available (meaning that ideal environmental conditions can be matched to maintain a group of species) which can allow new infectious agents or hosts to become established in an ecosystem. For example, some species groups (such as rodents) are more likely to increase in numbers in areas that have undergone human-induced change, potentially increasing chance of contact with people and consequently spillover. In comparison to more 'untouched' areas, these species groups who are likely to harbour zoonotic infectious agents decrease, with other species increasing and flourishing. Thus, loss of biodiversity does suggest an overall increased risk to humans for the potential for a spillover events.

However, to complicate matters, high levels of biodiversity can reduce the risk of disease (by a so-called 'dilution effect'), and/or concurrently increase disease risk (the 'amplification effect') depending on the type of infectious agent of concern, as well as the host animals' immune response, the host community and ecosystem (Keesing & Ostfeld., 2006; Keesing and Ostfeld., 2021; Faust *et al*., 2017). Further research into specific disease systems may shed light on the scenarios for either the dilution or amplification effect that could be used in one health approaches.

Despite the complicated dynamics involved in disease emergence, and the conflicting opinions, biodiversity still plays a key role in the functioning of ecosystems. Indeed, health can be seen as a property of an ecosystem and a biodiverse natural ecosystem is intrinsically healthy and resilient. Thus, maintaining and improving ecosystem biodiversity should be part of a holistic health approach that can reduce disease risks to wildlife, domestic animals and/or people.

2.5.3 Opportunities for improvement

Fully understanding determinants of health will lead to preventative or ecosystem approaches to health which are likely to have better outcomes when considering the broader contexts of sustainable agriculture, socio-economic development, environment protection and sustainability, and complex patterns of global change (Cromie *et al*., 2012).

Wildlife Health Systems

Wildlife health can be protected and fostered through the provision of robust and appropriately resourced wildlife health systems. Health systems are well established in the human health and domestic animal health sectors but have been commonly neglected and very poorly resourced in wildlife health. Enhanced systems for wildlife are critical in the development of preventative measures and to enable early detection of disease outbreaks in wildlife (Skerratt., 2022). An effective system would provide the expertise, facilities and funding required to enable effective disease prevention strategies, alongside prompt disease surveillance, diagnosis and management strategies. It should operate across scales with the emphasis placed on the development of robust systems at a local level. A wildlife health system should also be integrated with those supporting domestic animal health and human health within a One Health framework to create a more resilient and collaborative approach to health across sectors.

There is a lack of collaboration between sectors in current approaches, with too much of a focus on wildlife as the source of zoonotic and emerging infectious diseases. This can be detrimental to wildlife health and the conservation of biodiversity more broadly and is also ineffective in addressing the underlying drivers of disease emergence. The vast majority of zoonoses originate from livestock and domestic animals, with food systems playing an important role in transmission. Many infectious agents either come from, or are amplified in, the food production sector. Thus, improving food safety and biosecurity practices, and reducing live animals in markets, could vastly reduce the risk of disease emergence and zoonotic disease transmission (FAO., 2022). This also illustrates the need for more integrated health systems across sectors and equitable provision of resources.

Where resources are limited, it is also important to target them to areas where disease risks are considered to be greatest. Critical control points may be identified where risks of disease transmission, spillover and emergence are high and resources targeted accordingly. Strong wildlife health systems are required to identify these critical control points and to implement measures to reduce risk. This requires require capacity to identify these risks, via data collection and analysis (such as surveillance), and to collate these findings into a useful, practical, and realistic policy/programme for prevention and response (FAO., 2022). There is limited diagnostic capability in many countries, some of which have ineffective and inefficient veterinary capacities, especially for wildlife health. These countries often have a significant livestock sector, where veterinary care is vital but often inadequate.

[*Placeholder: wildlife health systems graphic*]

Intergovernmental recognition of the need for One Health and Ecosystem approaches

Intergovernmental processes have recognised the importance and interrelationships between the health of different sectors and the value of ecosystem approaches to health. As an example, in 2012, the Parties to the Ramsar Convention on Wetlands adopted a resolution on this subject in relation to wetlands following the Convention’s substantive work on ‘Healthy Wetlands, Healthy People’. Further prompted by the COVID-19 pandemic, the need for One Health approaches has been acknowledged recently with UNEP (United Nations Environment Programme) joining the Tripartite (Food and Agriculture Organization of the United Nations, World Organisation for Animal Health and the World Health Organization) in November 2020 to become the Quadripartite. In May of 2021 they established an interdisciplinary One Health High-Level Expert Panel (OHHLEP).

Global and national organisations have capacity to improve approaches to health across sectors by, for example:

- Promoting an understanding of the true determinants of health and the role of resilient biodiverse ecosystems within this context

- Encouraging equity in One Health approaches, and using these in decisions about planning, development, and in particular agricultural practices.
- Encouraging more effective contingency planning for wildlife health – both in terms of mitigation plans for minimising risks to wildlife and emergency response planning in outbreak situations to ensure the most appropriate and rapid management actions are taken.
- Promoting an understanding that preventative and prompt management is key. Disease risks to wildlife alongside the standard human and livestock risks should be included and considered in environmental impact assessments. This could help to identify which management actions could be used to reduce or mitigate disease risks. This will not stop all disease outbreaks, but may help to contain them more quickly, thus reducing the impact on both animals and humans (Machalaba *et al*., 2020; Kock & Caceres-Escobar, 2022).
- Establishing international guidance on preventative and constructive disease risk management approaches, to prevent ineffective and potentially damaging responses to wildlife disease outbreaks
- Improving capacity for wildlife disease surveillance, diagnostics and outbreak investigation.
- Establishing a global reporting system to track disease outbreaks and understand wildlife diseases (with full contextual ecological data for measuring the impacts of outbreaks).

KEY MESSAGES: On One Health and ecosystem health

- → Healthy, well-managed, resilient ecosystems positively influence health across sectors. Preventative approaches to managing health are more cost-effective than addressing health problems once they emerge.

- → Disease is often viewed as a matter of survival or death when, in fact, effects are often far more subtle, instead affecting productivity, development, behaviour, and ability to compete for resources or evade predation or susceptibility to other disease factors which can consequentially influence population status.

- → Diseases can affect conservation status of migratory species, and the usual drivers of population decline are also the drivers for disease emergence which can then exacerbate pre-existing threats. Therefore, addressing wider conservation threats contributes to reducing disease risks to wildlife, livestock, and people.

- → Interfaces, whether direct or indirect, between domestic livestock and wildlife, significantly risk negative health outcomes from infectious diseases in both sectors.

- → Responsibilities for the health of ecosystems and wildlife lie additionally with environment sections of government in addition to health and agriculture.

- → There are significant gaps in contingency planning for wildlife disease threats. Inadequate surveillance for wildlife diseases contributes to poor understanding of both diseases and means to manage them. Moreover, regulations for transporting samples from many species are delaying outbreak responses and hampering our understanding of epidemiology of diseases of wildlife.

- → Stronger wildlife health systems are required to enable effective prevention and control of disease in wildlife. These should be integrated with human and domestic animal health systems within a One Health framework.

3 KEY HEALTH ISSUES FOR MIGRATORY SPECIES

In this section, we will provide an overview of the main health issues that taxon-specific experts perceive to be affecting migratory species, specifically CMS-listed species, and the drivers of these issues. The output, i.e. disease table, has been designed as a living platform for the CMS Migratory Species & Health Working Group to work from in future, enabling identification of priority disease threats, patterns across taxa, drivers of disease emergence and important knowledge gaps.

3.1 Introduction

Infectious agents and non-infectious conditions

As briefly discussed in the One Health and Ecosystem Health section, health of wildlife is threatened by both infectious agents and non-infectious conditions. These may not cause disease in one species but may have severe effects in another.

Infectious agents cause infection in the host animal, which may then show clinical signs of illness; or can cause a 'silent' infection without outward signs. This means that some animals may look well but potentially be carrying agents which could cause infection in other individuals. Such agents can be transmitted directly between individuals; or indirectly through a vector, such as a mosquito or tick; or from environmental contamination via their bodily fluids.

Non-infectious agents can also be responsible for ill-health or death in animals. These include genetic diseases, physical agents (such as heat or cold), trauma (including unintentional trauma from humans such as vehicle collisions, or bycatch), nutritional issues, stress or disturbance from people like noise or light pollution, foreign object ingestions (such as plastic), and other forms of injury from the environment (e.g. drowning, burn injuries).

Drivers

To recap on Section 2, some drivers of biodiversity declines also cause disease emergence which can compound threats to populations. There is a lot of overlap between these, and most of the threats impacting ecosystem health also play a part in disease outbreaks. See Table 4, above, for our categorisation of drivers.

3.2 Methods

To determine the key health issues for CMS-listed migratory species, and their likely drivers, a disease table was constructed in order to solicit expert opinion on threats to the health of migratory species (see end of section).

Disease table

There are currently 657 CMS-listed species across different taxonomic groups. We grouped different migratory species together to streamline completion of this task in our limited timescale. We generally grouped species into orders. However, given the number of orders we needed to consider and the varying amount of knowledge regarding health conditions in these taxa, we used a higher taxonomic grouping for some fish (Class Chondrichthyes) species; for Orders Carnivora and Artiodactyla we grouped species according to family; and we grouped some avian orders together (for example, four orders were grouped together under 'birds of prey'). From our own review of the literature and expert knowledge, we identified infectious, non-infectious, and other problems that can affect the health of wildlife species. These were listed in this disease table with extra lines for expert contributors to add any agents/conditions we may have missed, and to provide comments on these threats as appropriate.

There were two other sections in the table. These were:

→ Ranking: proven/suspected impacts (ranked 5-1, 5 = highest priority).
The intention for this section was to prioritise identified threats to health with an emphasis on their wider impact at a conservation level, on domestic animal health (human livelihoods and economics) or human health, and to also identify potential future or emerging threats.

→ Drivers
The intention of this section was to identify the suspected or confirmed drivers of the identified threats. The drivers in the table were outlined in the above One Health and ecosystem health section (Table 4).

Expert consultation

The core research team identified the most appropriate experts with knowledge of health of each taxonomic group, from their contact networks. ‘Snowball recruitment’ was used to recruit additional experts for some taxa. Experts (aiming for a minimum of two experts per taxonomic group) were contacted and requested to complete the disease table: to add any extra health threats that we may have missed in our own review; to rank them according to their perceived threat level under each of the above categories (see **Error! Reference source not found.**-**Error! Reference source not found.** below); and to identify possible drivers of these threats.

Given the very short time frame for this project, it was difficult to get two experts for every taxonomic group. Although this was not ideal, we ensured that we had one expert per taxon so we could get a broad overview of the threats facing these species groups.

Across our expert's responses, we collated and analysed the results. For the scoring system when there were more than one expert per group, we averaged their scores for each identified threat. Threats with average scores over four were chosen.

For the ranking of threats 5-1, 5 being the highest threat, and 1 being the lowest, these were averaged among experts and the final 5 threats were noted in our results table.

Please note: average scores of a whole number were for groups that only had one expert contributor; average scores to one decimal point had more than one expert per group.

For the drivers, the top 5 drivers for emerging non-infectious and infectious diseases were recorded.

3.3 Results

Issues with collecting responses

Given the very short time frame we had to collect responses from experts, and the complicated nature of the task at hand, there were some problems with our data collection.

Some results were omitted due to incorrect responses. In an ideal situation, with more time, we would have held virtual workshops to go through how to fill in the table to reduce to likelihood of errors. One column named 'Ones to watch' which was supposed to have experts score threats that could be a possible future problem, had numerous incorrect/inaccurate responses so this was omitted from the results table. Table 5 illustrates the results of the drivers gathered with an asterisk for groups which the driver input seemed inconsistent.

3.3.1 Threats to health of migratory species

[*Placeholder: Summary text & figures – top-rated threats, inf & non-inf*]

See preliminary Appendix

3.3.2 Drivers of health problems

[*Placeholder: Summary text*]

Table 5. Drivers of top rated infectious and non-infectious conditions as per expert opinion: summary across:

a. Higher taxonomic groups

TAXONOMIC GROUP	NO. OF GROUPS	MEDIAN PROPORTION OF TOP-RATED THREATS FOR WHICH FACTOR CONSIDERED A DRIVER							
		Agriculture/ aquaculture	Habitat loss, degradation or disturbance	Harvesting or persecution	Invasive species	Pollution	Climate change or severe weather	Other	Undetermined / unknown
INSECTS *(Insecta)*	1	46	38	0	8	0	15	0	46
FISH (*Actinopterygii*)	3	16	7	7	26	40	14	0	9
SHARKS & RAYS (*Chondrichthyes*)	2	44	81	38	6	63	44	13	6
REPTILES *(Reptilia)*	2	53	62	5	0	48	29	5	10
MAMMALS *(Mammalia)*	16	23	53	22	11	25	47	0	0
BIRDS (*Aves*)	13	23	49	4	0	33	23	3	0
OVERALL MEDIAN	37	**34**	**51**	**6**	**7**	**37**	**26**	**1**	**8**

b. Lower taxonomic groups (as grouped for the purpose of this exercise)

Taxonomic group	No. of experts	Total no. top-rated threats[a]	Percentage (%) of threats where factor listed as a driver							
			Agriculture/ aquaculture	Other habitat loss, degradation or disturbance	Harvesting or persecution	Invasive species	Pollution	Climate change or severe weather	Other	Undetermined/ unknown
INSECTS										
Monarch butterfly	1	**13**	46	38	0	8	0	15	0	46
FISH										
Sturgeons*	4	**7**	14	14	14	43	71	29	0	0
Eels*	2	**11**	18	0	0	9	9	0	0	18
Median %			**16**	**7**	**7**	**26**	**40**	**14**	**0**	**9**
Median range min			14	0	0	9	9	0	0	0
Median range max			18	14	14	43	71	29	0	18
SHARKS & RAYS										
Rays	2	**8**	38	75	38	0	75	38	0	13
Sharks	2	**8**	50	88	38	13	50	50	25	0
Median %			**44**	**81**	**38**	**6**	**63**	**44**	**13**	**6**
Median range min			38	75	38	0	50	38	0	0
Median range max			50	88	38	13	75	50	25	13
REPTILES										
Crocodiles	2	**11**	45	64	0	0	36	18	0	9
Turtles	3	**10**	60	60	10	0	60	40	10	10
Median %			**53**	**62**	**5**	**0**	**48**	**29**	**5**	**10**
Median range min			45	60	0	0	36	18	0	9
Median range max			60	64	10	0	60	40	10	10
MAMMALS										
Felids	3	**12**	75	83	50	67	25	50	0	0
Seals & Sea-lions	2	**17**	18	53	12	0	24	29	0	0
Canids	3	**8**	88	63	75	50	38	63	0	0
Bears	1	**6**	0	0	0	0	33	83	0	0
Bovids*	2	**19**	58	53	21	26	26	42	0	0
Camels*	2	**15**	27	80	80	87	7	73	0	0
Deer*	1	**26**	0	0	0	19	0	0	0	0
Giraffe*	2	**13**	77	69	23	15	69	77	0	0
Equids	2	**15**	13	33	27	0	0	47	33	0
Elephants	2	**10**	90	60	40	20	70	80	0	0
Megabats	3	**8**	13	50	50	0	13	50	13	0
Microbats	3	**9**	11	33	22	11	22	33	11	0
Primates	3	**54**	13	13	15	9	0	15	0	0
Cetaceans	4	**13**	23	38	15	8	31	38	15	0
Dugongs & manatees	4	**10**	40	80	0	0	50	40	40	0
Median %			**23**	**53**	**22**	**11**	**25**	**47**	**0**	**0**
Median range min			0	0	0	0	0	0	0	0
Median range max			90	83	80	87	70	83	40	0
BIRDS										
Birds of Prey	2	**13**	54	62	23	15	46	23	15	0
Passerines, turtle dove, roller & bee-eater	1	**13**	23	23	0	0	0	23	8	0
Waterfowl & grebes	1	**17**	24	24	0	0	24	24	6	6
Waders/shorebirds, gulls	1	**11**	45	73	18	0	36	36	0	0
Seabirds	1	**14**	14	57	7	7	43	21	7	0
Flamingoes	1	**5**	0	40	0	0	40	60	0	0
Herons, storks, egrets & allies	1	**5**	100	60	0	0	60	100	0	0
Crakes & Cranes (gruiformes)	1	**9**	22	33	11	0	33	0	11	11
Penguins	3	**15**	33	20	13	0	20	33	33	0
Psittaciformes*	1	**2**	0	100	0	0	0	0	0	0
Bustards	1	**6**	50	67	17	0	33	0	0	0
Quail*	1	**27**	7	7	0	0	0	4	0	0
Median %			**23**	**49**	**4**	**0**	**33**	**23**	**3**	**0**
Median range min			0	7	0	0	0	0	0	0
Median range max			100	100	23	15	60	100	33	11

Footnotes:

Colour formatting percentage range	<25%	25-49.9%	50-74.9%	>75%

*driver input may have been inconsistent, either our instructions were not clear enough or they were misinterpreted

[a] Total number of top-rated threats for infectious and non-infectious threats only (other problems have been excluded)

NB: Unable to source experts in time for the following groups: catfish, otters, pelecaniformes. These have been excluded from the analysis.

3.4 Case studies

[*Placeholder: We will use information gathered from the experts consulted for this review to present case studies in the final report, illustrating how human activities are negatively impacting the health of CMS-listed wildlife species, and how this is driving disease problems.*

1 x Insecta: Monarch butterfly and OE

1 x fish: sturgeon/eel?

1 x sea turtle

1 x mammal (or do we have more than one as group so big?) wild dog snaring??]

Case Study: Avian Influenza Virus

Highly pathogenic avian influenza in wild birds: global One Health consequences

The case of highly pathogenic avian influenza (HPAI) in wild birds provides an example of the global One Health consequences of allowing spillover of infectious agents from domestic settings.

Waterbirds are reservoirs of low pathogenicity avian influenza viruses, which cause relatively minimal consequences for wild bird health. Mutations of such viruses when in dense poultry settings can allow emergence of highly pathogenic avian influenza (HPAI) viruses, which can cause high losses to livestock. The emergence of just such a virus in domestic geese in China in 1996, goose/Guangdong/96 (Gs/Gd) H5N1 HPAI virus, would eventually lead to devastating losses to poultry on a global scale, impacts to livelihoods and food security over five continents, population declines for wild bird species and human deaths with further pandemic potential.

Despite a perception of control of the original Gs/Gd H5N1 virus, it re-emerged in 2003 and then, likely assisted by the practice of wild bird farming, spilled spectacularly to wild birds in the spring of 2005 at a breeding site at Lake Qinghai in China. Some 10% of the world population of bar-head geese *Anser indicus* along with 1,000s of other individuals of other species were killed. The genie was in effect out of the bottle.

The following years saw sporadic wild bird outbreaks, some serious, some involving losses of smaller numbers of wild birds. With a perception of migratory wild birds as vectors of disease, ill-advised responses to HPAI including killing of wild birds, destroying habitats, and draining wetlands along with public fear and paranoia. Calls from the international animal health and conservation community (including CMS) helped to redirect responses into more sustainable and better-targeted actions.

With maintenance of virus in poultry flocks, particularly in Asia, and in wet market settings, practices such as grazing of domestic ducks in natural wetlands provided ample opportunity for viral exchange. Spillover and spillback, and re-assortment with other AI viruses and mutation over time has occurred with migratory birds and globally traded poultry and their products allowing international spread.

Until quite recently it would seem that maintenance of the virus in wild birds has been somewhat faltering. A shift in the virus to enable it to be in effect 'fitter' and better adapted to wild birds has happened within the last two to three years allowing far greater migratory spread of infection. At time of writing, the disease has caused significant population impacts to seabirds and other species with spread from the Old World to the New World in what is an on-going dynamic situation with potential for spread into oceanic seabird breeding colonies.

The rapid expansion of the poultry industry in the last few decades has been associated with HPAI epidemics and without reform, it is likely that further viruses will emerge. For now, a true reservoir of HPAI virus in wild birds will continue to seriously affect poultry production worldwide where there are wild/domestic interfaces. On-going significant conservation consequences are still emerging. At time of writing human-to-human transmission of virus is not thought to have occurred in recent years. However, the virus has a propensity to infect mammals as well as birds and mammal-to-mammal transmission is thought to have occurred in an outbreak of the virus in a mink farm setting. The risks of a pathogenic virus, which acquires the mutations to readily infect mammals, is clear.

It is not possible to accurately evaluate the wide-ranging costs to livestock, human health, and wildlife of H5N1 HPAI but what is clear is that prevention of escape of livestock diseases to the wild is both cost effective and the obvious One Health approach.

3.5 Discussion

3.5.1 Main findings

[*Placeholder: Summary text*]

3.5.2 Limitations

[*Placeholder: Summary text*]

4 MIGRATION AN DISEASE DYNAMICS

In this section, we review infectious disease dynamics in relation to migration, and the potential disease consequences of migration, and its disruption, for wildlife conservation as well as the health of domestic animals and people.

4.1 Migration

Introduction: Migration can be considered as the recurrent, usually seasonal, movement of animals to different geographical locations in search of beneficial resources and conditions for certain life stages (Dingle., 2014). For example, it may be undertaken in order to move to better habitats for feeding and/or breeding during certain times of the year, (Dingle., 2014), or to evade predators during breeding or other vulnerable periods. Frequently, however, the fundamental drivers for migratory behaviours are still unclear (Altizer et al., 2011).

Wild animals across taxonomic groups are known to undertake long arduous journeys in their migration, at considerable physiological expense. Not all animal movement is migratory however, with animals moving locally within their home range, sometimes in a daily pattern between feeding and resting sites, sometimes over international borders, travelling individually or in groups. Any movement comes at an energetic cost albeit offset when travel is to acquire food.

4.1.1 Definitions

Migration is typically the recurrent, usually seasonal, movement of animals to different geographical locations in search of beneficial resources and conditions for certain life stages (Dingle, 2014).

The Convention of Migratory Species (CMS) definition of migratory species is:

"…the entire population or any geographically separate part of the population of any species … of wild animals, a significant proportion of whose members cyclically and predictably cross one or more national jurisdictional boundaries" (CMS., 2023).

This definition differs from those in the scientific literature by including some species, or populations of species, that cross jurisdictional boundaries in addition to those that migrate to geographically separated areas. The species listed on the CMS Appendices I and II represent those of particular concern and in need of coordinated international conservation action. Many species are migratory but are not currently listed on the CMS appendices because they are not currently considered at risk, they are data deficient, or a proposal for their addition is awaiting approval by the Conference of the Parties (COP).

There are also taxa which are not considered by CMS, which can cross jurisdictional boundaries such as insects and even amphibians. Arguably these species, which are often hard to monitor and often in poor conservation status are generally not as protected globally as those listed on the CMS appendices.

For example, many insect species (numerous butterflies, moths, dragonflies etc) undertake seasonal migrations with similar benefits as other taxonomic groups (beneficial resources etc, see below). Recent research has identified that numbers of migrations in terrestrial species are highest in insects (4-6 billion for monarch butterfly, *Danaus plexippus*), with biomass comparatively close to wildebeest, *Connochaetes taurinus*, migration (200,000 tonnes for desert locust, *Schistocerca gregaria* versus 280,000 tonnes for wildebeest) (Holland *et al*., 2006).

Considering the focus of this review on wildlife health, diseases of insects remain poorly understood which is of concern given the range of specific pesticide chemicals to which they are exposed. Moreover, the single taxon which has suffered the greatest impacts of disease which has led to population declines and global extinctions is the amphibians. Although they are not considered further within this review (due to their judged non-migratory status) the impact of diseases such as ranavirus and chytridiomycosis of both anurans and uradeles is noted here.

Partial migration

As discussed above, migration definitions can vary. Partial migration is when within a species group, some individuals migrate, while others choose to remain as a ‘resident’ in their home area (Dingle., 1996; Chapman *et al*., 2011a). Technically, if a population has only a small percentage of animals choosing to remain a resident rather than take on the migratory journey, then the population is classed as a ’partial migratory population’. Examples of this are the arctic terns (CASE_EXAMPLE??). This can occur across all taxonomic groups and has been recorded in insects, fish, amphibians, reptiles, mammals, and birds (Chapman *et al*., 2011).

Table 6. Types of partial migration (Chapman *et al*., 2011b)

Type	Description
1. Non-breeding partial migration	Both migrants and residents breed together, but during winter the migrants leave
2. Breeding partial migration	Both migrants and residents stay together over winter but breed separately. This can be a barrier to gene flow.
3. Skipped breeding partial migration	Individual animals migrate to breed, but only some years. It is thought that individuals remain resident when they are not capable of making the migration journey to breed (poor condition, reduced fat stores etc).

Partial migration is important to keep in mind when discussing barriers and disruptions to migration. Changes in environment and climate can influence migratory behaviour in some species, with some choosing to remain resident or altering their normal behaviour which can have unfavourable consequences.

4.1.2 Migratory routes

Global migration routes and timings vary according to individual species and taxonomic groups; however, many routes overlap with each other allowing patterns to emerge. Migration by air and sea is considered in a little more detail in the following sections as illustrations of how infection has the potential to move over large distances.

Flyways

Flyways is the term given to describe the geographical area which encompasses routes migratory birds frequently take annually en masse from their breeding to non-breeding habitats and back. These routes can be a general route, or a more defined and narrower route (see Figure 2). Common migratory patterns include:

→ Breeding in the northern hemisphere (in more temperate, or Arctic climes) during northern summer, then going back south to warmer climates of the temperate regions or tropics for the non-breeding season
→ Some species travel very far to benefit from the temperate southern summer in the southern hemisphere.
→ Some tropical migratory birds pursue the wet season breeding in the north of the Topic of Cancer, before migrating to the neotropics (between Topics of Cancer and Capricorn), during the non-breeding season
→ Southern hemisphere migrants generally have their breeding season in South America, Africa and Australasia, before migrating in the southern winter to the tropics (Kirby *et al*., 2008).

As seen here, there is a lot of variety in routes and there are many overlapping areas or situations for migratory birds to meet. All this can have implications for infectious agent transfer between individuals (discussed later in this chapter). As examples, wildfowl may breed at low densities then converge at staging grounds on migration and spend the non-breeding season in close proximity to one another. Conversely, seabirds may breed at very high density and spend non-breeding seasons in less contact with conspecifics. Moreover, how long distance journeys are undertaken can have an impact on possible transfer of infection. Some species may ‘hop’ between sites, lingering en route, while others ‘skip’ over longer distances, and those which ‘jump’ long distances without many staging sites and reaching final destinations more quickly may in effect bring transfer infection over long distances in a relatively short period of time.

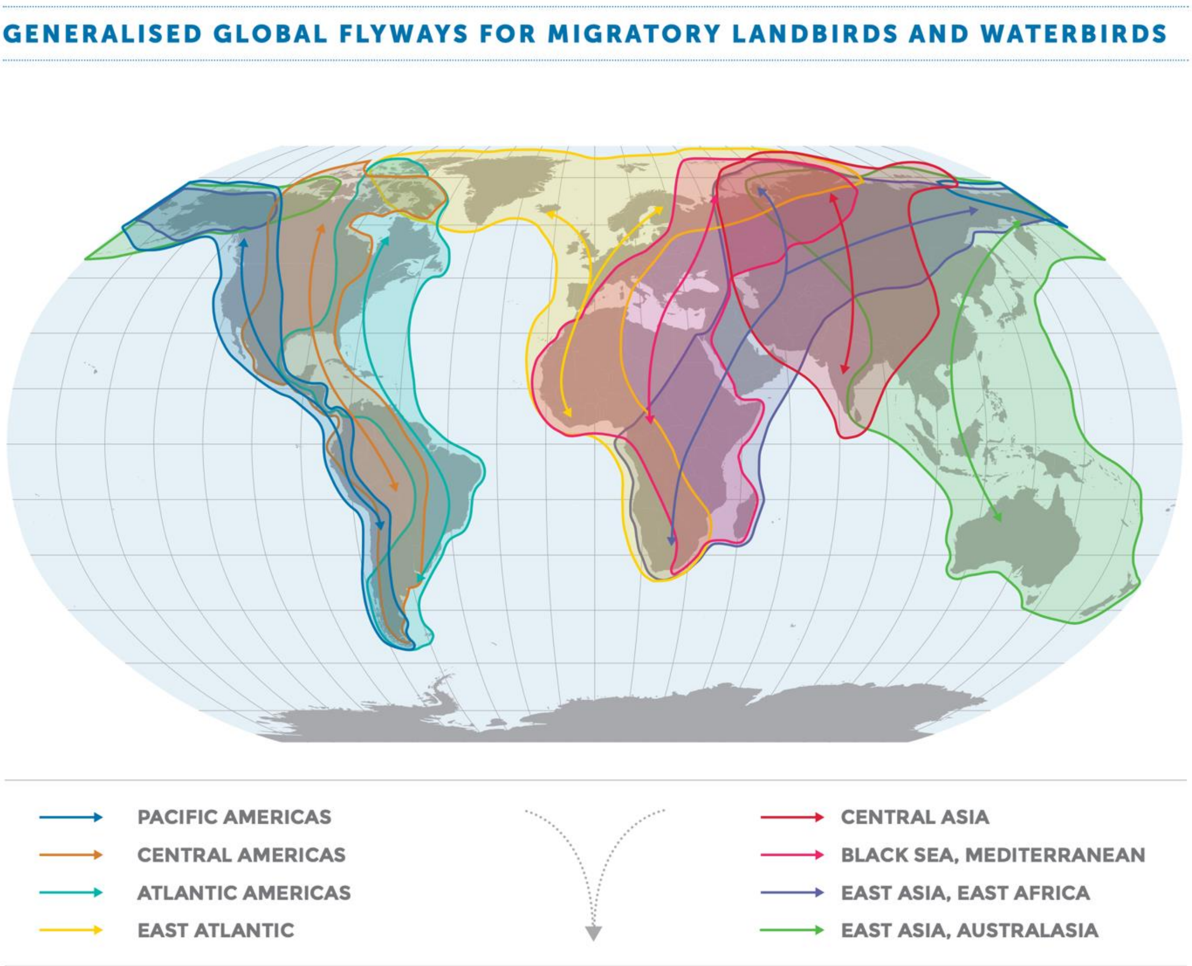

Figure 2. Generalised global flyways for migratory landbirds and waterbirds, taken from Birdlife International (2018).

Marine Highways/Blue corridors

Oceanic migratory pathways are in general less well studied than flyways. While many species from different taxonomic groups use such pathways only small numbers of species have well-researched defined routes. Some migrations are only within a small region, whereas other species travel vast distances across the globe. In 2022, WWF commissioned a report identifying ‘Whale Superhighways’ using satellite tracking data from various whale species (see Figure 3). Although not comprehensive for all species and taxonomic groups, their findings provide an overview of where these routes are.

As an example for other marine taxa Queensland’s Department of Environment and Science (DES) collaborated with CMS to create an interactive ‘TurtleNet’ Atlas, demonstrating turtle migration routes, along with other data. Tools like this can be useful to understand species movements and have the potential to assist in health research as well as being used as an educational tool. In general, the greater understanding we have of these routes for all taxa, the better we can understand the threats facing species during migration to try to mitigate these impacts.

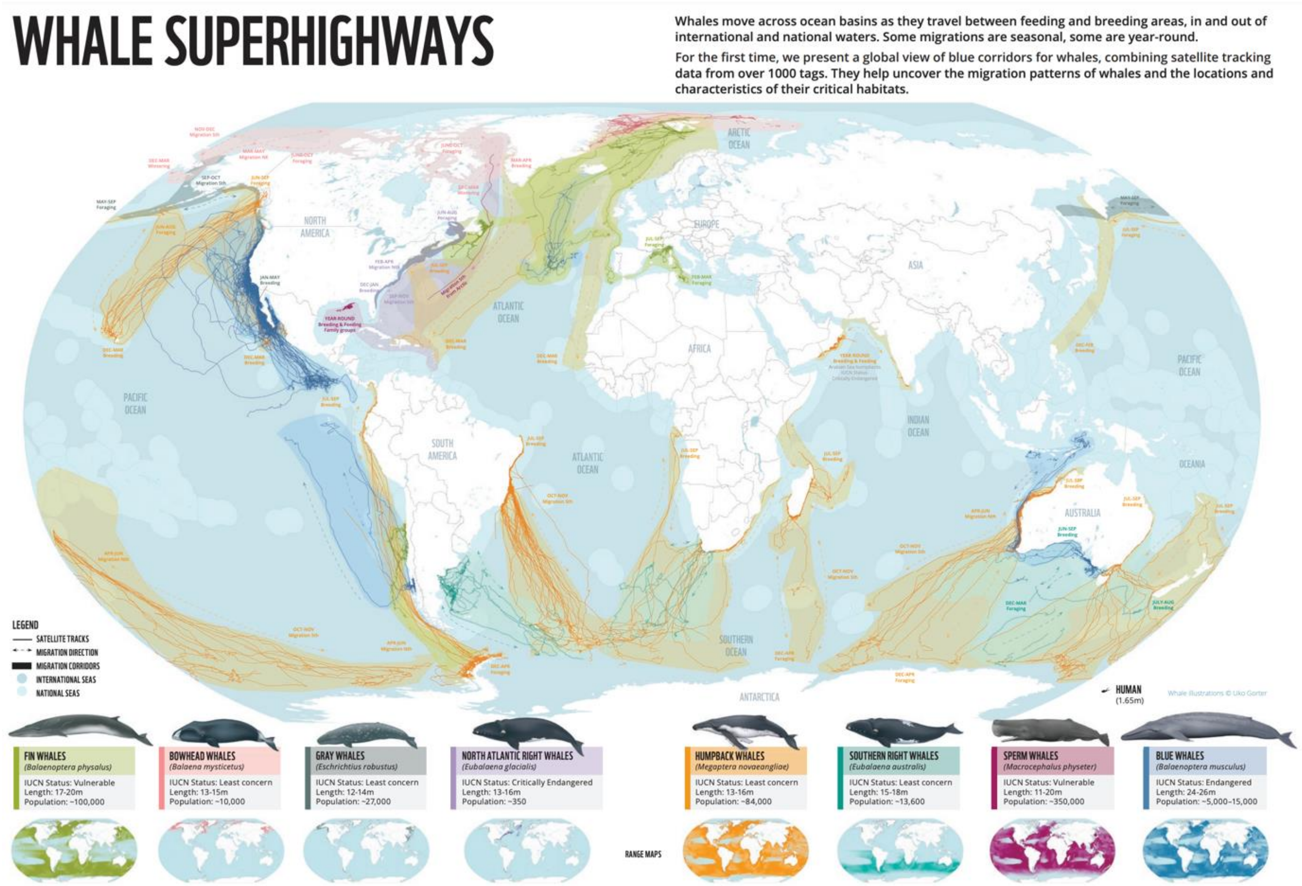

Figure 3. Whale migratory pathways (‘superhighways’) as identified from satellite tracking data. Taken from WWF report ‘Protecting Blue corridors’, Johnson et al., 2022.

Looking at Figure 3 &Figure 4, it is easy to see that many of the whales’ migratory routes overlap with shipping routes, which unfortunately poses great hazards of ship strikes for these large species. Global transport therefore can be a driver for trauma caused by vessel strikes.

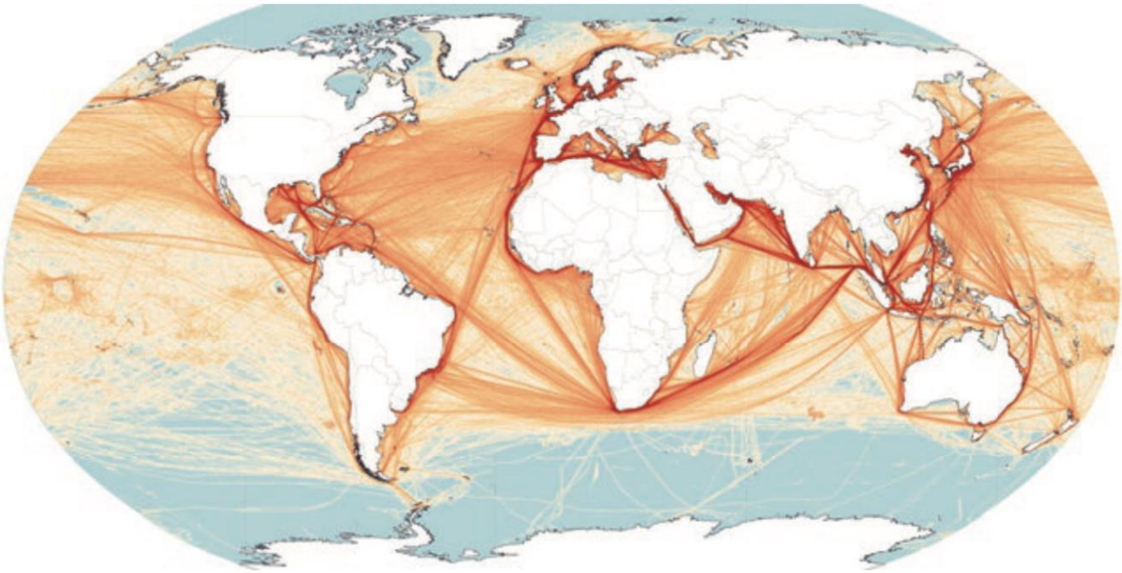

Figure 4. Shipping densities and routes. Taken from WWF report 'Protecting Blue corridors', Johnson et al., 2022.

4.1.3 Physiological impact

Migration, while providing access to resources and/or a means to escape unfavourable conditions, can come at considerable physiological expense. Migration can typically take a great physiological toll on the individual, so to warrant this behaviour its benefits must outweigh the costs. The physiological costs may differ depending on fluctuating environmental conditions along with any stressors the migrants may encounter. Anthropogenic activities (potential stressors) which create greater costs for the individual can shift the balance and result in poorer health outcomes.

Costs of migration to the individual

- High energy expense (Alves *et al*., 2013), this can be minimised by stopping for resource fuelling during the journey (Alerstam *et al*., 2003).
- Requires time: timing is crucial. If an individual takes too long to migrate then they may miss the benefits of improved resources, if they arrive too early then resources may not be available.
- High fuel/ energy (body fat) reserves are required prior to migration. This increases body mass, which can slow migration, and can increase predation risk.
- Loss of the benefits of residency (reduced stress, maintain energy obtained from resources).
- Mortality during migration itself (predation, weakness, infection) (Alerstam *et al*., 2003)
- Stress from migration can reduce the animal's immune response, causing immunosuppression. If an individual is harbouring a dormant infection, this can reactivate it (Hall *et al*., 2022).

- Multiple stopovers for refuelling can increase the likelihood of contact with other migratory species, and novel infectious agents from other host animals or from the environment increasing their exposure to parasites (Hall *et al*., 2022).
- Terrestrial animals' migration can be negatively influenced by the ground quality they are walking on. Weather can affect open areas such as grasslands. Storms and windy weather can impact birds' flight which can result in them being shifted to unknown locations causing disorientation, increases in energy expenditure and/or resulting in them perishing.

Benefits of migration to the individual

- Utilise increased resources from seasonal changes and avoid the potential reduction or variation in resource availability in the residents' range.
- Avoid competition for dwindling resources at resident site
- Beneficial habitat for breeding (increased and improved resources, lower numbers of predators etc.)
- Beneficial habitat with improved resources can improve host health and resilience to infection.
- Moving to environments with lower parasite levels allows individuals to escape high parasite burdens in breeding/wintering sites.
- The time taken to migrate can be reduced by exploiting currents and winds concurrently reducing their energy costs. Animals that swim or fly can benefit from this (Alerstam *et al*., 2003).
- There is some evidence that migratory animals can host less harmful strains of parasites than their resident counterparts (Altizer *et al*., 2011).

Table 7. Summary table comparing individual costs and benefits of migration

Costs of migration	**Benefits of migration**
High energy expenditure	Utilise increased environmental resources
Time	More suitable habitat for breeding/wintering/moulting
High expenditure of body fat reserves	Can increase health and resilience
Mortality	Can escape high parasite burdens
Stress, immunosuppression	Can exploit currents and winds to reduce migration time
Possible increased exposure to parasites	Reduced predation in some situations
Weather and environment influencing migration	Less harmful parasite strains

4.1.4 Ecosystem benefits and services from migration

The narrative that migration is inherently negative is misleading and can impede conservation action. Although migration can bring in infectious agents into new areas, there are many positives for the ecosystem, which if lost could have wider consequences (see below).

Migration can move nutrients into and out of ecosystems, playing a role in nutrient cycling, which can shape ecosystem structure. It can influence food web interactions and can improve ecosystem health. In the marine ecosystem, for example salmonoids, by the act of migration from marine environments to freshwater environments can shift nutrients and carbon upstream (from carcasses, eggs), influencing forest ecosystems.

Disruption of sediment by burrowing or feeding (by many marine creatures, migratory or not) can release nutrients into the water so they can be used elsewhere, rather than in the sediments (Holmlund & Hammer, 1999).

Migratory birds and insectivorous bats can improve overall plant health by feeding on insects that prey on plants and keeping the balance in check. They can also act as food sources for predators, which also act as regulators of healthy populations by removing weak or diseased individuals. Some migratory species act as ‘ecosystem engineers’ meaning that from their behaviours (indirectly or directly) they can alter resource usability within ecosystems. They do this by maintaining, creating, or destroying parts of the environment. This can be greatly beneficial to plant and animal species who concurrently reside in these altered habitats by getting them access to more resources and nutrients (Lopez-Hoffman *et al*., 2017).

4.1.5 Cultural benefits from migration

Migration brings many benefits to our societies such as

→ Crop pests can be eaten by birds and insectivorous bats, removing the need for such reliance on pesticides (which in themselves have negative impacts)
→ Pollination and seed dispersal by migratory insects, birds and bats for many plants, including food plants and crops
→ Migratory species link geographic regions playing a part in nutrient and energy transport between distant ecosystems.
→ Act as food sources for indigenous communities by subsistence hunting, increasing their food supply for storage of winter months.
→ Cultural benefits in the way of ecotourism, birdwatching, recreation, hunting, fishing, spiritual or religious. This can provide personal benefits, improve mental health and wellbeing and as services can bring economic benefits (income, jobs, funding for conservation actions) (Lopez-Hoffman *et al*., 2017).

4.2 Migration and disease

4.2.1 Principles of disease

Infectious disease events reflect a complex interplay between the infectious agent, host animal and their wider environment. Factors to consider with respect to infectious agents include how harmful an agent is, host numbers and the presence of vectors/intermediate hosts. Factors relevant to hosts include species, age, sex, nutritional status, immune status, and genetics. And factors relevant to the environment include habitat quality, competition, pollution, climate, and interference. The balance between health and disease of an individual or population depends on the complex interplay between these three elements (Thrusfield *et al*., 2018).

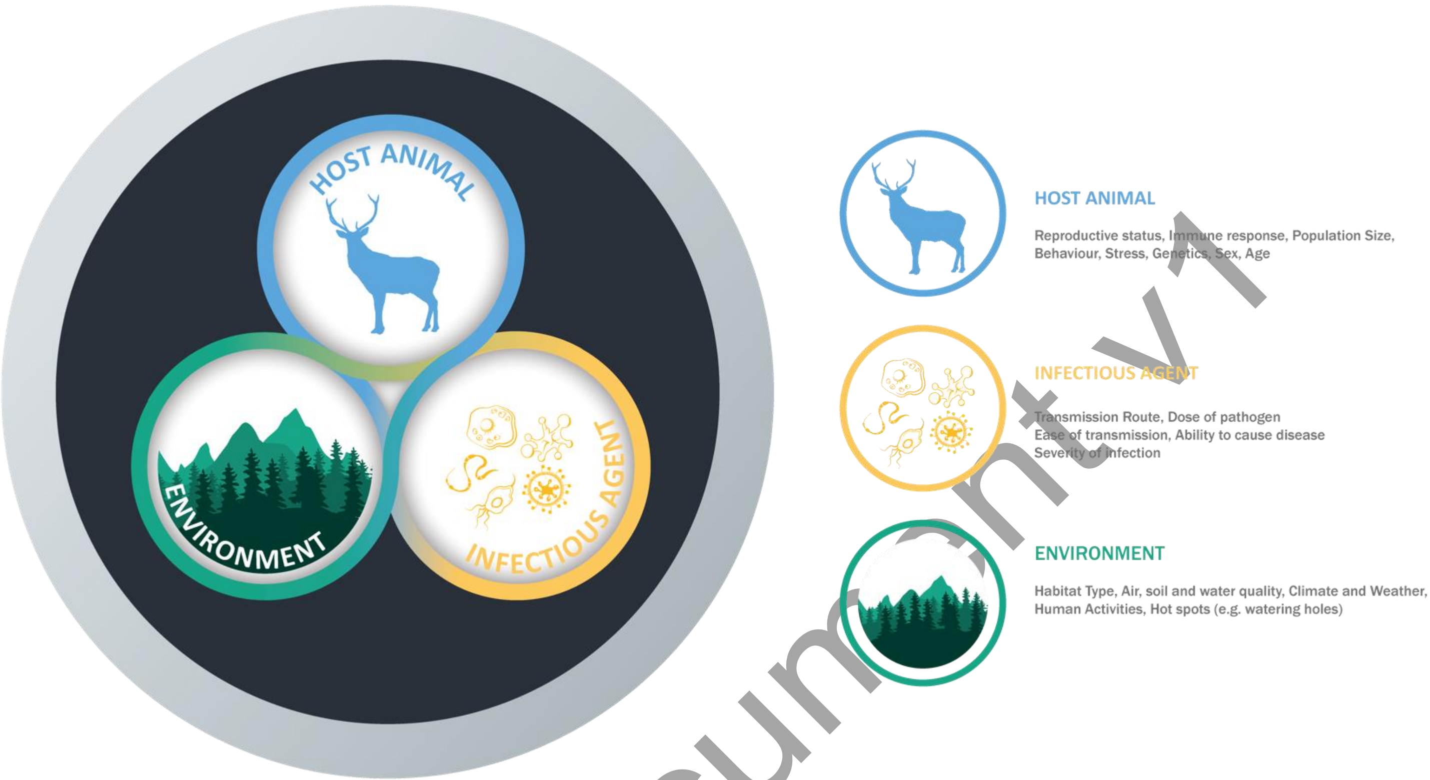

Figure 5. Adaption of the host-pathogen-environment triad with factors that influence each part of the triad (Thrusfield et al., 2018).

As depicted above, a range of factors influence whether, and how severely, disease occurs in an animal population. For example, if the host is immunosuppressed, i.e. the immune system is weakened, including by the stress of preparing for migration, it can increase an animal's vulnerability to disease (Alerstam *et al*., 2003). The type of environment, climate, human activities can influence how successful a pathogen (agent) may be, in infecting single or multiple hosts, and if it can survive outside a host (Thrusfield., 2018). Infectious agents can persist in the environment, and animal populations (wildlife or domestic animals) and act as a source of infection to others (Haydon *et al*., 2002). In this way, we can see how anthropogenic changes, such as habitat degradation or loss, or climate change, which impact animal populations can also considerably influence disease dynamics.

Other factors that need to be considered include what type of disease is present and the potential drivers of this disease. As discussed, many infectious agents can cause infections, but not necessarily harmful disease. These infections can be subclinical in some species, meaning they do not cause harm to the health of the infected host (See 2.1.2), but they could potentially act as maintenance host populations. This is particularly the case where species have co-evolved with infectious agents, and eventually adapt to them. These types of diseases are often referred to as **Indigenous diseases** and are often maintained in wildlife species. In comparison **introduced or exotic diseases** that have likely been introduced from domestic animals or livestock historically, can have severe impacts on wildlife health, who are more naïve to these agents. For example, Canine Distemper Virus (CDV) likely being introduced with domestic dogs, spilling over into lions and wild dogs causing significant infection and mortality (Bengis *et al*., 2002). Emerging diseases are novel diseases which have crossed over into different species and like exotic disease, can have significant impact (e.g. encephalomyocarditis in elephants) (Zachariah *et al*., 2013).

Case Example

Trypanosomiasis has a significant impact to livestock and domestic animals, and to human health. Multiple different mammal species living in tsetse fly habitat have tolerance to *Trypanosoma* infection with little ill-effect, thus are subclinically infected. They act as a significant maintenance population for trypanosomiasis for other domesticated species. However, with increasing encroachment from human activity, closer settlements and increased contact with domesticated animals, the spillover risk (including zoonotic risk) increases. This increasing pressure to wildlife could alter the balance of tolerance to infection in wildlife species. This could allow for more harmful strains to emerge, ultimately also posing a risk to wildlife species who may not have tolerance to new strains (Kasozi *et al*., 2021).

4.2.2 How migration can impact health

Migration can have both positive and negative health consequences for the wider environments that migratory species visit, and knock-on impacts for other species and humans. Migration can improve the health of an individual, by promoting access to better resources, and potentially 'escaping' parasite burdens. Migrants can introduce infectious agents to naïve hosts, potentially playing a role in disease emergence. A frequent assumption is that migrants are responsible for introducing infectious agents to new areas and for spreading diseases in both animals and people. This assumption can compromise conservation efforts for such species. While this can be true, the act of migration can equally serve to decrease infection burden (Table 8) (Altizer *et al*., 2011).

Table 8. Overview of the consequences of migratory behaviour. Key: ✓ = positive ✗ = negative

Migratory behaviour may:	Consequences for wildlife health, or the health of domestic animals or humans
Reduce the proportion of individuals with infection in the migratory population	✓
Increase the proportion of individuals with infection in the migratory population	✗
Increase exposure of migratory animals to novel infectious agents	✗
Increase the diversity of infectious agents in the migratory population	✓ / ✗
Improve health and resilience to infection	✓

Migration can both decrease and increase infectious agent burden within populations. This can involve migrants actively moving away from areas with high infectious agent loads, perishing on route (thus reducing infection within a population), to spreading their infectious agent (or parasites) to new areas. Table 9 describes these strategies in more detail.

[*Placeholder: summary diagram*]

Table 9. Migration and potential resultant impact on infectious agents (Adapted from Hall et al., 2022).

Impact on agent burden (reduces -; increases +)	Definition
Migratory escape (-)	Moving away from habitats with high parasite burden in certain seasons to 'escape' the agents
Migratory culling (-)	The act of migration removes individuals that are infected as they are unable to survive the journey
Migratory recovery (-)	Migrating to habitats with better resources improves individuals health, improving their chance of fighting and removing infection
Migratory avoidance (-)	Individuals 'avoid' certain areas that have high agent burdens on their migratory routes or stopover locations
Migratory allopatry (-)	Behaviour of migrants isolates them from certain vulnerable individuals in the population (e.g. juveniles) to reduce agent exposure to vulnerable hosts
Migratory relapse (+/-)	The intensive energy costs associated with migration can reactivate dormant infections in individuals. This can reduce infectious agents in the population by removing infected individuals (migratory culling) or increase it and transmit infection to others.
Migratory dropout and stalling (+/-)	Infected animals delay migration or take longer to migrate. Or they choose to remain a resident and not migrate. They can die during migration (migratory culling) or can be exposed to more agents during their delay or residency thus increasing infectious agent exposure
Environmental sampling (+)	Encountering different habitats at stopover sites or new sites can expose them to new novel infectious agents, increasing agent burden
Environmental tracking (+)	Animals follow the best environmental conditions (seasonal climates etc), however these environments may also be good for agent survival and transmission (especially if they can survive in the environment)
Host aggregation (+)	Many different animals, and of different species often stop at the same stopover sites, increasing their chance of exposure to other agents
Agent/parasite spread (+)	Animals travelling over distances to new areas can bring their infectious agents with them, introducing them to new areas and new hosts
Immunosuppression (+)	The energy costs to prepare for migration can decrease the immune response which can increase their vulnerability to infection.

With these in mind, the following section discusses how this applies in real life settings, influencing disease dynamics in migratory species.

→ Migration can reduce numbers infected in the migratory population

This reduces the likelihood of infectious disease in migratory animals, safeguarding their health and conservation status and reducing the likelihood of disease transmission to other wildlife, domestic animals, or people.

How?

- Animals may move away from habitats with a high infection burden to 'escape' infection burdens. They can also avoid such habitats on their migratory routes or stopover locations.
- Infected individuals may succumb during migration, thus removing infected individuals from a population. The intensive energy costs associated with migration may also reactivate dormant infections in individuals, exacerbating this effect. This may additionally in effect 'remove' genes for disease susceptibility from the population.
- Migration to habitats with better resources may improve the health of individuals and their resilience to infection.
- Through the act of migration, migrants can separate themselves from vulnerable individuals in the population, such as juveniles, therefore reducing both their own exposure to infectious agents and that of immunologically naïve, vulnerable individuals.
- Infected animals may choose to remain resident and not migrate; they may also delay migration or take longer to migrate.
- Once animals leave for migration, it can allow the environment to 'recover', in effect, decontaminating the environment.

Case example

Avian malaria infections in shorebird populations vary depending on which habitats they utilise during their migratory routes. Populations of shorebirds using the East Atlantic Flyway which travelled to northern and coastal environments had much lower levels of infection in comparison to southern populations using tropical habitats, inland and freshwater environments. This is thought to be due to shorebirds in marine and saltwater habitats 'escaping' the chance of exposure to infected mosquitos, as these habitats do not support the vectors as well as tropical and freshwater habitats (Mendes *et al*., 2005).

→ **Migration may increase exposure to novel infectious agents for both migrants and other animals encountered en route.**

This increases the likelihood of infectious disease in migratory animals, potentially compromising their health and conservation status and increasing the likelihood of disease transmission to other wildlife, domestic animals, or people.

Migration can therefore act as a means of increasing the distribution of a disease, by bringing it to new regions.

How?

- Many individuals can congregate at stopover, breeding, or non-breeding sites, increasing the chances of exposure to infectious agents.
- The intensive energy costs associated with migration can cause stress (immunosuppression), which may reactivate dormant infections in individuals.
- Migrants follow the most favourable environmental conditions; however, these conditions may also be beneficial for infectious agent survival and transmission, especially for those agents that persist long-term in the environment.
- Infectious agents can have varying impacts on different species, different age groups, and differing life stages. For example, older animals often have more resilience/immunity to infection in comparison to juveniles which are more immunologically naive. Pregnant animals can be more immunosuppressed, thus more likely to contract infections than non-pregnant counterparts. Migration can therefore 'introduce' more susceptible individuals into non-migratory populations which can have consequences for disease dynamics.

Case examples

→ Avian influenza viruses (AIVs), which more commonly infect juvenile birds, can be transmitted by migratory birds, to each other and other resident bird populations at their destinations or stop over sites. Habitat loss and degradation from human activities can lead to overcrowding at these sites, and/or closer contact with domestic animals and livestock (and people). For example, where domestic ducks are grazed in natural wetlands increasing the risk of transmission to livestock and subsequently to people (Hall *et al*., 2022).

→ Harp seals (*Pagophilus groenlandicus*) can encounter multiple other species (harbour, hooded and grey seals) during their migration. In 1987-8 a mass mortality event of seals in Europe was caused by an outbreak of phocine distemper virus (PDV). It is thought that harp seals migrated out with their usual range, and with PDV being endemic in harp seals, they acted as a reservoir/maintenance host triggering the outbreaks in seal populations throughout the North Sea (Duignan *et al.,* 2014).

→ **Migration may increase the diversity of infectious agents in the migratory population**

This may have a range of consequences: a higher likelihood of infectious disease or conversely, improved resilience to infectious disease, in the migratory population.

How?

- As above, encounters with different habitats and other species at stopover sites can expose migrants to a wider variety of agents.
- Exposure to new parasites, combined with the stresses (immunosuppression) associated with migration, may increase susceptibility to disease (Poulin and Dutra., 2021).
- Exposure from previous infection from parasites (Hoye *et al*., 2016) and/or increased parasite diversity (Faria *et al*., 2008) can improve resilience to negative impacts of infection (Moller and Erritzoe., 1998).

Case example

Previous exposure (natural infection) to low pathogenicity avian influenza (LPAI) in Bewick's swans (*Cygnus columbianus berwickii*) appeared to improve resilience to negative effects of infection if exposed to LPAI again. In contrast, naïve birds with no antibodies to LPAI demonstrated more negative effects of infection (Hoye *et al*., 2016).

4.2.3 Impacts of infection status on migration

→ Infected animals may choose not to migrate

Infected animals often reduce their movement due to the physiologic costs of infection, either as an immune strategy to cope with infection, or from negative effects of infection on the body. Thus, infection can lead to individuals choosing to remain resident rather than risk migration and potential mortality (Narayanan *et al*., 2020).

→ Infected animals may move away from habitats with a high infection load

The presence of parasites may even act as a force to encourage migration, such as animals migrating to move away from high-parasite areas, especially during vulnerable life stages (migratory escape). Migrating animals leaving a habitat, leaves any remaining parasites (such as ticks and mites) with little or no food to eat so their numbers decline naturally. The habitat that is contaminated with excrement etc has time to rest, and get 'cleaned' by the elements, thus improving habitat quality for when the migrants return. Migrating to different areas may also be a strategy for disease avoidance (migratory avoidance), particularly for internal parasites (worms). Often intermediate hosts are needed in a parasite's life cycle, so if the target hosts migrate to different areas then these parasites will struggle to survive, and warrant longer external parts of the life cycle until an appropriate host comes along (Loehle, 1995). Some individuals also demonstrate avoidance behaviour to move away from other infected individuals i.e., they will not share same dens with infected individuals (Narayanan *et al*., 2020).

Case example

Caribou/reindeer (*Rangifer tarandus*) groups that migrate to different summer sites after breeding, reduce their exposure to damaging warble flies (*Hypoderma tarandi*) in comparison to groups that stay on or nearby their calving sites throughout the summer. Warble fly larvae emergence occurs about the time of calving, thus groups that choose to migrate to distant summer grazing sites likely 'escape' the worst of the larval load. It is thought this is a behavioural migratory adaptation to reduce infection rates post calving (Folstad *et al*., 1991).

4.3 Migratory change

With ecological changes at a global scale, some populations are becoming more resident and choosing not to migrate; others are struggling to acclimatise to the changing climate and environment around them (Bowlin *et al*., 2010). Habitat reduction from human activities can reduce the available habitat for migrants to stop at, increasing the number of species occupying smaller areas. The resultant impacts on migrant species' population dynamics can, in turn, lead to negative consequences can emerge, such as increases in disease prevalence (Altizer et al., 2011).

4.3.1 Disruption to migration

Anthropogenic changes along with climatic changes are having an influence on migratory behaviour; many migratory species are sensitive to changes in land-use. Examples of migratory disruption, and its consequences, are given in Table 10.

Table 10. Consequences of disruption to migration

Migratory Disruption	Sequelae
Delays in migration	Missed resource abundance, increased competition, continuing parasite burden from ‘source site’ (see main text), difficult terrain (e.g. ice melt meaning terrestrial species need to swim)
Migrating earlier	Missed timings, seasonal resources not ready
Remaining resident / skipping migration	Reduced resources, competition, increased parasite burdens (see main text)
Habitat loss or degradation	Overcrowded stopover sites, increasing contact between populations, increased risk of spillover events (see main text)
Altered migration range or routes	Exposure to novel infectious agents in environments or different species; increasing disease distribution (see main text)

→ **Barriers to migration**

Physical barriers (such as fences, wind turbines, roads, buildings, other infrastructure) can disrupt migration in some populations so they either try to cross these migratory barriers or they remain resident and choose not to migrate (Altizer *et al*., 2011).

Physical barriers can disrupt migration in some populations so they either try to cross these reduced migratory corridors or they remain resident and choose not to migrate (Altizer *et al*., 2011). Migratory species are sensitive to changes in land-use from human activities. Fencing that has been erected to section off areas; for livestock grazing; veterinary fences to prevent disease transmission; can significantly impact populations (Kauffman *et al*., 2021). These barriers can lead to reduced access to resources, impeding migratory movement, fragment populations and reduce their connectivity which can all contribute to declines in population numbers of many migratory species. Wind turbines and windows can also act as barriers and are responsible for the deaths of many migratory birds and bats by collision and have been reported globally (O’Shea *et al*., 2016; Cusa *et al*., 2015).

Case example

Fencing in an important migratory area can be catastrophic to mass migratory behaviour. In one year (1983) with reduced rainfall and drought, approximately 50,000 wildebeest died in the Kalahari, largely thought due to their inability to access water due to veterinary cordon fencing (for foot and mouth disease) blocking their path. They had to access water from Lake Xau, which had a significant human presence, and consequently were hunted, prevented from drinking by farmers with their livestock and stressed by getting chased (Williamson *et al*., 1988).

→ Climate change

Climatic changes are predicted to alter habitats including reduction of suitable breeding or non-breeding sites, and stopover sites. This can and is already causing discrepancies in resource and prey availability. Potential consequences include changes in normal migration patterns and timings; alterations in migratory ranges; changes in breeding and mortality rates; delayed migration; populations remaining resident; or increased mortality from migration (Lopez-Hoffman *et al*., 2017). Changing migratory routes and ranges in response to climatic changes can expose migrants to novel parasites and/or transmit their parasites to naïve populations, increasing disease transmission. It is thought that terrestrial migrating populations may deviate their route to one that is at a higher elevation or latitude which could create cross species transmission of infection with novel populations not usually encountered (Harvell *et al*., 2009).

Climate change will also alter the distribution and abundance of disease vectors, many of which are arthropods whose distribution is largely determined by climate. The potential impacts on both migratory species and disease risks together are therefore complex and challenging to predict. For example, increasing temperatures observed in the Zambezi Valley, Zimbabwe seem to have reduced the distribution of tsetse fly populations which could reduce diseases such as Trypanosomiasis in the region. Conversely, in other regions, the environmental conditions could become ideal for certain vectors, increasing likelihood of disease emergence in new areas (Lord *et al*., 2018).

Case examples

→ Saiga antelope (*Saiga tatarica tatarica*) are susceptible to multiple mass mortality events (MMEs). In 2015, climate irregularities of increased humidity and high temperatures are thought to have been a driver to the death of over 20,000 individuals from haemorrhagic septicaemia caused by *Pasteurella multocida* Type B. So far, populations have recovered from these events owing to their specific life history favouring reproduction. Unfortunately, continuing drivers of their population decline, (poaching; reduced migratory corridors from development; increased encroachment from livestock) could diminish populations to a degree that they are unable to bounce back (Kock *et al.*, 2018).

→ Caribou (Rangifer tarandus caribou) prefer ice to migrate over rather than water, rarely choosing to swim. With warming climates and ice melting, they may have to navigate unfrozen lakes and which could increase their mortality rates due to the slower migration and increased energy expenditure (Leblond *et al.*, 2016).

→ Habitat loss or degradation

Habitat loss or degradation from human activities and encroachment can have significant impact on migrants and the interactions between the host, infectious agent, and environment. Changes in land use can cause stress to wildlife inhabitants and the ecosystems they inhabit. This can lead to reduced resources, reduced health in the animal and plant populations in the ecosystems, which in turn can drive increased risks for disease. These activities push wildlife to use smaller, crowded areas, competing for the resources, increasing their contact, and potentially increasing the likelihood of contact with livestock and humans if human activities are encroaching on the same land (Plowright *et al.*, 2021). These changes can drive alterations in migrants routes, stopover locations, duration of migration or can encourage populations to become more resident, choosing not to migrate.

Case example

Avian influenza viruses (AIVs) are frequently associated with migratory birds, with multiple studies demonstrating the role migratory birds play in disease spread. A recent study modelled AIV transmission during different scenarios on Greater white fronted geese (*Anser albifrons*) in the East Asian-Australasian Flyway (EAAF). The EAAF is known to be an AIV outbreak hotspot. This modelling study showed that geese crowding at smaller remaining sites (due to habitat loss) increased transmission and outbreak risk. They also showed that migratory behaviour reduced transmission rates (indicating the possibility of the migratory escape strategy), with higher rates of infection in populations of individuals choosing to remain more resident. Ultimately, these migrating individuals may become infected, but it staggers the outbreaks and could decrease infection burden at overwintering locations. If migration duration and distance is significantly decreased due to habitat loss, then this migratory escape strategy appears to be limited. These results suggest a potential increase in spread of AIVs at flyways with increasing habitat loss. This further illustrates the importance of protecting these habitats (Yin *et al.*, 2022).

4.3.2 Potential disease-related impacts of migratory change

By considering the complex interplay between migratory strategy and infection status, it is possible to see how alterations in migration patterns may have a significant impact on disease dynamics in migratory species (McKay & Hoye, 2016).

→ **Migratory change may increase infection burdens in migratory populations**

Changing migratory routes, ranges or behaviour in response to climatic changes can expose migrants to novel parasites and/or transmit their parasites to naïve populations, increasing disease transmission. Sea ice loss associated with warming in the Arctic could increase disease risk. The reduction or loss predicated to occur in Arctic Canada could allow for increased contact between groups of previously separated species in the east and west. This could allow for exposure to novel infectious agents in species who have little or no immunity (Post *et al*., 2013).

Case examples

Some populations of monarch butterfly (*Danaus plexippus*) are remaining resident and breeding year-round, rather than migrating to Mexico to breed. This is thought to be due to a habitat change, by increased abundance of non-native tropical milkweed in the southern United States acting as a supplementary food source. Migration usually reduces the parasite load of protozoal parasite *Ophryocystis elektroscirrha* (OE) by monarch butterflies escaping the parasite burden in the non-breeding habitat. However, by remaining resident, their OE burdens are up to nine times higher than their migratory counterparts (Satterfield *et al*., 2016).

Sea ice loss in the Arctic may play a role in the emergence of Phocine Distemper Virus (PDV). As discussed previously in another case example, PDV previously has been responsible for the mass mortality of seals. From 2004-2006, PDV was found in northern sea otters (*Enhydra lutris kenyoni*) in the North Pacific Ocean, either from routine screening or from post mortem examinations of unusual numbers of otter deaths. Northern sea otters ranges overlap with seal and sea lions that can act as carriers, suggesting that this PDV infections in otters were the result of a cross-species transmission. The reduction in sea ice could have increased contact rates between Arctic and sub-Arctic marine mammals, with resultant transmission of PDV (VanWormer *et al*., 2019; Goldstein *et a*., 2009).

→ **Migratory change and its associated drivers may act together to increase infection burden and contact with other species**

Habitat loss and degradation is a significant driver of disease emergence and could reduce the size of stopover sites. With increased numbers of animals and species occupying smaller and overcrowded areas, exposure to more and novel infectious agents is highly likely. Climate change can alter vector dynamics, with the warmer temperatures promoting range expansion for vectors. This could lead to a reduced ability for species to avoid/escape them by migration, thus leading to heightened parasite transmission (Hall *et al*., 2016). In a migratory species of conservation concern, this could be significant future risk to them. This could also lead to increased migration range as populations alter their routes to adapt to the changing climates and differing resources. This could potentially bring in novel infectious agents into new locations with naïve resident populations increasing disease transmission and potentially spill-over events (Harvell *et al*., 2009).

Case examples

Driver = Climate change

Changing climates are hypothesised to influence pathogen distribution and emergence. Avian malaria (*Plasmodium relictum*) is transmitted via mosquito vectors and is an important pathogen affecting many migratory bird species. Birds in the Arctic and northern regions have been thought to be protected from transmission of malaria as the climate was not suitable for the vectors. However, with warming temperatures, the region appears to now be able to sustain the life cycle for avian malaria in the Arctic affecting both the residents and migrants. This is of conservation concern as could expose naïve bird populations to avian malaria, potentially with disastrous consequences (Loiseau *et al*., 2012).

Driver = Aquaculture and agriculture

Migratory failure is more likely to occur in eels infected with *Anguillicola crassus*. This invasive nematode was accidentally introduced in the 1980's for aquaculture on the Japanese eel (Currie *et al*., 2020). It is thought to be a significant driver in the population collapse of European eel (*Anguilla Anguilla*). It causes damage to the swim bladder impacting on buoyancy control, decreased swimming ability (due to weight of parasites, weakness from infection and energy costs associated with infection). This results in many infected eels unable to complete their migration for spawning (Palstra *et* al., 2007).

Driver = Habitat loss or degradation

Deforestation appears to be a driver in changes in fruit bat migratory and behavioural patterns. It is thought that this reduction in food resources in Australia is increasing fruit bat reliance on fruit trees and flowering trees that have been planted in urban and suburban areas. This dynamic enhances the likelihood of contact events between people, domestic animals, livestock, and bats and is thought that this is a factor in the Hendra virus outbreaks in Australia (Daszak *et al*., 2006).

→ **Population declines of migratory species can increase the likelihood of disease events**

Emerging infectious diseases are more likely to appear in populations which are stressed by other factors. As above, stressors can include habitat fragmentation, loss, or degradation from human activities, and increasing encroachment from people, domestic animals, and livestock. These 'stressed' populations can have a diminished immune response, poorer genetic diversity (from small populations, inbreeding etc) and are more vulnerable to stochastic events. Declining local populations (such as from population fragmentation) can be significantly impacted by disease, which can lead to local extinction events. On larger scales generally disease does not impact on overall population numbers in this way. However, species that are negatively affected by other threats, such as overexploitation and habitat loss, are more likely to also be threatened by disease (Heard *et al*., 2013). Small, isolated wildlife populations are thus at a greater risk of disease outbreaks due to these stressors on their populations and genetic vulnerabilities, potentially increasing the chances of extinction (Aguirre & Tabor., 2008).

Case example

Population fragmentation (such as from fencing in nature reserves) leads to isolated groups of a species who are unable to connect with each other. The African Wild dog (*Lycaon pictus)* is endangered, and through habitat fragmentation they have increased contact with people and domestic and feral animals. Rabies outbreaks (from transmission from dogs) in these small populations can be catastrophic, and potentially could lead to local extinction events if the mortality rate is high in the group. For example, in 2014-2015 an African wild dog population in Botswana suffered a rabies outbreak, resulting in the mortality of 29 out of 35 individuals in the pack (Canning *et al*., 2019).

→ Loss of benefits from migration

Migratory behaviour, particularly mass migrations in ungulates, provides an array of ecosystem benefits (see 4.1.4). Grazing by large groups of ungulates help to keep grasses/plants growing, by providing nutrients via their excretions, and allowing light in. These groups of animals can also keep other plants in check, and depending on their feeding patterns and preferences, they can improve the diversity of other plant species (Kauffman *et al*., 2020).

The movement of herds and the corresponding mortality of individuals along the way, across vast areas, provides ecosystems with many nutrients as biomass from excretions and from decomposition (especially within African ecosystems, such as rivers, where mass drownings during wildebeest migration occur). They are also important prey species, being a food source for many carnivore and scavenger species, many of which are endangered (Middleton *et al*., 2020; Subalusky *et al*., 2017). Migrants also bring economic and cultural benefits to people by ecotourism, recreation, and food sources (see 4.1.5). For example, migrating bats can benefit famers by preying on crop pests and pollinating plants. This can save money and improve pollution by reducing the need for using pesticides (Lopez-Hoffman *et al*., 2017). If migrating species numbers continue to decline, then this could significantly alter ecosystem function and productivity. It could negatively impact plant diversity, affect cycling of nutrients in soil, alter on fire ecology (important for some ecosystems, renewal) and modify resources available to other species (Kauffman et al., 2020; Middleton et al., 2020).

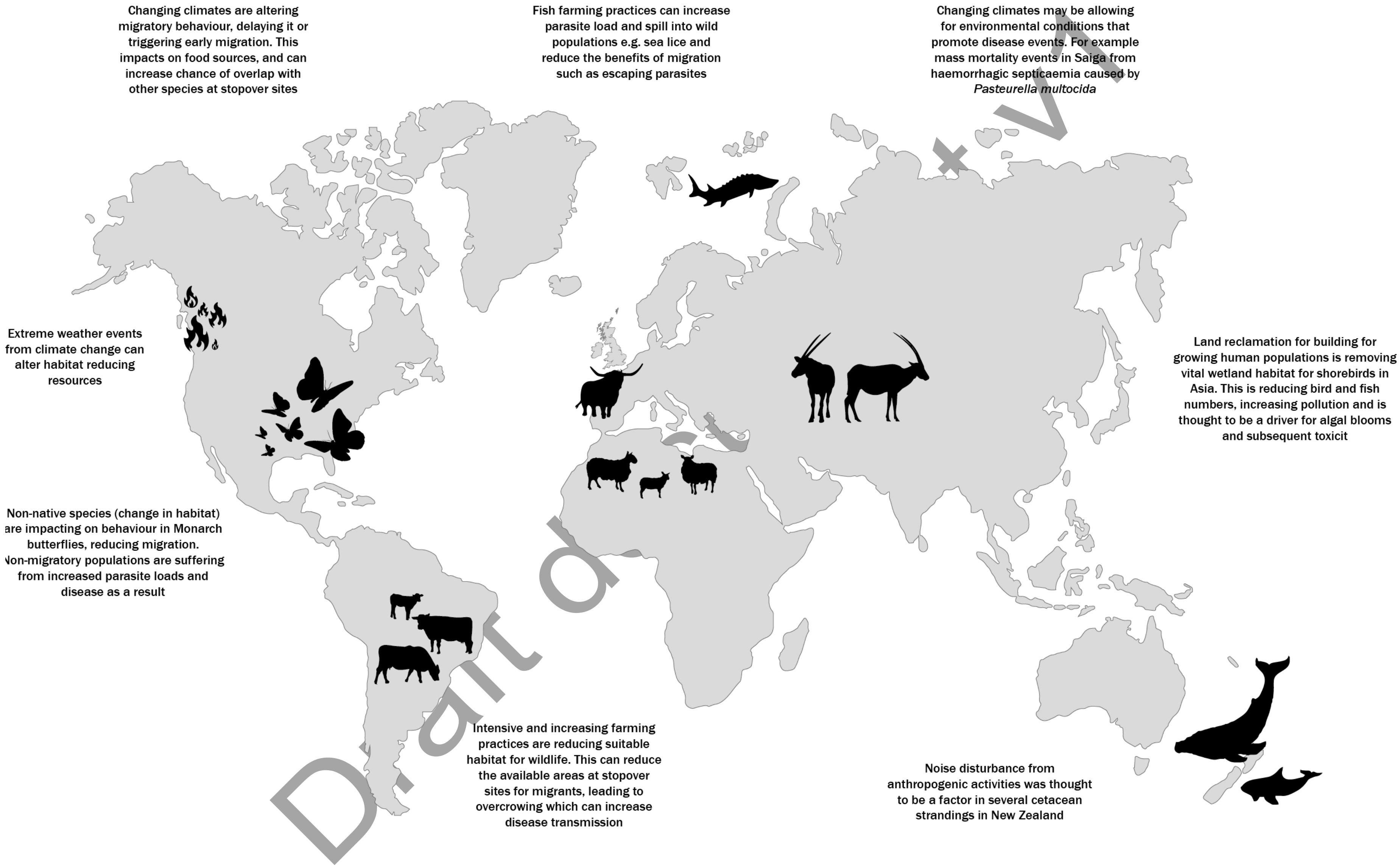

Figure 6. Representation of migratory changes and their impacts globally. [placeholder-draft version]

KEY MESSAGES: On migration and disease

→ The disease dynamics associated with migration are complex, and health outcomes for individuals and populations are situation dependent.

→ Migration itself does not necessarily increase infection burden or introduce new infectious agents, it can reduce infection within a population by removing those not fit enough to migrate, and with them their genes for disease susceptibility.

→ Therefore, migration may serve to safeguard the conservation status of wildlife, and the risk of infection in domestic animals and people, depending on the specific context.

→ Conversely, migration can bring novel infectious agents to new areas and to naïve populations, increasing the likelihood of infection and disease.

→ Meanwhile, increased exposure of migrants to different and diverse infectious agents can increase their resilience to infectious disease.

→ Infectious agents may influence migratory behaviour and migration outcomes.

→ Human activities are profoundly influencing migratory patterns. Changes in migration, along with the drivers of these changes, have the potential to increase infection burdens in migratory populations.

5 KEY MESSAGES AND RECOMMENDATIONS

[*Placeholder: draft version*]

5.1 Key messages

In conclusion, the health of migratory species is dependent on healthy ecosystems, which are an important platform for One Health approaches. The relationships between migration and disease dynamics are highly complex and many factors influence disease emergence. There is growing, global evidence demonstrating the severe impacts of human activity on populations and ecosystems, with many of the same drivers for conservation declines and ecosystem degradation being drivers of disease emergence.

Our understanding of the many diseases affecting migratory species, and how migration influences infection dynamics, is limited. Modelling papers exist but there have been limited real-world case studies. Further research is needed to improve our understanding of how migration, and migratory change, can alter infection and disease status in migratory populations.

5.2 Recommendations

PRELIMINARY RECOMMENDATIONS

→ Healthy resilient ecosystems create the setting for and determine health. Preventative approaches are both cost effective and required to promote health in migratory wildlife, livestock, and people. The role of those involved in biodiversity conservation and sustainable livelihoods should therefore be recognised for, and actively supported in, their contribution to health across all sectors. The role of UNEP in the FAO UNEP WHO WOAH Quadripartite is welcomed.

→ Efforts to address the drivers of population decline such as climate change, habitat loss and degradation, pollution, invasive species, and barriers to migration should be enhanced as these are also drivers of disease emergence across sectors.

→ One Health approaches appreciate the interconnectivity of health between wildlife, livestock, and people, yet can often be anthropocentric – such approaches should be used equitably in decisions about health management appreciating that promoting the health of wildlife reduces risks to humans and our interests, as well as bringing conservation benefits.

→ Rather than seeing animal health as the sole responsibility of agriculture ministries, environment sections of government need to engage and lead on wildlife and ecosystem health.

→ Preventing and responding to wildlife diseases requires good cross-sectoral working. Governments, their agencies, and all those managing wildlife are encouraged to contingency plan in peacetime involving all relevant stakeholders to both prevent wildlife health problems occurring but also to respond appropriately in emergency situations. This will minimise the adverse impacts of disease outbreaks and inappropriate control measures.

→ Livestock-wildlife interfaces caused by, for example, agricultural development and encroachment into wild areas, are particularly problematic for disease spillover and spillback. Every effort should be made to manage livestock to reduce these risks for the benefit of all. This might include improved biosecurity, better planning or significant changes and reassessment of livestock management particularly in medium and high-income countries where choices can be made about protein sources.

→ The health of migratory populations will be protected and fostered by strengthening 'wildlife health systems' comprising the expertise and resources to enable effective and prompt disease surveillance, diagnosis and management. Building this capacity is relatively inexpensive compared to the potential costs associated with reactive management of disease outbreaks.

→ Robust wildlife health surveillance, with conservation (rather than livestock protection) as its goal, is required to support robust planning and risk assessment, and surveillance can be integrated with ecological and population monitoring. Improvements in wildlife diagnostics, testing facilities and reporting systems, along with appropriate capacity building, are needed worldwide. Regulations for transporting specimens from threatened species across national boundaries are delaying outbreak responses and this also needs addressing.

→ There are significant knowledge gaps surrounding the epidemiology and drivers of many diseases of migratory species which prevent good health management. Research and resourcing should be targeted at priority health threats to migratory species, particularly those of poor conservation status.

6 Glossary

[*Placeholder: Link also at beginning of document*]

Host / animal / individual =	An individual animal of interest (see target host)
Infectious agent or parasite =	This can be a microparasite such as viruses, bacteria, protozoa, fungi, yeast, prions, or macroparasites such as helminths (parasitic worms), and parasitic arthropods (e.g. lice, ticks, fleas etc) that are capable of causing an infection in a host
Burden / likelihood of infection =	the proportion of a population (animal, human) who have a particular health condition or disease at a specific point in time
Populations or (species) =	Groups of individuals of the same species living in the same area
Infection =	The presence in an individual of an agent that can cause disease. An individual can be 'infected' with an agent, but may or may not suffer from disease as a consequence of the infection
Infectious (agent) =	An agent (e.g. virus, bacteria, protozoa, worms, fungi, yeast etc.) which can cause infection in an individual
Disease (clinical) =	Impairment of normal functions due to the presence of an infectious agent or other impairment
Contagious =	An agent which can cause infection and can also be transmitted from contact with an infected individual, their bodily fluids or contaminated environments/surfaces.
Communicable disease =	A term used in human health describing a contagious disease (see above)
Subclinical or 'silent' infections =	An infection by an agent causing little or no outward symptoms of disease in the individual. There may be little to no observable negative impact on the individual
Non-infectious disease =	Health impairments that are not infectious. This includes genetic diseases; disease resulting from physical extremes (heat, cold); trauma, degenerative (e.g. age-related) diseases; nutritional diseases or deficiencies; and diseases due to chemicals (human-related or natural toxins), heavy metals or other toxic substances
Zoonosis (or zoonotic disease) =	Diseases than can be transmitted between animals and humans
Endemic =	The continual and 'normal' presence of infectious agent, and or disease levels within a population and/or area

Spillover =	Agent 'spills over' into a target host, usually crossing a species barrier, causing a transient, non-self-sustaining infection within the target host population.
Target host/population =	The host or population of interest
Maintenance host population =	The agent/pathogen remains and circulates within the population despite the lack of transmission from other hosts
Maintenance host community =	Multiple connecting populations (or environments) where the agent/pathogen is perpetually sustained.
Reservoir host/population =	As maintenance host community where agent persistence is permanent. These can be hosts which have a high probability of agent transmission to within species and between other species.
Bridge host =	A host that can transmit an agent to others, but is not a maintenance host i.e. it is unable to maintain the agent/pathogen. They are the connecting link between the target host and the maintenance hosts.
Amplifier host =	A host which rapidly increases the amount of infectious agent in the population, usually due to changes in population dynamics (e.g. and can act as a source of infection to others over a short period and amplify the numbers infected).
Migratory escape =	Moving away from habitats with high parasite burden in certain seasons to 'escape' the agents
Migratory culling =	The act of migration removes individuals that are infected as they are unable to survive the journey
Migratory recovery =	Migrating to habitats with better resources improves individuals health, improving their chance of fighting and removing infection
Migratory avoidance =	Individuals 'avoid' certain areas that have high agent burdens on their migratory routes or stopover locations
Migratory allopatry =	Behaviour of migrants isolates them from certain vulnerable individuals in the population (e.g. juveniles) to reduce agent exposure to vulnerable hosts
Migratory relapse =	The intensive energy costs associated with migration can reactivate dormant infections in individuals. This can reduce infectious agents in the population by removing infected individuals (migratory culling) or increase it and transmit infection to others.
Migratory dropout and stalling =	Infected animals delay migration or take longer to migrate. Or they choose to remain a resident and not migrate. They can die during migration (migratory culling) or can be exposed to more agents during their delay or residency thus increasing infectious agent exposure

Environmental sampling =	Encountering different habitats at stopover sites or new sites can expose them to new novel infectious agents, increasing agent burden
Environmental tracking =	Animals follow the best environmental conditions (seasonal climates etc), however these environments may also be good for agent survival and transmission (especially if they can survive in the environment)
Host aggregation =	Many different animals, and of different species often stop at the same stopover sites, increasing their chance of exposure to other agents
Agent/parasite spread =	Animals travelling over distances to new areas can bring their infectious agents with them, introducing them to new areas and new hosts
Immunosuppression =	The energy costs to prepare for migration can decrease the immune response which can increase their vulnerability to infection.

7 References

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8 Appendices

[*Placeholder: CMS species & taxonomic groupings; expert instructions, more detailed table?*]

Taxonomic details as per CMS listing		Proximate threat to health		Ranking - proven/suspected impacts (1-5, 5=highest priority)					Drivers*							
Class, Order	No. of species represented (see Species List for details)	Potential threat	Category	Negative impact on biodiversity conservation*	Risk of epidemic in people*	Negative impact on human livelihoods or economics*	Top 5 Threats*	One to watch: a possible future threat*	Agriculture or aquaculture	Other habitat loss, degradation or disturbance	Harvesting or persecution (overexploitation)	Invasive species	Pollution	Climate change or severe weather	Other*	Undetermined / unknown
4. Order Charadriiformes (waders/shorebirds, gulls)		**Infectious**	**Category***													
		Avian influenza viruses - particularly highly pathogenic strains	Virus	5	5	5	5	Medium	☑	☑	☐	☐	☐	☐	☐	☐
		Avian paramyxoviruses (APMVs) including Newcastle Disease virus (APMV-1)	Virus			3		Unlikely	☑	☑	☐	☐	☐	☐	☐	☐
		Infectious bursal disease virus	Virus					Unlikely	☐	☐	☐	☐	☐	☐	☐	☐
		Avian poxvirus	Virus					Unlikely	☐	☐	☐	☐	☐	☐	☐	☐
		~~Puffinosis (viral disease, unknown cause)~~						Unlikely	☐	☐	☐	☐	☐	☐	☐	☐
		Salmonella sp	Bacterium			4		Unlikely	☑	☑	☐	☐	☐	☐	☐	☐
		Erysipelothrix spp	Bacterium					Unlikely	☐	☐	☐	☐	☐	☐	☐	☐
		Camplyobacter spp	Bacterium					Unlikely	☐	☐	☐	☐	☐	☐	☐	☐
		Chlamydia sp	Bacterium					Unlikely	☐	☐	☐	☐	☐	☐	☐	☐
		Yersinia sp	Bacterium					Unlikely	☐	☐	☐	☐	☐	☐	☐	☐
		Mycoplasma sp	Bacterium					Unlikely	☐	☐	☐	☐	☐	☐	☐	☐
		Mycobacterium avium complex	Bacterium					Unlikely	☐	☐	☐	☐	☐	☐	☐	☐
		Klebsiella pneumoniae	Bacterium					Unlikely	☐	☐	☐	☐	☐	☐	☐	☐
		Aspergillosus (A.fumigatus)	Fungus or Yeast					Unlikely	☐	☐	☐	☐	☐	☐	☐	☐
		Eimeria spp (~~renal~~ coccidiosis)	Protozoa					Unlikely	☐	☐	☐	☐	☐	☐	☐	☐
		Cestodes, trematodes & acanthocephalans - various spp	Helminth					Unlikely	☐	☐	☐	☐	☐	☐	☐	☐
		Nematodes - various including Capillaria spp	Helminth					Unlikely	☐	☐	☐	☐	☐	☐	☐	☐
		Trematodes (Cyclocoelum spp)	Helminth					Unlikely	☐	☐	☐	☐	☐	☐	☐	☐
		Ectoparasites including lice, mites & others	Arthropod ectoparasite					Unlikely	☐	☐	☐	☐	☐	☐	☐	☐
		Coronavirus	Virus		4			Low	☐	☑	☐	☐	☐	☐	☐	☐
	98	Circovirus, reovirus & various other viruses	Virus					Medium	☐	☑	☐	☐	☐	☐	☐	☐
		Pasteurella multocida (avian cholera)	Bacterium						☐	☐	☐	☐	☐	☐	☐	☐
		Avian malaria (Haemoproteus sp, Plasmodium sp)	Protozoa					Low	☐	☑	☐	☐	☐	☑	☐	☐
									☐	☐	☐	☐	☐	☐	☐	☐
		Non-infectious	**Category***													
		Chemical pollutants: pesticides, heavy metals, industrial chemicals, petroleum products (oil spills)	Toxin, pollution or eutrophication					Medium	☑	☑	☐	☐	☑	☐	☐	☐
		Eutrophication and changes in water quality	Toxin, pollution or eutrophication	3			3	Medium	☑	☑	☐	☐	☑	☑	☐	☐
		Road traffic or fence collisions, entanglements	Incidental anthropogenic trauma						☐	☐	☐	☐	☐	☐	☐	☐
		FB ingestion	Foreign body ingestion						☐	☐	☐	☐	☐	☐	☐	☐
		Bycatch (incidental offtake)	Incidental anthropogenic trauma	5			5		☐	☐	☑	☐	☐	☐	☐	☐
		Algal blooms - reducing quality of feeding areas and potential for direct toxicity	Toxin, pollution or eutrophication	3			3	Medium	☑	☑	☐	☐	☑	☑	☐	☐
		Avian botulism	Toxin, pollution or eutrophication	1			1	Low	☐	☑	☐	☐	☐	☑	☐	☐
		Nest disturbance	Anthropogenic stress or disturbance						☐	☐	☐	☐	☐	☐	☐	☐
		Microplastic or nanosilver pollution	Toxin, pollution or eutrophication					Medium	☐	☐	☐	☐	☑	☐	☐	☐
		Other problems*	**Category***													
		Habitat loss due to agricultural intensification and development - at wintering, breeding & stopover sites	Environmental conditions													
		Habitat degradation due to agricultural practices, wetland drainage and other developments - at wintering, breeding & stopover sites	Environmental conditions													

Screenshot of the table provided to expert contributors to fill in. This image demonstrates the ranking system and the drivers completed for Order Charadriiformes (waders, shorebirds, and gulls).

[*Placeholder: expert expertise – species & regions; inventory of expert-provided references; table below is draft*.]

Taxon	No. CMS-listed species*	No. of experts	Prominent threats (descending order)			Relative importance			One to watch?	Relevant CMS instrument	Details	Other expert comments	Key references
			Infectious/ non-infectious/ other problems	Category	Agent/condition	Median score across taxonomic groups							
						Conservation	People	Livelihoods		Y/N	MoU / agreement		
INSECTS													
Monarch butterfly	1	1	Non-infectious	Toxin, pollution or eutrophication	Pesticides (glyphosphate)	5	5	3	4	[TO BE ADDED]			[TO BE ADDED]
			Non-infectious	Other threat to health	Arthropod predators (e.g., Formicidae ants, Polistes wasps, spiders, mantids, and a diverse group of other insect predators)	5		2	4			Ants (especially invasive fire ants) are probably the most abundant monarch predator. There are a large diversity of natural enermies to monarchs (insect predators).	
			Infectious	Virus	Baculoviruses (aka nucleopolyhedrosis viruses) NPVs	4		2				Somewhat understood in monarchs	
			Infectious	Parasitoid	Natural parasitoid flies (Tachinids or other)	4		1				Moderately well studied in monarchs	
			Non-infectious	Toxin, pollution or eutrophication	Neonicotinoids (clothianidin, imidacloprid)	3	4	3	4				
			Infectious	Bacterium	Wolbachia spp	3		2				Not well studied in monarchs	
			Infectious	Parasitoid	Natural parasitoid wasps (including Brachonids, Chalcids, Trichogammids, etc.)	3		1				Minimally studied in monarchs	
			Infectious	Protozoa	Ophryocystis elektroscirrha (OE)	3			3			Very well studied in monarchs	
			Infectious	Bacterium	Pseudomonas sp	2		2				Not well studied in monarchs	
			Infectious	Fungus or Yeast	Beauvaria bassian	2		3				Not well studied in monarchs	
			Infectious	Fungus or Yeast	Cordyceps	2		3				Not well studied in monarchs	
			Infectious	Fungus or Yeast	Microsporidium	2		3				Not well studied in monarchs	
			Non-infectious	Incidental anthropogenic trauma	Vehicle collision	1	2						
			Other problems	Ecological problems	Arthropod predators, including invasives (e.g., Formicidae ants, invasive fire ants, Polistes wasps, spiders, mantids, and a diverse group of other insect predators)	5		4					
			Other problems	Ecological problems	Reduced nectar sources to fuel adult migration	5		3					
			Other problems	Ecological problems	Milkweed reduction from both agriculture (herbicide use) and climate change	5		1					
			Other problems	Climatic conditions	Drought	3		4					
			Other problems	Environmental conditions	Reduction in suitable habitat for overwintering. Agricultural crops reducing suitable habitat for important species (Abies religiosa (Oyamel, sacred fir))	3		1					
			Other problems	Climatic conditions	Fires	2		4					
			Other problems	Ecological problems	Competition due to reduced space			4					
FISH													
Sturgeons	21	1 (4*)	Non-infectious	Toxin, pollution or eutrophication	Prymnesium (haptophyte algae)	5	1	2	5				
			Non-infectious	Incidental anthropogenic trauma	Bycatch, entanglement	4	0	3				Sturgeons are bycatched by poachers fishing e.g. silurus	
			Infectious	Helminth	Nitzschia stuionis	3	0	4					
			Non-infectious	Toxin, pollution or eutrophication	Eutrophication from chemial run offs (pesticides, nitrates, nitrites)	3	3	2					
			Non-infectious	Toxin, pollution or eutrophication	Heavy metals	3	2	3					
			Non-infectious	Toxin, pollution or eutrophication	Persistant organic pollutants (POPs), Polychlorinated biphenyls (PCBs)	3	2	3					
			Non-infectious	Foreign body ingestion	Foreign body ingestions, plasticosis	1	1	3				Sturgeons are bycatched by poachers fishing e.g. silurus	
			Other problems	Environmental conditions	Damming- habitat loss	5	2	2					
			Other problems	Persecution	Poaching	5	0	3					
			Other problems	Environmental conditions	Navigation construction - habitat loss	4	2	3					
			Other problems	Environmental conditions	Dredging - habitat loss	3	0	0					
			Other problems	Climatic conditions	Temperature fluctuations	3	2	3					
			Other problems	Ecological problems	Invasive species	3	1	1				Globally neg impact on biodiversity 3, but in other rivers higher to 5	
			Other problems	Climatic conditions	Climate change affecting nutrition, altering food sources	2	3	4					
			Other problems	Persecution	Overfishing affecting prey stocks	2	0	3					

Eels	1	2	Non-infectious	Incidental anthropogenic trauma	Water power and sluices : grinding eels	4	0	3	4				
			Infectious	Helminth	Anguillicola crassus	3.5	0	3	4			invasive, thought to have contributed to population collapse in areas in Europe; Potentially emerging	
			Infectious	Protozoa	Trypanosoma spp.	3	0	3					
			Non-infectious	Toxin, pollution or eutrophication	Contaminants	3	0	3					
			Non-infectious	Toxin, pollution or eutrophication	Intoxication during spawning travel to Sargasso Sea	3	0	3					
			Non-infectious	Toxin, pollution or eutrophication	Pollution	3	0	3					
			Non-infectious	Toxin, pollution or eutrophication	Toxin (Prymnesium parvum intoxication)	3	0	3					
			Infectious	Virus	Alloherpesvirus Anguillid herpesvirus 1 (AngHV1)	2.5	0	2.5	3			Potentially emerging	
			Infectious	Virus	Rhabdovirus Eel virus European X (EVEX)	2.5	0	2.5				currently eel viruses are more of a ranching/eel farm/aquaculture issue but assocviated with occassional wild outbreaks following stocking of infected farmed juveniles.	
			Infectious	Bacterium	Pseudomonas (P. anguilliseptica)	1.5	0	2	2			associated with stressed eels, obstructed during migration	
			Non-infectious	Incidental anthropogenic trauma	Bycatch	1.5	0	1.5					
			Other problems	Persecution	Overfishing	5	0	4.5	5				
			Other problems	Climatic conditions	Climate extremes	5	0	4	5				
			Other problems	Environmental conditions	Habitat loss	5	0	4					
			Other problems	Environmental conditions	Barriers to migration	5	0	4					
SHARKS & RAYS													
Rays	21	2	Non-infectious	Incidental anthropogenic trauma	Bycatch, entanglement	4			3			All species at rish, sawfish paritcularly an issues in waters around Bangladesh, SL, as with guitarfish. Trawler lines are a probolem and many coastal rays get trapped also.	
			Non-infectious	Incidental anthropogenic trauma	Ship strike	3			2			Ship strike trauma likely only recorded in non-lethal strieks, lehtal strikes the animals likely sink. likley underrated	
			Non-infectious	Toxin, pollution or eutrophication	chemical pollution/developmental defects	3			3			developmental defects and hermaphroditism/albinism can all lead to loss of fecundity, survival and population decline	
			Non-infectious	Foreign body ingestion	Foreign body ingestion, plastic ingestion	2.5			1.5			as microplastics, a lot is theoretical but likley given quantities of microplastics in water, esp for filter feeders like rays	
			Non-infectious	Toxin, pollution or eutrophication	Heavy metals	1	1		3			Rays freq close to shores, so at risk from contaminants and pollutants, as some bioaccumulate this could lead to endocrine disruption which could potentially alter reproductive abilities	
			Non-infectious	Toxin, pollution or eutrophication	polychlorinated biphenyls	1	1		3				
			Non-infectious	Toxin, pollution or eutrophication	Brevoxotoxins	1			2			Many species vulnerable to this (rays, guitarfish, sawfish) but little info describing direct mortality.	
			Non-infectious	Toxin, pollution or eutrophication	Cyanotoxins	1			1				
			Other problems	Persecution	Guitarfish : fin trade	5			4				
			Other problems	Persecution	Sawfish: fin trade, medicinal	5			4			Cultural beliefs for medicine	
			Other problems	Persecution	Gill plate trade	4			4				
			Other problems	Persecution	Overfishing	4			5				

Sharks	19	2	Non-infectious	Toxin, pollution or eutrophication	Paint fumes - multiple volatile organic chemicals (VOCs)	4	4	4	5			causing mortality in sand tiger sharks; concentrations of some toxic compounds exceed the limit for human consumption; postulated health effects in sharks: endocrine disruption, acute toxicity, altertion of immune function, disruption pf reproduction and development/teratogenicity, olfactory responses impairing prey location and feeding	
			Non-infectious	Foreign body ingestion	Foreign body ingestion, plastic ingestion	4	1	3	5			this includes direct and delayed trauma associated with retained fishing gear, entangelemnt in abandoned "ghost" fishing gear, ingestion of macroplastic and microplastics (plastic items possibly harboring high levels of organic anthropogenic toxins)	
			Non-infectious	Incidental anthropogenic trauma	Bycatch	4		1	5			bycatch with release of unwanted sharks results most likely in high levels of delayed mortality; similarly recreational fishing with catch and release may produce delayed stress/relate mortality (see rhabdomyolysis below), the very high numbers affected by commercial and recreational activities have a serious negative impact on shark populations	
			Non-infectious	Anthropogenic stress or disturbance	Exertional rhabdomyolysis	3			3			Stress from capture/handling, may result in delayed mortality and stranding	
			Non-infectious	Incidental anthropogenic trauma	Ship strike	3		1	1			is incrreasing due to commercial ship routes crossing over shark migratory paths and nurseries; increases turist activity in shark protective areas resulted in numerous documented ship strike wounds; the frequent encounters with ships may lead to changes in behaviour impacting reproduction and population structure	
			Non-infectious	Toxin, pollution or eutrophication	Heavy metal toxicosis: sublethal copper exposure has been documented, exposure to tin (tributyltin oxide in paint)	3	1	1	3			rare (Chondrichthyans generally resistant), tissue levels in some sharks exceed consumption levels in humans; neurotoxicity associated with starnding	
			Infectious	Bacterium	Tenacibaculum maritimum	3		3					
			Non-infectious	Toxin, pollution or eutrophication	Brevotoxins (Karenia brevis - red blooms)	2	3	3	3			Brrevitoxicosis- transfger to humans; associated with stranding, embryo mortality and gill hemorrhage, vertical transfer to embryos/eggs; algal blooms associated with hypoxia	
			Other problems	Persecution	Overfishing	5		3	5			This is by far the greatest threat to shark species in the Caribbean regions; one of the leading identifiable causes of population decline in many shark species/populations	
			Other problems	Persecution	Shark fin trade	5			5			similar to overfishing in the sense of delayed mortality in sharks that loose their ability to escape predation etc.	
			Other problems	Climatic conditions	Climate change resulting in changing (increasing) water temperatures (affecting sharks directly as well as reducing available prey species)	3			4				
			Other problems	Invasive species	Lionfish/invasive species- competition for prey and destruction of habitat	1			2			Sharks have actually been documented preying on lionfish in Little Cayman so there is a chance they are adapting to this invasive species but the lionfish are still having a negative impact on the sharks habitat and compete for some of the same food sources/prey	
			Other problems	Ecological problems	Stony Coral Tissue Loss Disease - loss of habitat and prey	2			2			Rapidly spreading, lethal disease affecting over 20 species of hard corals (reef buildling corals)- desimating coral reefs and habitat for many prey species	

REPTILES													
Crocodiles	2	2	Non-infectious	Toxin, pollution or eutrophication	Heavy metal bioaccumulation (Mercury, Lead, Zinc)	3.5	2	1	3.5			crocodiles are quite resistant to effects but could be human health hazard from ingestion of meat. Gharials are likely to be at greater risk than salwater crocodiles (piscivorous reptiles). As long lived animals and because they are seemingly resilient to the effects of heavy metals, they have the potential to bioaccumulate significantly, which may be toxic if consumed by humans.	
			Non-infectious	Toxin, pollution or eutrophication	Pesticides bioaccumulation	3.5	2	1	3.5			endocrine disruptors affect sex ratio of hatchlings. May be similar issues to heavy metal bioaccumulation, but literature in this area is lacking.	
			Infectious	Virus	West Nile virus (WNV) in farmed crocodiles	3	4	2	4			Potentially significant zoonotic risk. Co-infection and superinfection with various flaviviruses is possible in saltwater crocodiles. However, the role of reptiles in the epidemiology of WNV remains obscure. Spill-over into wild populations is possible. no legal farming in India	
			Infectious	Helminth	lung worms	3							
			Infectious	Helminth	skin nematodes	3							
			Infectious	Virus	Eastern Equine encephalitis virus (EEEV)	2	3	1	2			Zoonotic potential and has been found in crocodilians	
			Infectious	Bacterium	Mycoplasmosis and Mycobacteriosis	1.5	1.5	1	2			in crocodiles. Difficult to evaluate these under the same heading. Mycobacteriosis in crocs seems to be non-turburculin and non bovine, therefore the risk to humans from wild animals (and probably also farmed) is likely to be none. Mycoplasmosis probably represents a greater risk both to humans and crocs, but has only been seen in diseased farmed crocodiles, probably secondary to stress/immunosuppression.	
			Infectious	Helminth	hookworms	1.5							
			Infectious	Helminth	Trematodes	1.5							
			Infectious	Protozoa	Cryptosporidia	1.5							
			Infectious	Virus	Crocodile pox (parapoxvirus) (and caiman pox)	1.5	1	1.5	2			Mostly of cosmetic concern for farmed crocodile hides. Morbidity in very young farmed crocodiles may be high, but mortality is very low.	
			Other problems	Environmental conditions	Habitat loss, including loss of prey and loss of nesting habitat	4						Significant issue for Gharial, would rank as one of the greatest threats. Less of a concern for saltwater crocs, but climate change resulting in loss of nesting habitat one of the greatest risks to species.	
			Other problems	Persecution	Drowning from entanglement in nets	3			5			Fishing in rivers	
			Other problems	Persecution	Local consumption	2	1		3			Significant issue for Gharial, would rank as one of the greatest threats. Much less of a concern for saltwater crocs	
			Other problems	Persecution	Often wild caught for farm stocking: risk of disease transfer between wild and farmed stock	0.5	0.5	1	3			Wild caught individuals are likely to experience greater stress, therefore more likely to exhibit disease states. Some of these may be zoonotic (e.g. salmonellosis), some may be transmissible to other crocodiles.	
Turtles	8	3	Non-infectious	Incidental anthropogenic trauma	Bycatch	4			1.5				
			Non-infectious	Incidental anthropogenic trauma	Entanglement	4			1				
			Non-infectious	Foreign body ingestion	FB ingestion of plastics, plasticosis	3							
			Non-infectious	Other environmental injury	Drowning from entanglement in nets	3			3.5				
			Non-infectious	Toxin, pollution or eutrophication	Poisoning by bioaccumulation of natural marine toxins	2.5	0.5		4			Only possible human risk to those eating turtle eggs or meat. To turtles, may represent one of the most significant 'non-lethal' threats (especially highly neritic species) resulting in immunosuppression, debility, disease susceptibility, reproductive dysfunction. Suspected link to harmful algal blooms (see neurological diseae above)	
			Non-infectious	Toxin, pollution or eutrophication	Poisoning by bioaccumulation of agricultural and industrial pollutants	2			2			Natural marine toxins: There is not really any evidence that agricultural and industrial pollutants are linked to factors having demographic effects on turtles.	
			Non-infectious	Incidental anthropogenic trauma	Ship strike	2			1				
			Non-infectious	Physiologic response to extreme climate	Cold stunning	2			1			Severity of cold stun may be greater in numbers and more severe in presentation in diseased/debilitated/immunosuppressed individuals (as a result of sublethal impacts of anthropogenic factors)	
			Infectious	Virus	Chelonid alphaherpesvirus 5 (ChHV5)	2			1			thought to cause Fibropapillomatosis. Seemingly more common in green turtles. Immunosuppression/debility may predispose to disease.	
			Infectious	Virus	Chelonia mydas papillomavirus (CmPV-1) and Caretta caretta papillomavirus (CcPV-1)	1			2			Limited information regarding impact on morbidity and mortality in turtles.	
			Other problems	Environmental conditions	Malnutrition from habitat degradation, reduction in food sources etc	4			4				
			Other problems	Climatic conditions	Global (seas and nesting beaches) warming	2	3	3	4			May change migratory patterns. Has potential to markedly shift male:female ratio towards higher numbers of females (due to temperature-dependent sex determination). If temperatures become very high may result in egg hatch failure.	
			Other problems	Persecution	Poaching for local consumption, Turtle shell trade	2			2				

MAMMALS													
Felids	5	3	Infectious	Virus	Canine distemper virus (CDV)	5	2	0	3				
			Non-infectious	Incidental anthropogenic trauma	Snare entanglement	5			5			Significant mortality in lions is part of the 'edge effect' around protected areas. Snares often for herbivores killed for bushmeat but catch other species also. totally indiscriminate mortality agent in both predators and prey. And if you get the opportunity emphasize that recovery rate of edible carcasses is extremely low, We cannot understand why people destroy animals by unspeakably cruel means but then make it worse by hardly utilizing the meat. So the wildlife resource gets destroyed but benefits nobody at all.	
			Non-infectious	Toxin, pollution or eutrophication	Targeted poisoning	5	4	3	4.5			Significant mortality in lions is part of the 'edge effect' around protected areas. Snares often for herbivores killed for bushmeat but catch other species also. totally indiscriminate mortality agent in both predators and prey. And if you get the opportunity emphasize that recovery rate of edible carcasses is extremely low, We cannot understand why people destroy animals by unspeakably cruel means but then make it worse by hardly utilizing the meat. So the wildlife resource gets destroyed but benefits nobody at all.	
			Infectious	Virus	Rabies virus	4	5	4	2			Domestic dogs source, significant impact on cheetah (score 4 for neg biodiversity conservation)	
			Non-infectious	Nutritional disease or deficiency	Malnutrition from reduced prey sources	3	2	2.5					
			Infectious	Virus	Feline panleukopenia virus	3	0.5	1.5					
			Infectious	Virus	Feline rhinotracheitis virus (felid herpesvirus1)	3	1	1.5				Transmissible disease to domestic feral cats	
			Infectious	Virus	Avian influenza virus - reported in tigers, leopards	1.5	1	3.5	3				
			Infectious	Prion	Bovine spongiform encephalopathy	2.5	2.5	3					
			Infectious	Protozoa	Toxoplasma gondii	2	2	1	4				
			Infectious	Arthropod ectoparasite	Mites including Sarcoptes sp. (sarcoptic mange)	1.5	1.5	2				sarcoptic mange high prevalence in cheetahs known morbidity/mortality; overall consider more risk than FIV in wild felids as FIV widely prevalent but seems incidental	
			Other problems	Environmental conditions	Habitat loss	5							
			Other problems	Persecution	Poaching	5							
			Other problems	Persecution	Retaliatory killings	5							
Seals & Sea-lions	6	2	Non-infectious	Incidental anthropogenic trauma	Bycatch, entanglement	5		3	5				
			Infectious	Virus	Phocine distemper virus (PDV)	4.5		1	4				
			Infectious	Virus	Influenza A viruses	4	4	4.5	5				
			Non-infectious	Toxin, pollution or eutrophication	Domoic acid	4	3	4.5	5				
			Non-infectious	Foreign body ingestion	FB	3.5		1.5	4				
			Infectious	Protozoa	Toxoplasma	3.5	1.5	1.5					
			Infectious	Virus	Canine distemper virus (CDV)	3.5							
			Non-infectious	Toxin, pollution or eutrophication	Endocrine disruptors	3	2.5	2	4				
			Non-infectious	Toxin, pollution or eutrophication	Heavy metals	3	3.5	2.5					
			Non-infectious	Toxin, pollution or eutrophication	Organochlorines	3	1	1					
			Infectious	Virus	Phocid herpesvirus 1&2	2.5		0.5	3				
			Infectious	Bacterium	Brucellosis sp: B.ceti & B.pinnipedalis	3	2	3	3				
			Infectious	Bacterium	Mycobacterium spp: M.pinnipedi	3	2	4					
			Infectious	Helminth	Nematodes	3	1.5	1.5					
			Non-infectious	Other threat to health	Urogenital carcinoma	3							
			Infectious	Bacterium	Leptospira	3	2	2					
			Infectious	Virus	(Eastern Equine Encephalitis Virus - EEEV)	1	1	3					

Canids	1	3	Infectious	Virus	Rabies virus	5	4	4	4.5			Expansion of domestic dog populations; low vaccination coverage of domestic dogs; can affect whole packs	
			Non-infectious	Incidental anthropogenic trauma	Snare/trap wounds	5		5	5				
			Non-infectious	Toxin, pollution or eutrophication	Poisoning	5	1	4	4			Retaliatory killing in response to livestock predation which can be very severe for some households; reflection of underlying power inequalities and antagonism towards wildlife authorities; exacerbated by livestock losses, food security challenges as a result of climate and landuse change	
			Infectious	Virus	Canine distemper virus (CDV)	4			4			Expansion of domestic dog populations; low vaccination coverage of domestic dogs; changing epidemiology of CDV (emergence of wildlife reservoir systems with multiple potential sources of infection and routes of transmission); can affect whole packs	
			Infectious	Virus	Canine parvovirus	3.5	1	2					
			Infectious	Virus	Canine herpesvirus 1	3	2	4	1				
			Infectious	Bacterium	Brucella sp. (brucellosis)	2	4	3					
			Infectious	Helminth	Nematodes (Angiostrongylus vasorum; Eucoleus aerophilus, crenosoma vulpis)	1		3					
			Other problems	Persecution	Other forms of persecution	5						Retaliatory killing in response to livestock predation; also in response to undelying inequalities in costs/benefits of wild dogs in communities (economic benefits through tourism accrue to a few local elites but not to those bearing the costs of livestock predation); exacerbated by livestock losses, food security challenges as a result of climate and landuse change	
			Other problems	Environmental conditions	Road traffic accidents	4						Expansion of road infrastructure and highways	
			Other problems	Ecological problems	Feral dogs (interspecies aggresion)	3		3					
Bears	2	1	Non-infectious	Anthropogenic stress or disturbance	Anthropogenic environmental insult (e.g. oil spill, human conflict)	3			5				
			Non-infectious	Nutritional disease or deficiency	Starvation/changes in prey population dynamics and body condition	4			5			Lack of food, climate change	
			Non-infectious	Other threat to health	Novel inter- and intra- specific competion	4			4				
			Non-infectious	Physiologic response to extreme climate	Climate Change, loss of habiat	5			5				
			Non-infectious	Toxin, pollution or eutrophication	Heavy metal (mercury)	3			3				
			Non-infectious	Toxin, pollution or eutrophication	Poisoning: persitent organic pollutants (POPs); PFAs	2						PFAs: Immune supression and risks of cancer, reproduction and infections.POPs: bioaccumulation in polar bears. Multiple studies. The health outcome is unknown, however, some subclinical lesions are likely to occur such as effects on the immune system and endocrinology posing risks towards infections and survivial and reproduction	
Bovids	21	2	Infectious	Bacterium	Anthrax (B.anthracis)	5	3.5	5					
			Infectious	Virus	Peste des petitis ruminants (PPR) (Morbilliviruses)	4.5	0.5	5	5				
			Infectious	Virus	Rift Valley Fever (bunyavirus)	4	5	5					
			Infectious	Bacterium	Haemorrhagic septicaemia (P.multocida, Mannheimia)	3	0.5	2					
			Infectious	Bacterium	Pasteurella sp	3	0.5	1.5					
			Infectious	Virus	Foot and mouth disease (FMD)	3	0.5	5					
			Infectious	Arthropod ectoparasite	Sarcoptes scabei	2.5	1.5	2.5					
			Infectious	Virus	Rabies	2.5	2.5	3.5					
			Infectious	Bacterium	Brucella (B.abortus)	2	2.5	4					
			Infectious	Helminth	Thysanosoma	2	2.5	3					
			Infectious	Virus	Lumpy skin disease (Capripoxvirus)	2	0.5	4					
			Infectious	Bacterium	M.bovis (TB)	1.5	1.5	3					
			Infectious	Bacterium	Mycobacterium avium ssp paratuberculosis (Johne's)	1.5	1.5	3					
			Non-infectious	Toxin, pollution or eutrophication	Mycotoxicosis from contaminated supplemental feeding: Aspergillosis; Penicillium; Fusarium sp	1.5	1.5	3					
			Infectious	Bacterium	Mycoplasma spp: Contagious bovine pleuropneumonia (Mycoplasma mycoides)	1	0.5	3					
			Infectious	Helminth	Echinococcosis (E.granulosus)	1	4	2					
			Infectious	Protozoa	Theileriosis (Theileria parva, T.annulta)	1		4					
			Infectious	Protozoa	Trypanosomiasis (Trypanosoma spp.)	1	1	3					
			Infectious	Virus	Malignant catarrhal fever (ovine-herpesvirus2)	1	0.5	3.5					
			Other problems	Environmental conditions	Displacement by development	5							
			Other problems	Persecution	Poaching	5							

Camels	2	2	Infectious	Arthropod ectoparasite	Mange mites (sarcoptes, chorioptes, psoroptes)	5	1	3	5			Not studied	
			Non-infectious	Anthropogenic stress or disturbance	Constant displacement from feeding sites by Alpaca farmers	4			5				
				Physiologic response to extreme climate	Scarcity of resources during dry season	3	2	4	4				
			infectious	Bacterium	Paratuberculosis	3	2	5	3				
			Infectious	Helminth	Fascioliasis (F.hepatica)	2		3	4				
			Infectious	Protozoa	Sarcocystis (S.aucheniae y S.lamacanis)	2		2	4				
			Non-infectious	Toxin, pollution or eutrophication	Mining tailing	2		2	2				
			Infectious	Helminth	Echinococcus granulosus	2		1	2				
			Infectious	Bacterium	Leptospirosis (L.pomona,L.grippot,L.copenahenn)	1	1	3	2				
			Infectious	Helminth	Lamanema Chavezi	1		2	1				
			Infectious	Helminth	Nematodirus battus	0.5		1				Not studied	
			Infectious	Helminth	Nematodirus cf. spathiger	1		2	2				
			Infectious	Protozoa	Eimera punoensis y E.alpacae	1		2	2				
			Infectious	Virus	Foot and mouth disease (FMD)		0.5	1	0.5			Not studied	
			Other problems	Environmental conditions	Overgrazing of natural feeding sties by alpaca farmers	5		5	5			overgrazing of natural feeding sites by livestock	
			Other problems	Persecution	Poaching because of its fur	5			5				
			Other problems	Climatic conditions	More recurring droughts	4	3	4	5				
			Other problems	Environmental conditions	intensive use of water by mining companies	4	4	4	4			overuse of water by mining companies	
			Other problems	Genetic problems	Low density at unprotected areas	3			4				
Deer	3	1	Infectious	Virus	Cervid herpesviruses 1&2	5		4	5				
			Infectious	Virus	Deer alpha herpesviruses	5		4	5				
			Infectious	Bacterium	Johne’s (M.avium ssp paratuberculosis)	5	3	4	5				
			Infectious	Arthropod ectoparasite	Mange mites (sarcoptes, demodex)	5		3	5				
			Infectious	Virus	Deer fibromatosis (delta papilloma virus)	4		1	2				
			Infectious	Bacterium	Tuberculosis (M.bovis, M.tuberculosis)	4	4	5	5				
			Infectious	Helminth	Dictyocaulus spp	4			2				
			Infectious	Helminth	Fascioloides spp	4	1	3	4				
			Infectious	Bacterium	Brucella spp	3	3	5	5				
			Infectious	Arthropod ectoparasite	Ticks	2	1	5	4				
			Infectious	Bacterium	Pasteurella	2		3	4				
			Infectious	Helminth	Haemonchus spp	2			3				
			Infectious	Helminth	Nematodirus spp	2			3				
			Infectious	Helminth	Trichostrongylus	2			3				
			Infectious	Bacterium	Anthrax (B.anthracis)	1	3	5	2				
			Infectious	Bacterium	Borrelia spp.Lyme borreliosis	1	2	5	3				
			Infectious	Bacterium	Clostridium spp: C. chauvoei; C.perfringens	1	3	2	3				
			Infectious	Bacterium	Escherichia coli	1	3	2	2				
			Infectious	Bacterium	Leptospira	1	3	5	4				
			Infectious	Bacterium	Listeria	1	3	5	2				
			Infectious	Bacterium	Salmonellosis	1	3	5	2				
			Infectious	Bacterium	Staphylococcus spp	1	3	5	2				
			Infectious	Bacterium	Streptococcus spp	1	3	5	2				
			Infectious	Bacterium	Tetanus	1	3	5	3				
			Infectious	Helminth	Spiculopteragia	1	3						
			Infectious	Protozoa	Babesia spp	1	3						
			Other problems	Climatic conditions	Climate change	5		5	5				
			Other problems	Ecological problems	Apparent competition with livestock and exotic abundant prey species	5			5				
			Other problems	Ecological problems	Small and declining populations	5			5				
			Other problems	Environmental conditions	Habitat fragmentation	5			5				
			Other problems	Persecution	Dogs attack	5		5	5				
			Other problems	Persecution	Poaching	2		1	4				
Giraffe	1	2	Infectious	Virus	Foot and Mouth Disease (FMD)	5	1	5					
			Infectious	Bacterium	Anthrax (Bacillus anthracis)	4	4	4	3				
			Infectious	Bacterium	Brucellosis	3	2	3					
			Infectious	Bacterium	Clostridium perfringens	3	1	3	3				
			Infectious	Bacterium	Mycobacterium bovis and M. tuberculosis	3	3	3	2				
			Non-infectious	Nutritional disease or deficiency	Nutrition			1	2			Primarily a threat in small fenced game camps	
			Non-infectious	Toxin, pollution or eutrophication	Environmental pollution			1	2			Suspected, not proven	
			Infectious	Bacterium	Listeriosis	2	1	2	4				
			Infectious	Bacterium	Q-fever (Coxiella burnetti)	2	1	2	3				
			Infectious	Protozoa	Theileria	2		3					
			Infectious	Virus	Lumpy skin disease (Capripoxvirus)	2		3					
			Infectious	Virus	Malignant catarrhal fever	2							
			Infectious	Virus	Rinderpest (eradicated)	1						Significant historical loses to rinderpest	
			Other problems	Environmental conditions	Habitat fragmentation							Due to increased human population, infrastructure	

Equids	5	2	Non-infectious	Nutritional disease or deficiency	Starvation	5	3	5				primary driver of starvation is habitat loss/degradation (which is exacerbated by climate change).	
			Infectious	Bacterium	Anthrax (bacillus anthracis)	4	4.5	3.5	5			Drought and adverse environmental conditions thought to predispose to Anthrax outbreaks (dry conditions > trauma in oral cavity > anthrax spores risk increases) Exposure to livestock anthrax , degraded soils from habitat ldegradation, exposed soils from climate change can all act as drivers; Diffuse interface between livestock and wildlife	
			Infectious	Helminth	Anoplocephala spp	4		1					
			Infectious	Helminth	Anoplocephaloides spp	4		1					
			Infectious	Helminth	Strongylus spp.	4		2				degraded range	
			Infectious	Arthropod ectoparasite	Ticks	3.5	1	3				Diffuse interface between livestock and wildlife	
			Infectious	Helminth	Parascaris equorum	3.5		2				degraded range	
			Infectious	Helminth	Strongyloides spp.	3.5		2				degraded range	
			Non-infectious	Incidental anthropogenic trauma	Snares - non-targetted	3							
			Non-infectious	Nutritional disease or deficiency	Vit E deficiency (equine degenerative myeloencephalopathy)	3		3					
			Infectious	Bacterium	Tetanus (Clostridium tetani)	3	2	2	2			injury from predators	
			Non-infectious	Other threat to health	Colic (sand impactions, intestinal accidents, enterocolitis); Enteroliths	3		1					
			Infectious	Virus	African horse sickness (AHS)	1		1				zebra can support virus replication Ex situ exposure	
			Infectious	Virus	Rabies (lyssavirus)	1.5	3.5	3.5					
			Infectious	Virus	West Nile Virus (WNV)	1	2	2				Climate change- shifting exposure patterns; other - translocation of virus	
			Other problems	Environmental conditions	Habitat loss	4							
Elephants	3	2	Infectious	Virus	Elephant Endotheliotropic herpesvirus (EEHV)	5	1	5					
			Non-infectious	Incidental anthropogenic trauma	Snare entanglement	5		5	5			Snaring can cause life-threatening injuries through septicaemia or compromised movement. Snares are put down to catch herbivores for bushmeat	
			Infectious	Virus	Encephalomyocarditis virus (EMC)	4		5					
			Infectious	Virus	Rabies (Lyssavirus)	4	3	4					
			Infectious	Bacterium	Anthrax (Bacillus anthracis)	4	3	2.5	3				
			Infectious	Bacterium	Mycobacterium tuberculosis and M.bovis causing elephant tuberculosis	4	2	4					
			Non-infectious	Toxin, pollution or eutrophication	Poisoning: Organophosphates, pesticides, Strychnine, Arsenic, heavy metals, Cyanide	3	1	1	4				
			Infectious	Bacterium	Salmonellosis	3	3	3	2				
			Infectious	Bacterium	Acute pasturellosis (P.multocida)	2.5	1	1	2.5				
			Infectious	Virus	Foot and Mouth Disease (FMD)	1	1	5					
			Other problems	Environmental conditions	Reduced habitat, reduced resources	5		3					
			Other problems	Persecution	Human elephant conflict	5		1.5					
			Other problems	Persecution	Poaching for ivory	5		2.5					
			Other problems	Environmental conditions	Barriers impeding movement (fencing, roads etc)	3		3					
Megabats	7	3	Non-infectious	Toxin, pollution or eutrophication	Pesticides, insecticides	3	3	3	3			Potential toxicities, but also loss of insect populations for food.	
			Non-infectious	Physiologic response to extreme climate	Extreme heat mass mortalities	3		3	4				
			Infectious	Virus	Coronaviruses	1	5	3	4.5			Note the risk to conservation is very high here due to persecution, but that is listed separately below. The risk of the CoV infection to the bats themselves is zero. Re: drivers - Other = wildlife trade and farming; Sarbecoviruses endemic in Rhinolophus bats have sever pandemic potential in humans. Other coronaviruses are endemic in a range of bats with unknown zoonotic potential. New world bats have proven susceptible to sarbecoviruses, but impact on these species is unknown	
			Infectious	Virus	Lyssaviruses (Australian bat virus; Lagos bat virus; West Caucasian bat virus; Khujand virus); European bat lyssavirus 1&2 (Myotis sp)	1	5	3	4				
			Infectious	Virus	Marburg virus and Ebola virus (Filoviruses)	1	4	4	4.5				
			Infectious	Virus	Nipah virus (Paramyxoviruses) reservoir	1	4	3	1.5			The particular bat species in the CMS list don't overlap with Hendra or Nipah virus themselves. I added 'other henipaviruses' below and assessed the two African fruit bats. ; Nipah virus in bats occurs with cyclic prevalence, and is associated with low morbidity/mortality in host species. The virus can spill over and cause disease in swine, and possibly horses. Human exposure can be directly from bats, indirectly from date palm sap, or through 2ndary hosts (swine), and disease in humans is significant with high mortality rates	
			Infectious	Virus	Other henipavirus		4	4	4				
			Infectious	Bacterium	Leptospira spp	0.5	2.5	1.5	3				
			Other problems	Persecution	Retaliatory killings	4	1	1	4.5			Bats' association with zoonotic diseases makes them a target for retaliatory killings/culling. This may increase over time following the Covid-19 pandemic. Paridoxically, this can increase human exposure to bats and possible zoonotic pathogens	
			Other problems	Persecution	Poaching for meat	3	3.5	0.5	2.5			Consumption of bats as bushmeat has been associated with spillover of important zoonotic diseases (eg filoviruses, possibly henipaviruses).	

Microbats	50	3	Infectious	Fungus or Yeast	White Nose Syndrome (WNS) (Pseudogymnoascus destructans)	5		3	4.5			the species in your species list have so far not been shown to affected, but only to carry the fungus. But of course one could argue the need of keeping an eye on future developments. to WNS limited to North Americn bat species (score "4"); P. destructans was introduced to N. America in 2006 and has advanced through most of the continent causing extreme mortality events in hibernating bat spp. Populations first hit are starting to slowly recover. Relatives of P. destructans are found throughout western Europe with no known impact on bat populations	
			Non-infectious	Incidental anthropogenic trauma	Collisions with wind farm blades	5		1	3			Only certain functional guilds (aerial insectivore bats e.g. Pipistrelles, Vespertilio murinus, Nyc noc, Lasiurus); Negative impact on human livelihoods or economics: eco-service of bats will drastically be reduced with loss of animals	
			Infectious	Virus	Coronaviruses	2.5	4.5	3	4.5			difficult to enter cloumns D-F as "Coronavirus" very broad term in regard to large Coronavirus family; e.g. newborn offspring can suffer from enteric C-virus diarrhoe; so far direct SARS-CoV-related spill-over to humans not known, instead intermediate host/s necessary; Sarbecoviruses endemic in Rhinolophus bats have sever pandemic potential in humans. Other coronaviruses are endemic in a range of bats with unknown zoonotic potential. New world bats have proven susceptible to sarbecoviruses, but impact on these species is unknown	
			Infectious	Virus	Rabies	2	2	1	3			Rabies is endemic in bats throughout the Americas, with low but persistent mortalities. Habitat loss may change disease dynamics and sp. specific strain exposure. Spillover of bat rabies to humans and other animals occurs regularly	
			Non-infectious	Toxin, pollution or eutrophication	Lead poisoning	2			3				
			Infectious	Bacterium	Leptospira spp	1	1	0	3				
			Infectious	Virus	Hendravirus	1	1	3				not relevant in Yangochiroptera	
			Infectious	Virus	Marburg virus and Ebola virus (Filoviruses)	1	1	3				not relevant in Yangochiroptera	
			Infectious	Virus	Nipah virus (Paramyxoviruses) reservoir	1	1	3				not relevant in Yangochiroptera	
			Other problems	Persecution	Retaliatory killings	4	1		4.5			Bats' association with zoonotic diseases makes them a target for retaliatory killings/culling. This may increase over time following the Covid-19 pandemic. Paridoxically, this can increase human exposure to bats and possible zoonotic pathogens; for Europe + North America not relevant, but Asia, Africa: chirotpera colonies killed in fear of viral pathogens (not listed, but South America: Desmodus rotundus (and other species alongside) colonies killed because of fear of rabies)	
			Other problems	Environmental conditions	loss/fragmentation of habitats	4		2				loss of roosts, foraging grounds, insect abundancy (for insectivores and where geographically applicable)	
			Other problems	Environmental conditions	light pollution	3			3			negative impact will be indirect, however, light pollution is thought to reduce fitness	
			Other problems	Persecution	Poaching for meat	2	3		3			Consumption of bats as bushmeat has been associated with spillover of important zoonotic diseases (eg filoviruses, possibly henipaviruses). Note poaching normally involves megabat spp.; for regions where bats are part of bushmeat (parts of Asia, Africa)	
			Other problems	Ecological problems	Predation by introduced species	1	3					Domestic cats are known to predate on bat spp., although their impact on populations is unknown. Cats may be exposed to rabies, which then expose people	

Primates	7	2 (3*)	Infectious	Undetermined (please specify in comments)	Undetermined Virus or bacteria can be from sympatric wildlife/ domestic animals or human	5	5	5	3				
			Infectious	Virus	Ebola virus (Filovirus)	5	5	5	5				
			Infectious	Virus	Human metapneumovirus	5	3	3	5				
			Infectious	Virus	Marburg virus (Filovirus)	5	5	5	5				
			Infectious	Virus	Measles (Rubeola or morbillivirus)	5	5	5	5				
			Infectious	Virus	Rhino C virus	5	4	5	5				
			Infectious	Bacterium	Streptococcus pneumoniae (bacterial meningitis)	5	3	2.5	4.5				
			Infectious	Bacterium	Tuberculosis (M.tuberculosis; M.bovis)	5	3	3	5				
			Infectious	Fungus or Yeast	Streptomyces	5	4	4	4				
			Non-infectious	Toxin, pollution or eutrophication	Heavy metals: Lead; Zinc	5	4	3					
			Non-infectious	Toxin, pollution or eutrophication	Pesticides	5	3	3					
			Non-infectious	Toxin, pollution or eutrophication	Polychlorinated biphenyls (PCBs)	5	3	4					
			Infectious	Virus	Anthrax (Bacillus anthracis)	5	3	3	5				
					New unknown emerging pathogen				5			for great apes, anything that impacts humans, should be assumed will also impact great apes	
			Infectious	Virus	Respiratory syncital virus (pneumovirus)	4.5	4	4	5				
			Infectious	Bacterium	Coronaviruses	4	5	5	5				
			Infectious	Helminth	Yersiniosis (Y.pseudotuberculosis; Y.enterocolitica)	4	3	3	3.5				
			Infectious	Helminth	Ancylostoma duodenale	4	2.5	2.5	3				
			Infectious	Helminth	Ascaris lumbricoides	4	2.5	2.5	3				
			Infectious	Protozoa	Echinococcus spp	4	2.5	2.5	3.5				
			Non-infectious	Toxin, pollution or eutrophication	Cryptospridium parvum	4	4	4	4				
			Non-infectious	Toxin, pollution or eutrophication	Botulinum toxin	4	4	3					
			Infectious	Arthropod ectoparasite	Phytotoxins (ingestion of toxic plants)	4	3	3					
			Infectious	Bacterium	Sarcoptes scabeiei	3.5	3	2.5	3				
			Infectious	Fungus or Yeast	Shigellosis	3.5	2.5	2.5	3				
			Infectious	Helminth	Cryptococcal infections: C.neoformans and C.gatti	3.5	2.5	3	3				
			Infectious	Helminth	Strongyloides fulleborni, S. stercoralis	3.5	2.5	2.5	3				
			Infectious	Protozoa	Trichuris trichura	3.5	2.5	2.5	3				
			Infectious	Protozoa	Entamoeba histolytica	3.5	2	2	4				
			Infectious	Virus	Plasmodium spp	3.5	2.5	2.5	4				
			Infectious	Virus	Encephalomyocarditis virus (EMCV) - Picornavirus	3.5	2	2	2.5				
			Infectious	Virus	Monkeypox virus (MPXV) -poxvirus	3.5	3	3	3				
			Infectious	Virus	Simian immunodeficiency virus (SIV) (retrovirus)	3.5	2.5	3	3.5				
			Infectious	Bacterium	Simian T-lymphotropic virus (STLV) (retrovirus)	3.5	3	3	4				
			Infectious	Bacterium	Campylobacteriosis	3	2.5	2	3				
			Infectious	Bacterium	Colibacilosis (E.coli)	3	2	2.5	3				
			Infectious	Bacterium	Meloidosis (Psudomonas psudomallei)	3	2	2	3				
			Infectious	Helminth	Salmonellosis	3	2	2	3				
			Infectious	Helminth	Nector americanus	3	2.5	2.5	2.5				
			Infectious	Virus	Oesophagostomum spp	3	2.5	2.5	2				
			Infectious	Virus	Epstein-barr virus	3	3	4	3				
			Infectious	Virus	Influenza virus	3	3	3	4				
			Infectious	Virus	Papilloma virus	3	2.5	2.5	3.5				
			Infectious	Virus	Parainfluenza III (paramyxovirus)	3	3	3	4				
			Infectious	Virus	Polio (poliovirus - enterovirus)	3	1	1	3.5				
			Infectious	Other threat to health	Rabies	3	2	1	4.5				
			Non-infectious	Toxin, pollution or eutrophication	Myocardial fibrosis	3	3	3					
			Infectious	Virus	Snake and spider venoms	3	3	3					
			Infectious	Virus	Mayaro virus	2.5	2.5	2.5	3.5				
			Infectious	Protozoa	West Nile Virus (WNV)	2.5	2.5	2.5	3.5				
			Infectious	Protozoa	Balamutharis mandrillaris	2.5	2	2	3				

Cetaceans		3 (4*)	Non-infectious	Incidental anthropogenic trauma	Bycatch, entanglement (marine debris, ALDFG)	5	1	2	4.5			Risk varies between regions and across taxa. Future threat ranking is specific to large whale entanglement in Scotland. Other drive is fishing. Risk varies between regions and across taxa. Risk higher for active gear which we've covered under bycatch	
			Non-infectious	Toxin, pollution or eutrophication	Persistent organic pollutants (PCBs, PFAs, BDEs etc)	4.5	3	2.5	3.5			Variation between populations, species and taxa. (e.g., threat ranking would be higher for UK Killer Whales) - see note**	
			Non-infectious	Anthropogenic stress or disturbance	Noise pollution (e.g. ADDs, pleasurecraft, naval sonar, seismic surveys etc)	4		2	3			Lots of species variation and lots of unknowns (e.g., Beaked whales, naval stranding). There are several drivers of noise pollution attributed to the different sources.	
			Non-infectious	Nutritional disease or deficiency	Prey depletion	4	2	5	4				
			Infectious	Virus	Canine distemper virus (CDV); dolphin morbillivirus (DMV); Porpoise morbillivirus (PMV)	3.5		1	3				
			Non-infectious	Incidental anthropogenic trauma	Trauma (e.g. boat strike)	3.5		0.5					
			Non-infectious	Toxin, pollution or eutrophication	Algal Blooms (Cyanobacterial toxicosis)	3	0.5	1.5	3.5				
			Non-infectious	Toxin, pollution or eutrophication	Brevitoxicosis	3	1	1.5					
			Infectious	Bacterium	Brucellosis sp: B.ceti & B.pinnipedalis	2.5		0.5	3				
			Infectious	Protozoa	Coccidioides spp.: C.immiys and .posadasii	2	0.5	0.5	1				
			Non-infectious	Toxin, pollution or eutrophication	Seabed mining	2	1	1	3			Risk varies between regions and across taxa. the noise component (possible impacts on deep diving beaked whales, which are noise sensitive species) would be captured under the wider noise category. We therefore wanted to consider the additional pressure/risk of mining releasing toxins/pollutants potentially bound up in seabed substrate; and substrate plumes potentially causing wider issues across the submarine ecosystem (either temporary or more permanent in nature).	
			Infectious	Virus	Caliciviruses	1.5	0.5		2.5				
			Infectious	Virus	Herpesviruses: Bottlenose dolphin herpesvirus; Tursiops truncatus (bottlenose dolphin) alphaherpesvirus	1.5			1.5				
			Other problems	Climatic conditions	Climate change (e.g. shift in prey distribution, habitat degradation, direct physical impacts etc)	3	2	2	3				

Dugongs & manatees		4	Non-infectious	Anthropogenic stress or disturbance	Coastal development and habitat loss	5						A threat to all Sirenian species	
			Non-infectious	Physiologic response to extreme climate	Cold Stunning (including loss of thermal refuges)	5			4			Cold stress in Florida manatees (West Indian subspecies) but not Antillean; it can be also viewed as anthropogenic disturbance because the construction of power plants created artificial warm water sites for manatees; some of these power plants now close and therefore impact manatees migrations; This is not a result of extreme climate and only effects the Florida manatee. This subspecies is already at the extreme end of the natrual history range (tropical mammal in a temporate enviroment). Similar epeisodes in dugong are noted in Queensland, again at the extreme end of the nautral range.	
			Non-infectious	Incidental anthropogenic trauma	Watercraft trauma (boats, commercial platforms, properller wounds, working barges, tugs or cruise ships)	4			3.5			Blunt trauma and pneumothorax often results. Important for individual manatee mortality but population grow only slows; it is not negative. Another manaifestation of human-animal conflict.	
			Non-infectious	Toxin, pollution or eutrophication	Algal blooms: Brevetoxicosis (Karenia brevis)	4	1	3	5			Although red tide itself is considered a natural phenomenon, it is suspected that fertilizers use is in part responsible for exacerbating the blooms; Brevetoxicosis is the most significant threat to the ecostsrem in which Florida manatees live. the impacts are not specific to manatees alone and have huge economic and health impacts to peopple and other species, including food species for both animal and people.	
			Non-infectious	Foreign body ingestion	Fishing gear ingestions, plastic ingestion (including microplastics)	3			2			Very minor event and has no effect on population level. Microplastics have been explored and have no known negative impact as of yet.	
			Non-infectious	Incidental anthropogenic trauma	Entanglement	3			2			fishing gear; This is a result of humna-animal conflict with manatees affected with what amounts to be pollution	
			Non-infectious	Nutritional disease or deficiency	Starvation (loss of habitat)	3			3			Acute loss of forage has had localized population effcets in Florida manatees and in West Adrican manatees.	
			Non-infectious	Physiologic response to extreme climate	Hurricanes	2		4	2			The occasional threat for West Indian manatee but can cause strandings, dispersal, trauma, and stress (eg. Irma cat.5 hurricane in 2017)	
			Non-infectious	Toxin, pollution or eutrophication	Pollution and starvation to death	2	1	1	3			E.g. increased mortality of Florida manatees due to starvation since 2021, is suspected to be due to pollution and subsequent loss of food sources, although to my understanding the issue is still under investigation (to verify true facts)	
			Infectious	Virus	Morbillivirus (dolphin)	1			4			morbillivirus impact on cetaceans	
			Other problems	Environmental conditions	Loss of seagrass				5			All drivers of seagrass loss ultimately impact the survival of Sirenians worldwide	
			Other problems	Climatic conditions	Drought and low water levels in the rivers				3			Amazonian manatee	
			Other problems	Ecological problems	Increasing Sargassum spp. blooms in the Antilles, Mexico, parts of Florida				3			The seaweed is expanding in the Caribbean and appears on the shores where it can impact the health of humans, wildlife and the ecosystems. It can impact the seagrass health and therefore the health of manatees (future potential threat for manatees)	