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

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THE UNIVERSITY *of* EDINBURGH

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Prepared for: The Secretariat of the Convention on the Conservation of Migratory Species of Wild Animals (CMS).

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*Cover image: African wild dog (*Lycaon pictus*). Photo credit: Canva.*

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1 FOREWORD

A desire for good health unites us all. Still in a time of COVID-19 and with the looming threat of future pandemics, we are reminded of the fragility of our collective health. Now more than ever, we understand that human health is inexorably linked to the health of the environment in which we live and the species, be they wild or domestic, on which we depend. As we threaten and change our climate, transform natural landscapes, intensify our agriculture activities, unsustainably exploit resources, and pollute our air, land and water, the pressures on the environment and on migratory species have never been greater. All of these actions in turn drive the emergence of diseases and increase our fragility.

I have lived through a time when diseases of wildlife may have been only of scientific interest to some. Now we see the wider and significant consequences of the emergence of both infectious and non-infectious diseases and the growing threat they pose to the very survival of species.

Bringing UNEP into the health Quadripartite to work alongside the World Health Organization, UN Food and Agriculture Organization and the World Animal Health Organization is a clear sign that, as a society, if we are to tackle global human ill-health we need to pay significant attention to One Health, taking a holistic approach to disease issues at the global level. Yet within One Health the environment and wildlife health are too often the 'poor relation.' There remains too little understanding of disease dynamics and scant consideration of wildlife health when making decisions on food production, trade, land planning, energy production and infrastructure development. Due to the now obvious interconnectivity of health, we know that what is bad for wildlife health, is ultimately bad for us.

Too often we overlook the value of wildlife *health*, only opening our eyes when we feel the negative consequence for human ill-health. For example, when we are confronted with the appalling sights of acute outbreaks of diseases like highly pathogenic avian influenza, or when wildlife diseases spill into livestock or zoonotic infections affect people and present pandemic risks. There is a need to turn the adage of 'no prizes in prevention' into applauded actions to maintain the integrity and resilience of ecosystems to stop disease emergence at its source. Developing cost-effective ways to prevent disease emergence that also benefit ecosystems is surely a key challenge for the future.

This Report, authored and reviewed by a world leading team of wildlife health specialists, led by the University of Edinburgh, contributes to the growing body of work which highlights the needs for interdisciplinary action to protect the health of us all. Instead of viewing issues through the single anthropocentric lens of human health, it takes the perspective of the wider environment and of the species within, helping to rebalance and improve our thinking about One Health.

The Report is a seminal contribution to the work of the Convention on Migratory Species (CMS) on the issue of wildlife health and will guide the work of the CMS Working Group on Migratory Species and Health. It adds to the CMS work on One Health issues such as the poisoning of species, and highly pathogenic avian influenza, which has helped guide Parties and other stakeholders dealing with the negative health consequences of human activities.

The Report examines our current understanding of the determinants of health and considers the gains to be made from taking One Health approaches. With a frequent perception of migratory species as vectors of disease it reviews the complexities of their disease dynamics and considers both the benefits and dis-benefits that migration brings for health in all sectors. Importantly, the report provides the findings from a global expert consultation of key health threats for CMS-listed species. Despite the diversity of species considered, from insects to elephants, and their diverse health threats, there is remarkable similarity in the underlying drivers of their health threats, namely the human induced pressures outlined above.

The key recommendations[1] outline the frameworks required to deliver One Health, and how to reduce risks at wildlife interfaces, tackle non-infectious diseases, improve disease prevention and preparedness, fill knowledge gaps, and improve wildlife health reporting and information sharing. These actions will not only improve the conservation status of migratory species, but they will also reduce the health risks to people and livestock.

In a climate changing world with an interlinked global biodiversity crisis where the consequences of the current Covid pandemic still playing out, we need no more warnings, we now know now what we have to do to act for the health of us all.

Professor Colin Galbraith

Appointed Councillor on Climate Change to the Convention on Migratory Species

Chair of NatureScot, UK

[1] Also appended to Resolution 12.6(Rev.COP.14)

2 EXECUTIVE SUMMARY

The United Nations Environment Programme (UNEP)'s Convention on the Conservation of Migratory Species of Wild Animals (CMS) has worked on aspects of wildlife health since 2005 and played a key role in responding to poisoning and highly pathogenic avian influenza.

With increased awareness of the importance of wildlife health, CMS has responded with the establishment of a new Working Group on Migratory Species and Health[2] and a substantive review of the issues related to health of migratory species[3,4]. The review both supports the Group's work and provides information and recommendations to Parties.

The review comprises four main sections:

Wildlife health: key concepts, and the interdependence of health and environmental sectors

A summary of key concepts in wildlife health, and the relevance of wildlife disease to biodiversity conservation and to domestic animals and humans. The chapter explores the anthropogenic drivers and activities that can lead to disease emergence, and the benefits of One Health and ecosystem approaches to health.

Migration, migratory change and disease

A review of key concepts, and our current understanding of health and infectious disease dynamics in relation to migration. The chapter also explores the potential consequences of migration disruption for the health of migratory wildlife and infectious disease dynamics.

Key health issues in migratory species and their broad underlying causes

An expert consultation to determine, at a high level, key known health issues affecting migratory species listed on the CMS Appendices I and II, and broad driving processes considered to underlie these problems.

Conclusions and recommendations

A concluding chapter drawing together key messages from the report and recommendations for action.

The cross-cutting key messages and recommendations drawn from these four sections are presented below and summarised in Figure 2.1.

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[2] Terms of reference of Working Group on Migratory Species and Health: UNEP/CMS/ScC-SC5/Outcome 11

[3] UNEP/CMS/COP14/Inf.30.4.3

[4] Terms of Reference for a Review of Migration and Wildlife Disease Dynamics and the Health of Migratory Species CRP 6.4.1/B: https://www.cms.int/en/document/draft-terms-reference-review-migration-and-wildlife-disease-dynamics-and-health-migratory

2.1 Key messages

1. Key concepts

Preventative One Health approaches are needed to address the risks to migratory species from infectious and non-infectious diseases.

1.1. Migratory species can be affected by infectious and non-infectious diseases. These can have serious implications for their health and survival, as well as associated impacts on livestock and human health.

1.2. The environment is the setting and determinant for health across wildlife, domestic animal and human sectors: intact and well-managed ecosystems positively influence health.

1.3. The health of wildlife, livestock, companion animals, humans and their ecosystems are interdependent – for example, many pathogens (disease-causing infectious agents) are able to infect multiple species.

1.4. Disease is often viewed as a matter of survival or death when, in fact, its effects can be far more subtle. Disease may negatively affect reproductive success, development, host behaviour and the ability to compete for resources or to evade predation.

1.5. An animal or population can be affected by multiple infectious and/or non-infectious disease conditions coincidentally and these can be mutually reinforcing, increasing the potential for adverse effects on an individual or population.

1.6. Disease can negatively affect the conservation status of migratory species, especially when populations are small and fragmented.

1.7. Infectious disease is a conservation concern for a diverse range of threatened migratory species. Highly pathogenic avian influenza (HPAI) poses a particular threat to many migratory avian species, while a range of infectious diseases are important in other taxa. Alongside infectious threats, toxins, pollutants and anthropogenic trauma commonly compromise the health of migratory species.

1.8. Controlling disease once it has emerged can be very challenging due to the complexity of many wildlife diseases and the ecological context within which they operate. Hence, preventative approaches to health management, in effect working ‘upstream’, are more cost-effective than addressing human, animal and ecosystem health problems once they occur.

1.9. The One Health approach aims to sustainably balance and optimize the health of people, wild and domestic animals, and ecosystems. It has become an established, integrated and unifying approach to health, including to address emerging infectious diseases, and is endorsed by multiple national and international organizations and intergovernmental agreements.

Picture 2.1. Maintaining resilient, functioning ecosystems represents a preventative approach to health management, in effect working 'upstream'.
This is more cost-effective than addressing human, animal and ecosystem health problems once they occur. *Photo credit: Canva.*

2. Human-driven changes in ecosystems and the impacts on health and disease

Drivers of population decline are responsible for disease emergence in wildlife, livestock and people, which is exacerbating threats to migratory species.

2.1. The usual drivers of population decline are also the drivers of disease emergence. This can then exacerbate the susceptibility of migratory species to pre-existing threats.

2.2. Disease emergence is influenced by multiple factors, which can be synergistic or cumulative in their contribution to ill-health. These include socioeconomic conditions, the sustainability of agricultural practices, and changes in land use and climate. Human-driven changes to ecosystems are increasing disease risks and escalating negative impacts on the health of humans and animals. Disease emergence is driven by, for example, the processes of landscape fragmentation, land-use change, unsustainable agricultural or aquacultural practice, overexploitation, invasive non-native species, pollution, climate change and other types of ecosystem disruption and ecosystem service loss. These problems, in turn, are the consequences of unsustainable pressures on resources.

2.3. Climate change is affecting the health of migratory species in multiple ways. Climate-induced changes in habitat and land use are altering environmental conditions for hosts, infectious agents and their invertebrate vectors (which are particularly sensitive to changes in temperature), with unpredictable consequences for the emergence of disease, including in new geographic locations.

2.4. Non-infectious disease conditions are also increasingly having negative effects on migratory species. For example, ill-health can be caused by pervasive toxic pollutants such as plastics, poisons, and chemical and organic pollution; human-induced injury; undernourishment; and stress from environmental disruption. In turn, these problems can reduce the resilience of wildlife populations to other diseases.

3. Interfaces and infectious diseases

Human activities that create interfaces between wildlife, livestock or people generate infectious disease risks, with particular zoonotic risks originating from intensive production systems.

3.1. Livestock-wildlife interfaces are areas of direct or indirect contact between livestock and wildlife, which are increased through, for example, agricultural development and expansion into wild areas. They are particularly problematic for transmission and spillover[5] and spillback[6] of infectious agents between species. Whatever the original source of the pathogen, livestock are a common source of zoonotic[7] pathogens for people.

3.2. However, pastoral systems with resilient adaptive breeds of livestock can be well-integrated within natural systems; these may share pathogens with wildlife without causing or suffering much harm.

3.3. Emerging zoonoses originating from wildlife, including those with potential human pandemic risk, typically stem from a change in human activity or unusual

[5] Spillover: transmission of an infectious agent from a host population or community where its prevalence may be relatively high, to a new host, usually crossing a species barrier.
[6] Spillback: transmission of an infectious agent in the reverse direction from that of the above.
[7] Zoonosis: an infection transmissible between humans and animals; 'zoonotic' is the adjective.

interactions with wildlife; livestock frequently act as intermediate host species, and transmission may also occur via invertebrate vectors.

3.4. Some live animal market systems have been shown to increase risks of pathogen transfer between hosts and can also act as drivers of pathogen change, increasing the likelihood of transmission between species, including to humans.

3.5. Especially when unregulated, trade in wildlife (both live animals and animal products) risks creating regional and international movements of pathogens, which can then lead to emergence of infectious diseases in wildlife, domestic animals and/or humans.

3.6. Intensive domestic animal farming and some other high-risk farming methods can act as sites where pathogens (from whatever source) may be amplified to epidemic proportions and/or transformed (e.g., by mutation, re-assortment or recombination) into more virulent or transmissible variants. These pathogens may subsequently spill over into wildlife and/or humans causing high mortality, sometimes with subsequent spillback of these pathogens into livestock.

4. Disease dynamics in relation to migration and migratory species

Migration can act as a strategy for improving wildlife health but may also result in long-distance transmission of pathogens, especially following contact with livestock.

4.1. Migratory species are essential components of well-functioning and resilient ecosystems. They provide a wide range of ecosystem services, from pollination and seed dispersal to multiple provisioning and regulatory services, and exceptional societal benefits.

4.2. The disease dynamics associated with migration and the physiological costs of migration are complex; the health outcomes for individuals and populations are situation dependent.

4.3. Although migration can create a potential risk of long-distance movement of pathogens, migration itself can be used as a strategy to reduce pathogen burdens. For example, migration can reduce the likelihood of infection within a population by, in effect, removing individuals too unfit to successfully migrate, and with them their genes for disease susceptibility.

4.4. Exposure of migrants to different habitats, and potentially different and diverse infectious agents, can build their resilience to infectious disease. Therefore, migration may serve to safeguard the health of wildlife, and, in turn, reduce the risk of infection transmission to domestic animals and people, depending on the local context.

4.5. Migratory species can host endemic, emerging or re-emerging infections, including those that have been transmitted from livestock. Consequently, migration can bring infectious agents to new areas and to naïve populations, including livestock, increasing the likelihood of disease.

4.6. Migratory species can be viewed as both the victims of disease and, at times, the vectors of infection. As a consequence of the latter, they can suffer indirectly if they are subject to inappropriate disease control measures (including lethal responses) or other consequences arising from negative public perceptions.

4.7. Migration can also increase the likelihood of a range of non-infectious health conditions as animals move through different habitats, or if migration patterns change in response to climate change. For example, migratory wild animals may suffer or die from anthropogenic traumatic injury; undernourishment; exposure to toxins or pollutants; or overexploitation.

4.8. Human activities are profoundly influencing migratory species. Changes in migration, along with the drivers of these changes, can not only have wide-ranging ecosystem and population-level effects, but also influence infection dynamics.

4.9. The effects of migratory change and disruption on infection dynamics are difficult to predict, and, as yet, there is a lack of real-world data on these relationships. Nevertheless, there is potential for increased pathogen burdens to compromise the health of migratory wild animals, and to negatively impact the health of domestic animals and people.

5. Key health issues in migratory species

An expert consultation identified infectious and non-infectious disease issues in CMS-listed species and the importance of human drivers in their emergence.

5.1. A pilot expert consultation was conducted as part of this review, with the aim of exploring disease issues in migratory species listed in CMS Appendices I and II.

5.2. Infectious disease was viewed as a ‘highly important’ conservation issue in a majority of species groups and was a particular concern in avian and terrestrial species (85% of groups).

5.3. While the role of wild birds as a reservoir and source of HPAI viruses in domestic species and humans is well recognized, importantly, this consultation highlighted that HPAI is a notable conservation concern in a large, taxonomically diverse range of migratory avian species.

5.4. Other infectious diseases were considered highly important conservation concerns in terrestrial and aquatic species. These included anthrax, tuberculosis, rabies and mange in a range of terrestrial mammal species, and canine distemper in multiple marine mammal species.

5.5. Experts viewed the most prominent underlying drivers of priority infectious disease issues to be habitat loss, degradation or disturbance, climate change, and agriculture/aquaculture; the latter was considered a particularly important driver of HPAI. Frequently, multiple drivers were considered important.

5.6. Chemical toxicants, biological toxins, such as those produced by algal blooms, and pollutants were considered a highly important health issue, in particular for avian and aquatic migratory species (62% and 55% of species groups respectively).

5.7. Incidental anthropogenic trauma was also considered a highly important issue in a broad range of taxa, especially aquatic species (73% of aquatic species groups), which are commonly affected by catch and injury from, or entanglement in, marine debris.

5.8. There is a notable lack of knowledge about the infection and disease status of many migratory species. Even in better-studied species such as primates, there remains the potential for currently unknown or unrecognized pathogens to become a future threat.

6. Knowledge gaps and shortcomings in national and institutional approaches to wildlife health

Lack of planning for and understanding of threats to wildlife health compromise preparedness.

6.1. There remain significant gaps in national and organizational prevention, contingency and response planning for wildlife disease threats. Preparedness is compromised where countries lack functional wildlife health-related programmes and policies, and where there is a lack of institutional structures to protect human, agricultural or wildlife interests from endemic or introduced diseases.

6.2. Despite widespread acceptance of the value of One Health approaches, wildlife is often the ‘poor relation’; inequity in decision-making about health can lead to poor health outcomes across the sectors.

6.3. Our understanding of the causes and epidemiology of wildlife disease is often poor, a situation exacerbated by limited surveillance, outbreak investigation and research. This reduces our ability to prepare for, prevent or mitigate disease risks across all sectors of wildlife, people and domestic animals.

6.4. A perception of wildlife disease as a matter for agriculture rather than wildlife conservation has meant that environment sections of government are often reluctant to lead on wildlife and ecosystem health issues, with potential negative health outcomes across sectors as a consequence.

6.5. There remains a clear need for improved global systems for wildlife disease surveillance and reporting to aid preparedness and responses.

Picture 2.2. Experts considered highly pathogenic avian influenza (HPAI) to be a highly important conservation concern in a large, diverse range of migratory avian species.
In recent years, HPAI has caused multiple mass mortalities of seabirds and waterbirds, including these white pelicans (*Pelecanus onocrotalus*) in Senegal. *Photo credit: FAO.*

2.2 Recommendations

1. Tackling key drivers of disease emergence

1.1. It is important to recognize the commonalities between the drivers of both migratory species population decline and disease emergence.

1.2. As such, urgent enhanced actions are required to address the drivers of population decline, including through climate change mitigation and adaptation; reducing habitat loss, fragmentation and degradation; limiting pollution; reducing overexploitation; preventing the spread of invasive non-native species; and addressing high-risk agricultural and aquacultural practices. Addressing these drivers of disease emergence will reduce threats and pressures on wildlife and ecosystems, and is key to limiting ill-health and improving resilience to disease across sectors.

2. Enabling frameworks for health

2.1. Implementation of the Sustainable Development Goals would significantly enhance the health of people, animals and the environment worldwide.

2.2. One Health and ecosystem approaches appreciate the interconnectivity of health between wildlife, livestock and people, and are essential for maximizing health across sectors. However, One Health approaches can often be anthropocentric, with insufficient attention on promoting the health of wildlife. They should instead be used to promote equitable decision-making about health management, appreciating that promoting the health of wildlife reduces risks to humans and their interests as well as bringing conservation benefits.

2.3. One Health approaches require multisectoral and transdisciplinary collaboration and appropriate organizational structures and communication. These approaches should be promoted and enhanced at the national level, along with cooperation at the international level, in order to prevent and respond to wildlife health threats.

2.4. Preventative approaches are both cost-effective and necessary to safeguard health in migratory wildlife, domestic animals and people. They should be a key feature of any future pandemic instrument being negotiated under the auspices of WHO. The role of those involved in biodiversity conservation and sustainable livelihoods should therefore be recognized for and actively supported in their contribution to health across all sectors. The role of UNEP in the FAO UNEP WHO WOAH Quadripartite is warmly welcomed.

3. Managing interfaces and infectious diseases

3.1. Livestock-wildlife interfaces created by, for example, agricultural development and expansion into wild areas, are particularly problematic for infectious agent transmission and emergence. There should be a focus on ensuring effective protection of well-connected natural habitat and minimizing fragmentation to reduce 'edge effects' where transmission of infections could occur.

3.2. Every effort should be made to better manage livestock to reduce risks for the benefit of all. Measures include:

a) Improving biosecurity, livestock vaccination, and better planning of both the location and nature of livestock management.

b) Reassessing and reducing dependence on intensive livestock production systems that present particular threats to human and wildlife health. Reducing consumption of animal protein from these systems is desirable, both from an environmental and wildlife health perspective.

c) Using resilient, adaptive local breeds of livestock that pose a lower risk in terms of pathogen spillover and spillback.

3.3. Robust efforts should be made to prevent additional sources of pathogen pollution/introduction to wildlife and their environment, always recognizing the value of robust risk assessments and preventative approaches. These sources include feral animals, traded plants and animals, non-native species and animals released for game, conservation or other purposes.

3.4. Efforts should be made to reduce or otherwise manage practices in live animal market systems that pose a high risk of pathogen transfer and are drivers of pathogen change.

4. Tackling non-infectious disease

4.1. In addition to tackling the overarching drivers of disease emergence, measures to minimize non-infectious causes of wildlife mortality include:

a) Taking action to reduce and mitigate pollutants and poisons, particularly where regulatory restriction and/or enforcement is required to prevent release or use of pollutants and poisons at source.

b) Mitigating human-induced injury of wildlife from infrastructure and other human developments and activities.

c) Removing barriers to migration such as habitat fragmentation, or physical barriers that can result in death through undernourishment.

d) Considering the effects of nutritional deficits and stressors in terms of resilience to other diseases when planning changes to land use or altering habitats.

5. Improving institutional preparedness, planning and response

5.1. Rather than seeing animal health as the sole responsibility of agriculture ministries, environment sections of government also need to fully engage in wildlife health and recognize their roles in promoting resilience of ecosystems and health outcomes across sectors, including in human pandemic prevention.

5.2. The development of national wildlife health strategies is encouraged, noting the important role they play in successful One Health approaches.

5.3. The health of migratory populations can be protected and fostered by strengthening wildlife health systems. These comprise the expertise, resources and organizational structures that enable effective planning, and disease surveillance, diagnosis and management. Building this capacity is relatively inexpensive compared with the potential costs associated with reactive management of disease outbreaks. These should be integrated with human and domestic animal health systems within a One Health framework.

5.4. Governments, their agencies, and all those with responsibility for managing wildlife are encouraged to carry out contingency planning during times without outbreaks (‘peacetime’), ensuring that all relevant stakeholders are involved. This will not only help prevent wildlife health problems occurring in the first place, but also facilitate swift and appropriate responses in emergency situations. It will also minimize the adverse impacts of disease outbreaks and guard against inappropriate control measures such as lethal responses.

5.5. Robust wildlife health surveillance, with conservation (in parallel to livestock protection) as a key goal, is required to support contingency planning, early warning systems and risk assessments. Ecological and population monitoring should be integrated into surveillance systems so that the epidemiology and impacts of disease can be better understood.

5.6. Thorough investigations of outbreaks of wildlife disease are needed to help inform epidemiological understanding and assist in future disease planning to minimize impacts across health sectors.

5.7. Improvements are needed in wildlife diagnostics, including increased capacity in testing facilities. Additionally, it is important to prevent delays in diagnosis and research caused by regulatory limitations on transporting diagnostic and research specimens across national boundaries.

6. Filling knowledge gaps and prioritisation

6.1. In line with Article II.3.a) of the Convention, Parties should promote, cooperate in and support research relating to migratory species in the context of disease.

6.2. Efforts should be made to address the significant gaps in our knowledge of the epidemiology and drivers of many diseases of migratory species.

6.3. Research and resourcing should be targeted at priority health threats to migratory species, and particularly to species with a poor conservation status.

7. Improving reporting and information sharing

7.1. Global disease information and reporting systems for wildlife are essential for early warning as well as other aspects of disease control. These systems require further improvement to ensure rapid reporting and inclusion of contextual epidemiological and environmental information to better inform understanding of disease events and their conservation impacts.

7.2. Timely information and data sharing on wildlife health issues between nations is encouraged, to enable early warning and risk assessments for management decision-making.

8. Using information sources for wildlife health

8.1. Guidance on managing wildlife health and responding to diseases is available, and those with responsibilities for wildlife are encouraged to use it and adapt it for national and specific settings.

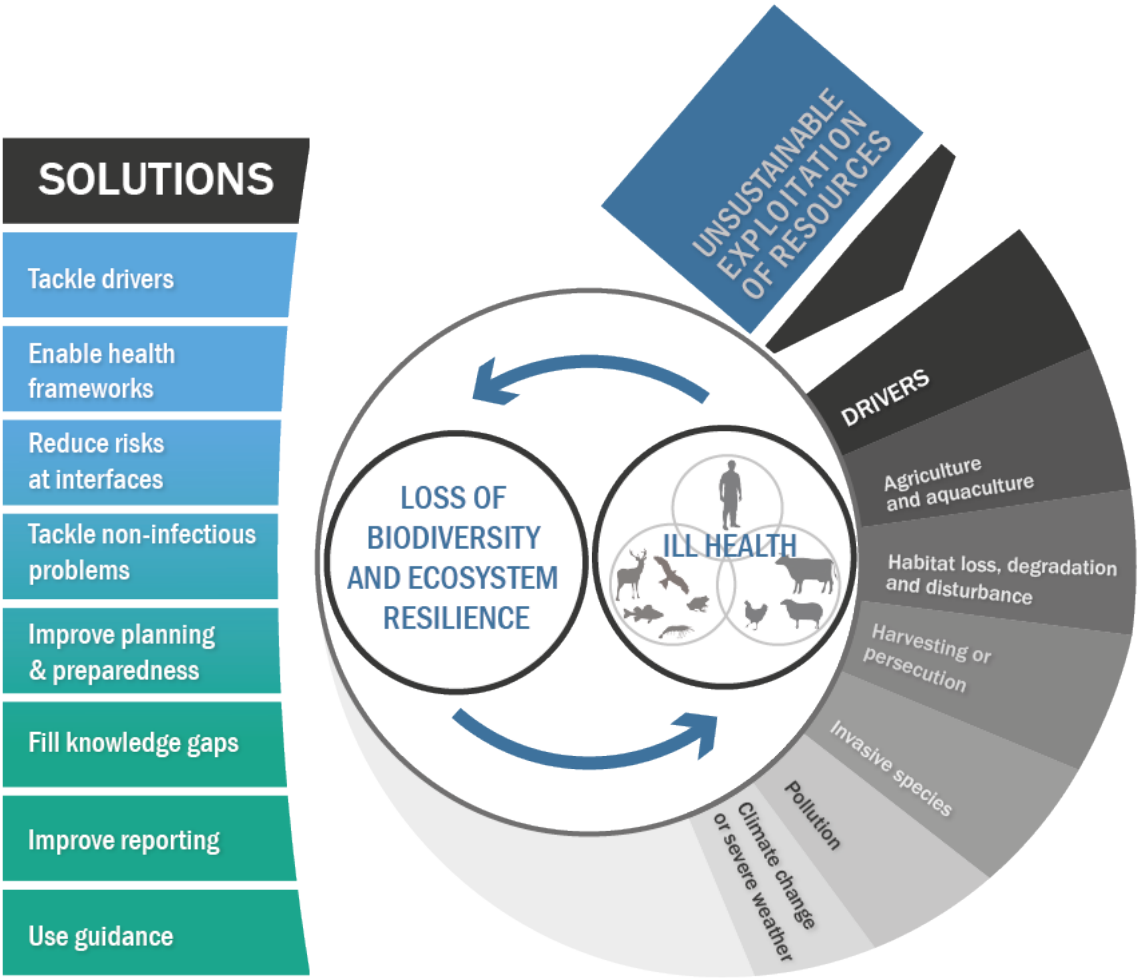

Figure 2.1. Overview of the problem and recommendations to enhance the health of migratory species plus linked populations of wildlife, domestic animals and people. The environment is the 'setting' for health: unsustainable exploitation of natural resources drives loss of biodiversity and ecosystem resilience, as well as disease emergence. Disease emergence, in turn, drives loss of biodiversity and ecosystem resilience, further compounding problems. Health is interconnected: ill-health in wildlife often has knock-on effects for people and livestock (see Chapter 4).

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3 INTRODUCTION

3.1 CMS and wildlife health

The United Nations Environment Programme (UNEP)'s Convention on the Conservation of Migratory Species of Wild Animals (Convention on Migratory Species, or CMS) has worked on specific aspects of wildlife health since 2005. It has played an important role in responding to poisoning and avian influenza in migratory species and at the CMS COP12, in 2017, adopted the UNEP/CMS/Resolution 12.6 on Wildlife Disease and Migratory Species. As will be explored further within this report, a wide range of conservation threats relate to the health of wildlife and arguably CMS is already playing an important role in prevention of health problems. Although wildlife disease was not prominent on the COP13 agenda, the COVID-19 pandemic has since led to renewed interest in wildlife health and the broader context of One Health, with the CMS contributing to the Preventing the Next Pandemic report (UNEP and ILRI, 2020).

Other than the above Resolution and those specific disease activities with their respective Resolutions, a review of other CMS Resolutions and other CMS 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 number of these documents discuss 'hazards' to species, they mainly discuss non-infectious threats, with little or no focus on infectious disease, overall health, health monitoring or infectious agent surveillance. Recognizing the increasing anthropogenic pressures on wildlife and thus the increasing infectious and non-infectious disease threats that arise from unsustainable pressures on natural resources, it is worth noting that some of the older action plans may not necessarily reflect recent or emerging disease threats. Moreover, a paucity of good wildlife health surveillance systems compounds our poor understanding of disease threats to species.

With increasing awareness of the importance of wildlife health it was recognized that there is scope for increased CMS focus on this topic. Following the COP13, the CMS Sessional Committee of the Scientific Council undertook action regarding the health of migratory species, and consequently proposed the establishment of a new Working Group on Migratory Species and Health[8], alongside this commissioned report and updated health resolutions for avian influenza and wider wildlife health for consideration at COP14.

3.2 Remit and structure of this report

3.2.1 Aims and objectives

For this report, we aimed to conduct a review of the health of migratory species for CMS based on the terms of reference set out in UNEP/CMS/ScS-SC5/Doc.6.4.1. We aimed to inform the development and prioritisation of the work programme of the CMS Working Group on Migratory Species and Health. We also aimed to inform this Working Group's contributions to the One Health High-Level Expert Panel (OHHLEP) – which advises the UNEP, WHO (World Health Organization), FAO (Food and Agriculture Organization of the United Nations (UN)) and WOAH (World Organization for Animal Health) in their collaboration under the Quadripartite for One Health – as well as other relevant initiatives

[8] Working Group on Migratory Species and Health terms of reference: https://www.cms.int/sites/default/files/document/cms_scc-sc5_outcome11_tor-wg-migratory-specides-and-health_e.pdf

such as the Scientific Task Force on Avian Influenza and Wild Birds, co-convened by CMS and FAO, and the Working Group on Wildlife under WOAH (and WOAH's Wildlife Health Framework).

Our objectives were to:

- Review the context of wildlife health and conservation.
- Review the interdependence of health across the sectors, and the need for One Health and ecosystem approaches to health.
- Review disease dynamics in relation to migration, highlighting the potential consequences of migration disruption for disease dynamics, including zoonotic risks.
- Explore at a high level the key known health issues affecting CMS-listed migratory species.
- Explore the underlying processes driving ill-health in migratory species and associated populations.
- Bring further attention to these topics, with specific requests for action to promote health in migratory species and to manage associated disease risks.

3.2.2 Report structure

The report comprises the following main chapters:

Chapter 4. Key concepts in wildlife health, and the interdependence of health and environmental sectors

A summary of key concepts in wildlife health, the relevance of wildlife disease to biodiversity conservation and to domestic animals and humans. The chapter also explores the anthropogenic drivers and activities that can lead to disease emergence, and the benefits of One Health and ecosystem approaches to health.

Chapter 5. Migration, migratory change and disease

A review of key concepts relating to wildlife migration, and our current understanding of health and infectious disease dynamics in relation to migration. The chapter also explores the potential consequences of migration disruption for the health of migratory wildlife and infectious disease dynamics.

Chapter 6. Key health issues in migratory species and their broad underlying causes

An expert consultation to determine, at a high level, key known health issues affecting migratory species listed on the CMS Appendices I and II, and the broad driving processes considered to underlie these problems.

Chapter 7. Conclusions and recommendations

A concluding chapter drawing together key messages from the report and recommendations for action.

3.2.3 Methods

Chapters 4, 5 and 7 were compiled through synthesis and review of peer-reviewed papers and other published literature. In Chapter 6, an expert consultation exercise was conducted.

3.2.4 Timeframe

This report was principally compiled from March to June 2023. The draft was refined following input from the Sixth Meeting of the CMS Sessional Committee of the Scientific Council[9] (July 2023), and in light of comments from reviewers.

3.2.5 Accessibility

The authors of this report are mindful that the field of health is particularly jargon-laden and have deliberately attempted to make the language accessible for the intended audience of decision makers, policy makers and interested parties who may not be so familiar with health terminology. For reference, there is a Glossary and Abbreviations section (Chapter 8) at the end of the report listing and explaining the main terms and abbreviations used.

[9] https://www.cms.int/en/meeting/sixth-meeting-sessional-committee-scientific-council-scc-sc6

4 KEY CONCEPTS IN WILDLIFE HEALTH, AND THE INTERDEPENCE OF HEALTH AND ENVIRONMENTAL SECTORS

This chapter introduces some key concepts in wildlife health and the relevance of wildlife disease to biodiversity conservation. It explores how health and disease in wildlife are linked to disease in domestic animals and humans (including pandemic risk), the drivers and activities that can lead to disease emergence, and hence the benefits of One Health and ecosystem approaches to health.

4.1 Key concepts and terminology

This section summarises some key concepts and terminology relating to wildlife health and disease. Definitions are also listed in the Glossary (Chapter 8).

4.1.1 Wildlife health

For this review, we define wildlife health as,

"*The physical, physiological, behavioural, and social wellbeing of wild-living*[10] *animals measured at an individual, population and wider ecosystem level, and their resilience to change*" (Meredith *et al.*, 2022).

From this perspective, 'health' in individuals and wider populations infers that the basic needs of individuals and populations are met and they are able to perform their usual functions. It infers that populations are resilient and have capacity to adapt to social, epidemiological or ecological change (Stephen, 2014).

4.1.2 Disease

4.1.2.1 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 the above definition, it is important to appreciate that not all disease is caused by infectious agents, as there is also a wide range of non-infectious conditions which can impair health and function (see below).

Disease may have a range of outcomes. Animals can recover from disease, and an infection or infectious disease may lead them to be more resistant to future infection through development of immunity. However, diseases make animals ill, and can have a range of other, more subtle impacts such as negatively affecting reproductive success, development, behaviour and/or an individual's ability to compete for resources or evade predation. Disease may lead to death, or to ongoing health issues. An infection or disease may also increase susceptibility to other disease conditions, exacerbating any detrimental effects at a population level.

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[10] We include feral animals in this term.

See Table 4.1 for descriptions of terms.

Table 4.1. Common terminology.
Adapted from *e.g.* Wobeser (2006) and Thrusfield *et al*. (2018).

Terminology	Description
Dead-end host	A host which is infected by a particular infectious agent but not able to transmit it to other hosts.
Disease	Impairment of normal functions due to the presence of an infectious agent or other, non-infectious impairment.
Emerging infectious disease	An infectious disease that has recently appeared in a population or is rapidly increasing in incidence or geographic range (Morse, 2004).
Endemic	The continual and 'normal' presence of an infectious agent or disease within a population and/or area.
Infection	The presence of an infectious agent in an individual. An individual host can be 'infected' with an agent, but this may or may not cause 'disease' in the host.
Infectious	An ability for an agent to be transmitted from an infected individual to another individual.
Infectious agent	Here, defined as a parasite (infectious organism) or other agent that is transmissible between hosts, either directly (via *e.g.* contact or aerosol) or indirectly (via *e.g.* food or a vector species) (see Table 4.2; WHO, 2020).
Infectious disease	Disease resulting from an infectious agent.
Non-infectious disease	A health impairment other than that caused by an infectious agent (see Table 4.2 for examples).
Pathogen	An infectious agent that has potential to cause disease.
Parasite	An infectious organism, which may be a microparasite, *e.g.* virus, bacterium, protozoan or fungus, or microparasite, such as a helminth (parasitic worm).
Reservoir	A host population, species or environment that serves as a persistent source of an infectious agent to other populations of animals or humans in the same locality.
Silent infection	An infection that causes no, or subclinical, disease.
Spillover	Here, defined as transmission of an infectious agent from a host population or community, where its prevalence may be relatively high, to a new host, usually crossing a species barrier.
Subclinical disease	A low-grade disease that is not outwardly (clinically) detectable.
Transmitter	A host which is infectious to other hosts, *i.e.* serves to transmit an infection on to other individuals, whether of the same or a different species.
Vector	An organism (frequently an arthropod) responsible for transmitting an infectious agent from one host to another.
Virulence	The degree to which an infectious agent is harmful to the host.
Zoonosis	Here, defined as an infection transmissible between humans and animals; 'zoonotic' is the adjective of this[11].

[11] Noting that the WHO (2020) defines a zoonosis more specifically as, "Any disease or infection that is naturally transmissible from vertebrate animals to humans".

4.1.2.2 Infection and infectious disease

Animals can be 'infected' by any type of infectious agent (Table 4.2), however, if the infection has no negative impact (is not impairing normal functions), the individual is not regarded as being 'diseased' and does not exhibit clinical signs. In this case, they are silently infected (Table 4.1). However, depending on the type of infectious agent, it may have the potential to cause disease (thus being considered a pathogen) and associated clinical signs, whether in individuals of the same, or other susceptible, species.

An infected animal is not necessarily infectious (Table 4.1): it is only infectious if capable of transmitting the infectious agent to another animal directly, for example via contact, or indirectly via, for example, contamination of a surface or environment with bodily fluids, or through a vector (usually an arthropod, such as a mosquito or tick). Hosts that are unable to transmit a particular infectious agent to other individuals can be referred to as 'dead-end' hosts (Table 4.1).

Infectious disease reflects a complex interplay between the infectious agent, host animal and their environment. Factors that influence whether, and how severely, disease occurs in an individual and the wider population include how harmful (pathogenic) the agent is; host factors such as their species, age, sex, nutritional status, immune status, concurrent disease, genetics and population size; and environmental factors such as habitat quality, pollutants, climate, local human activities and the presence of vectors in the environment (Thrusfield *et al.*, 2018) (Figure 4.1). These environmental factors also influence how successful an infectious agent is in surviving outside a host, as well as the number of hosts a particular type of agent has the potential to infect (Thrusfield *et al.*, 2018).

It should be appreciated that any individual wild animal represents a "biological package", likely to be hosting a range of infectious agents (Davidson and Nettles, 1992), many of which will not be pathogenic to it; and that a host may also be subject to various non-infectious conditions. External stressors such as food shortage or inclement weather conditions have the potential to precipitate or exacerbate infectious or non-infectious disease in the host. For example, a host animal could have a low-grade toxicity from ingesting a heavy metal such as lead, while concurrently hosting multiple infectious agents, such as viruses and parasite burdens (worms, ticks etc.), which could be causing sub-clinical or clinical disease. When the host is exposed to external stressors, these individual diseases can be cumulative, interacting and often mutually reinforcing adverse effects on individuals and populations (Stephen, 2022). Within this context, it is possible to appreciate the complexity of the balance between health and disease, and the importance of resilience.

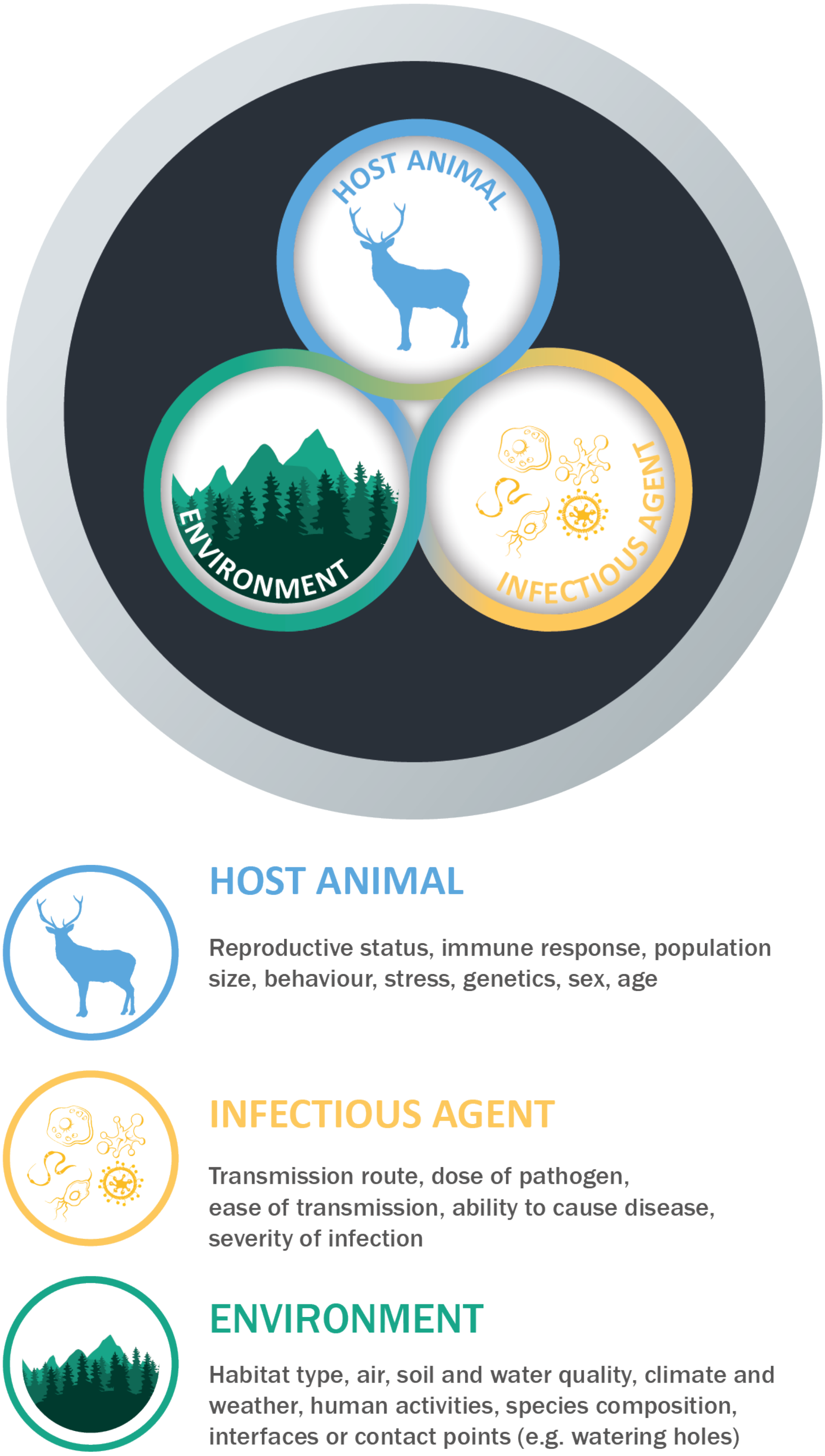


Figure 4.1. Factors influencing whether an infectious agent causes disease: a representation of the classic host-pathogen-environment triad.
Adapted from Thrusfield *et al.* (2018). This is intended as a simple, schematic representation, with the central intersections representing the points of overlap at which disease occurs. The outcome of the presence of an infectious agent will depend on a wide range of host, environmental and agent factors, and the degree of influence each node has on disease occurrence will vary depending on the system. Possible outcomes include no infection, silent infection, subclinical disease, disease, death, recovery and/or immunity.

4.1.2.3 Non-infectious disease

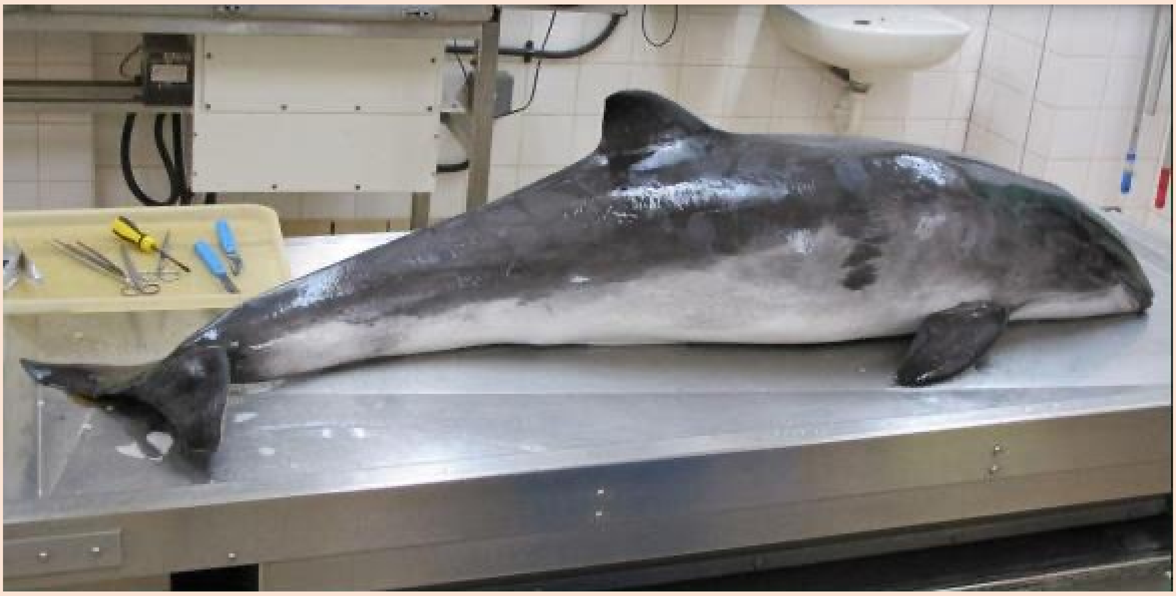
As discussed above, wild animals are also susceptible to a range of non-infectious disease conditions, which can be natural in origin or originate from human activities. These include: toxicity from toxicants (defined as harmful substances introduced into the environment, such as lead, chemicals (see Box 4.1) or pharmaceuticals) or toxins (defined as poisons originating from biological sources, such as algal toxins, plants or animals); traumatic injury, including anthropogenic trauma such as from vehicle collisions or interaction with fishing gear and marine debris; chronic stress, including through human disturbance, noise or light pollution; developmental or genetic disease; disease from extremes of temperature; undernourishment or nutritional disease; disease from ingestion of foreign objects, such as plastic; and other forms of environmental injury such as drowning or burn injury.

Table 4.2 lists infectious agents and non-infectious causes of disease as categorised for the purpose of this review (in particular, the expert consultation conducted in Chapter 6).

Box 4.1. Case example: Mutually reinforcing disease conditions.

Toxin exposure in marine mammals

Marine mammals are susceptible to the effects of chemical compounds that persist and accumulate over time within their bodies. Included in these are compounds known as persistent organic pollutants (POPs). In particular, polychlorinated biphenyls (PCBs) are very long-lasting and can significantly impact the health of marine mammals. These chemicals enter the marine environment most commonly as a result of industrial processes, as well as from landfill and environmental run-off. In Europe, a ban on PCBs was enforced in the 1980s (EEA, 2001), however, significant levels of these persistent compounds are still present in European waters, despite the ban, and pose a threat to marine mammal health. A recent study demonstrated that PCBs are present in relatively high levels within the blubber of stranded harbour porpoises (*Phocoena phocoena*) in the United Kingdom. They are linked to an increased risk of infectious disease through compromised immune system function, as well as mortality and reduced overall reproductive health (Hall *et al.*, 2006; Williams *et al.*, 2020).



Picture 4.1. Persistent organic pollutants, such as PCBs, can compromise the immune system and increase the risk of infectious disease.
This effect has been demonstrated in marine mammals such as harbour porpoises, which can accumulate high levels of these compounds in their blubber**.** *Photo credit: CSIP-ZSL*.

Table 4.2. Categorisation of a. infectious and b. non-infectious causes of disease. Adapted from Beckmann *et al.* (2022).

a. Infectious agents

Viruses
Bacteria
Fungi or yeasts
Protozoa
Helminth endoparasites (worms)
Arthropod ectoparasites, such as fleas, ticks, mites or lice[1]. Includes nest parasites
Other: including parasitoids[1], myxozoa, prions and transmissible tumours[1]

b. Non-infectious causes of disease[2]

Category	Description
Toxin or pollutant	A toxicant (harmful substance introduced into the environment), toxin (poison originating from a microorganism, plant or animal) or pollutant (any environmental contaminant).
Incidental anthropogenic trauma[3]	Incidental causes of traumatic injury such as collision, entanglement or other injury. Includes interaction with fishing gear (often referred to as bycatch) and marine debris.
Anthropogenic stress or disturbance[4]	Anthropogenic chronic stress or disturbance, including through noise or light pollution/disturbance.
Physiological response to extreme climate	Physiological responses resulting from climatic extremes, such as hyperthermia, hypothermia or frostbite.
Nutritional deficiency or disease	Undernourishment (starvation or lack of water), or nutritional disease relating to an imbalance, excess or lack of certain nutrient(s) in the diet.
Foreign-body ingestion	Ingestion of plastic (the cause of plasticosis (Charlton-Howard *et al.*, 2023)) or other foreign material.
Other environmental injury	*E.g.*, electrocution, drowning, burn injury.
Other	*E.g.*, degenerative (age-related), developmental, genetic or behavioural condition, neoplasia (other than transmissible tumour), immune condition including allergy or autoimmune disease, or other health condition.

[1] For the purpose of this report, arthropod ectoparasites, parasitoid flies and transmissible tumours are categorised as infectious agents: ectoparasites are more correctly considered to cause an infestation, parasitoids are parasitic insects and some transmissible tumours may not strictly be considered to cause an infection.
[2] As categorised for the expert consultation described in Chapter 6.
[3] This category is named 'incidental' anthropogenic trauma to differentiate it from persecution-related traumatic injury that leads to outright mortality (persecution was categorised as an 'other problem' for the purposes of the expert consultation in Chapter 6, as per Table 11.2). Traumatic injury that might occur through natural ecological processes such as predation or competition was also categorised under 'other' ('ecological') problems' (Table 11.2) rather than as a cause of disease.
[4] Chronic stress or disturbance can be anthropogenic or natural in origin: in Chapter 6, the latter is categorised as an 'other ('ecological') problem as opposed to a cause of disease.

4.2 Wildlife health and biodiversity conservation

4.2.1 Conservation status of migratory species

Populations of many migratory and non-migratory wild species are in decline owing to a multitude of factors which are commonly driven by human activities. These declines and their drivers, which are of key relevance to this report, are explored further in the State of the World's Migratory Species report (UNEP-WCMC, 2023).

4.2.2 Wildlife health and biodiversity conservation

Infectious agents are a natural component of ecosystems. Consistent with the definitions of wildlife health and disease provided above, disease in some individual wild animals is to be expected and can be a mechanism for regulation of population size. Diseases of concern to wildlife conservation are those to which a particular population is unable to respond or to which it is not resilient 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 is indication of a negative impact at the population level. Disease can be a particular concern when populations are declining as a result of other drivers such as habitat loss, pollution or persecution, at which point disease events may cause a decline of such severity that the population is unable to rebound. This can lead to local extinction events (Aguirre and Tabor, 2008).

As previously discussed, animals carrying infectious agents may not necessarily demonstrate any clinical signs of infection (disease) but can still act as a source of infection to other animals. An infection that causes no harm in one population may have the potential to cause severe disease in another population or species, particularly if it is novel to them. Such introduced or 'exotic' infections are of the greatest concern to species conservation and are commonly associated with invasive non-native species and other released wild animals.

Disease-induced declines in wild animal populations can negatively impact ecosystems via loss of the ecological benefits they provide, such as negative impacts on food webs, nutrient cycling, pollination and pest occurrence, which may in turn impact human livelihoods and economics (Machalaba *et al.*, 2020a). Large herds of grazing ungulates, for example, provide essential nutrients to grasses and plants via their excretions; their feeding or foraging behaviours can also regulate plant growth, sustaining the biodiversity of plant and animal species in the ecosystem they inhabit (Kauffman *et al.*, 2021). Thus, disease outbreaks in such species may have wider ecosystem impacts. The impact of rinderpest on wild ungulates and their grassland ecosystems in East Africa has been a commonly cited example of this (see Box 4.2): eradicating rinderpest from wildebeest (*Connochaetes taurinus*) may have ultimately shifted the Serengeti ecosystem from being a net source of carbon to a net carbon sink (Holdo *et al.*, 2009).

Box 4.2. Case examples: Ecological impacts of wildlife diseases

Sylvatic plague in prairie dogs

Population declines in prairie dogs (*Cynomys spp.*) in North America as a consequence of sylvatic plague due to infection with *Yersinia pestis* have led to wider ecosystem change. This includes changes in grassland plant composition and altered nitrogen content in soil. There has also been linked mountain plover (*Charadrius montanus*) population decline, since this species has a preference for nesting on sparsely vegetated prairie dog burrows (Eads and Biggins, 2015).

Rinderpest in wildebeest

Loss of wildebeest (*Connochaetes taurinus*) due to rinderpest (originally spread from domestic cattle at the end of the 19th century) changed the ecology of East African grassland systems. The concerted efforts to eradicate rinderpest in cattle and wildlife may have ultimately shifted the Serengeti, Tanzania, from a carbon source into a carbon sink (Holdo *et al.*, 2009).

Picture 4.2. East African grasslands were transformed by the impact of the introduction and ultimate eradication of rinderpest in wildlife.
Photo credit: Canva.

Closely allied to the concept of wildlife health is the value of genetic diversity in wildlife populations, which also confers resilience to environmental and ecological change. Small and/or fragmented populations are at greater risk from the negative impacts of inbreeding, harmful genetic mutations and reduced genetic variation. These intrinsic factors can compromise the ability of populations to adapt to change and may increase their susceptibility to infectious disease, and potentially their risk of extinction (Frankham *et al.*, 2012).

4.2.3 Conservation threats as drivers of disease

As per above, the health of wildlife and their ecosystems are strongly interconnected. The environment can be described as the setting (place and context) and determinant for health, and large-scale anthropogenic changes such as habitat degradation or loss, or climate change, can not only influence population size, but also infectious disease dynamics and wildlife health (see Figure 2.1). In this way, the presence and severity of diseases in wildlife can reflect the integrity of the ecosystem they inhabit (Stephen, 2022) (see Box 4.3). Threats to ecosystems often stem from broad driving factors such as landscape fragmentation, infrastructure development, agricultural expansion, overexploitation, pollution and climate change, which in turn may be the result of deep-rooted socio-political issues such as the increasing drive for economic wealth (Manfredo *et al.*, 2020; IPBES, 2020). These forms of ecosystem disruption and ecosystem service loss have been linked to an increased likelihood of disease events, as have human-driven changes such as introduction of invasive non-native species (frequently sources of novel pathogens) and human activities such as those described later in this chapter (IPBES, 2020). Such ‘drivers’ may be synergistic or cumulative in their contribution to disease.

Reduced habitat availability and/or quality can predispose wild populations to disease outbreaks in a number of ways, such as pushing populations to forage further afield where they may encounter novel infectious agents; causing nutritional deficits and stress, which may shift a sub-clinical infection into overt disease; and leading to closer contact with domesticated animals and humans, which increases the likelihood of disease transmission to, or from, wildlife (IPBES, 2020; Kock and Caceres-Escobar, 2022). Climate change is also affecting the health of wildlife, including migratory species. Climate-induced changes in habitat and land use are creating altered environmental conditions for hosts, infectious agents and their invertebrate vectors (which are particularly sensitive to changes in temperature) with unpredictable consequences for the emergence of disease, including in new geographic locations (*e.g.* Harvell *et al.*, 2009; Lord *et al.,* 2018).

In this way, the main conservation threats to wildlife species are also drivers of disease emergence, both in wildlife and linked populations of domestic animals and humans (Machalaba *et al.*, 2020a).

Picture 4.3. Conservation threats, such as habitat loss, also drive disease emergence. Habitat loss or degradation can additionally increase disease risk via stresses caused by disturbance or nutritional deficits, displacement of animals which then feed in novel habitats increasing exposure to new diseases, and via increased risk of infectious diseases from people and domestic animals. *Photo credit: Srikanth Mannepuri/Ocean Image Bank.*

Box 4.3. Case example. Deforestation, climate change and disease outbreaks

Hendra virus in bats

In Australia, the loss and degradation of natural forest through human activity appears to have increased the reliance of fruit bat (*Pteropus* spp.) populations on fruit and flowering trees planted in urban and suburban areas. This has enhanced the likelihood of contact events between bats and domestic animals and people and is considered a driving factor in Hendra virus outbreaks in horses, and in turn, humans (Daszak *et al*., 2006). Recent studies have supported this link and shown that spillovers of Hendra virus from bats to horses are associated with times of food shortage for bats, when they are more likely to use agricultural and urban areas. This contributes to higher rates of spillover of Hendra virus from bats to horses during winter in subtropical Australia, when limited native food sources are available, and after climate-induced nectar shortages in winter flowering *Eucalyptus* (Eby *et al*., 2023). As well as leading to behavioural changes that increase contact opportunities, nutritional stress appears to increase the risk of bats shedding Hendra and other viruses (Peel *et al*., 2019; Becker *et al.*, 2022). The destruction of native habitat, along with the increased risk of viral spillover to horses, and from horses to humans, has led to increased human-wildlife conflict (Eby *et al*., 2023).

Picture 4.4. Anthropogenic drivers of increased disease risk from bats.
Changes of habitat and impacts of climate change are increasing likelihood of contact between species like this black fruit bat (*Pteropus alecto*), domestic animals and people with consequent zoonotic disease risks. *Photo credit: Canva*.

4.3 Wildlife health and 'spillover'

Many infectious agents can remain and circulate within a wild population in the absence of transmission to or from other host species. This is typical for infectious agents and species that have co-evolved, and if a species is physiologically adapted to an infectious agent. Such host animals in which an infection is present but does not typically cause disease can potentially serve as 'reservoirs', that is persistent sources of an infectious agent to other populations in the same locality. Infectious agents can also persist in the environment, with this also serving as a potential reservoir of infection. More than one host species may also contribute to the maintenance of an infectious agent, thereby forming a reservoir community (Haydon *et al.*, 2002).

The term 'spillover' refers to transmission of an infectious agent from a host population or community (which may or may not be a reservoir), where its prevalence may be relatively high, to a new host, usually crossing a species barrier (see Table 4.1). The term does not necessarily infer that the infection is self-sustaining in the new host species, and spillover does not always lead to disease (Nugent, 2011; Fenton and Pederson, 2005). Spillover may lead to transient infection in the new host species, or should the infectious agent be able to adapt to and cause disease in the new host species – wildlife, domestic animal or human – then it may become an 'emerging' infectious disease. Emerging infectious diseases have been defined as those, "that have newly appeared in a population or are rapidly increasing in incidence or geographic range" (Morse, 2004, Table 4.1). The likelihood that spillover will lead to emerging infectious disease varies with the system and is challenging to predict. This is because an infectious agent may evolve and transform over time, and because the outcomes of exposure are greatly influenced by the aforementioned, complex interactions between an infectious agent, its host animal(s) and environment (Keesing and Ostfeld, 2021) (Figure 4.1).

Many wild taxa, including bats, rodents, ungulates, waterbirds, reptiles, amphibians, and primates, are known to host zoonotic infectious agents, that is agents which are transmissible between animals and humans[12] (Table 4.1) and might be pathogenic in the latter (a concept distinct from spillover, which is relevant only to novel instances of such transmission). Some migratory species in such taxa have been associated with the spread of zoonotic pathogens to people (Guy *et al.*, 2019; Johnson *et al.,* 2020). Where transmission from wildlife to people occurs, it is frequently through indirect transmission, for example via vectors (Table 4.1) such as mosquitos, as occurs with West Nile virus (Kock and Caceres-Escobar, 2022). Zoonotic pathogens may also be transmitted from wildlife to people through very close contact. For example, reptiles and amphibians are often in the higher risk groups for emerging zoonoses since they are frequently kept as pets (which can be sourced by the legal and illegal wild pet trade). They commonly harbour *Salmonella spp*. including multi-drug resistant strains and are a zoonotic risk in this context given their close contact with humans (Marin *et al.*, 2021).

Livestock or other domestic animals also, frequently, provide an intermediate link in the chain of transmission from wildlife to people. Zoonotic diseases most commonly originate from domestic animals, and particularly livestock, however. Food systems play an important role in transmission, which may occur through, for example, the consumption of livestock products (Rahman *et al.*, 2020; Grace *et al.,* 2012).

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[12] Noting that the WHO (2020) defines a zoonosis more specifically as, "Any disease or infection that is naturally transmissible from vertebrate animals to humans".

Picture 4.5. In terms of human health, zoonotic risks arise from wildlife but most commonly livestock.
Transmission of ‘wildlife’ pathogens to humans may occur directly through close contact or indirectly via a vector such as a mosquito. However, zoonoses commonly originate from domestic animals such as livestock, with food systems playing an important role in transmission. *Photo credit: Michael Kock*.

4.4 Health implications of livestock-wildlife interfaces

The wildlife-livestock interface may be described as the physical space in which some form of contact or shared use of resources occurs between wildlife and livestock populations. There is often a degree of spatial and/or temporal separation in this contact or shared resource use, so its nature may be difficult to characterise and quantify. Wild and domestic animal populations can share a wide range of pathogens and where extensive interfaces exist, the risk of disease transmission between these populations can be considerable. Examples include the extensive interfaces between wild waterbirds and domestic ducks when they are grazed in wetlands in some farming systems in Asia (Cromie *et al.*, 2012) (see Box 4.4) and the seasonal sharing of grasslands in the Kafue Flats in Zambia where cattle and lechwe (*Kobus leche*) share pasture (Kock *et al.,* 2002).

Transmission of infectious agents between wildlife and livestock is more likely to occur when species have close phylogenetic relationships (Cleaveland, Laurenson and Taylor, 2001; Davies and Pedersen, 2008). For example, cattle and ungulates, particularly in the Bovidae family, share a number of infectious agents transmitted across the wildlife-livestock interface. African buffalo (*Syncerus caffer*) can be reservoirs for many diseases transmissible to livestock including foot and mouth disease (FMD), theileriosis, brucellosis, and bovine tuberculosis, noting that the original source of these infections has often been livestock. When it comes to disease risks to wildlife, domestic animals are often the source of infection and act as reservoir hosts. It is worth noting, however, that indigenous breeds of livestock can be more resilient to infectious disease, and in this way are more suited to integration within natural systems. With increasing expansion of livestock into natural areas the transmission of pathogens from these populations is a significant concern for many wildlife species and can have severe consequences for their populations (Kuiken and Cromie, 2022).

Picture 4.6. Livestock-wildlife interfaces create disease risks to both sectors. At livestock-wildlife interfaces agents can be transmitted in either direction between the two, particularly where there is a close phylogenetic relationship. Both livestock and wildlife may act as reservoirs hosts. Some indigenous breeds of livestock, including these Ankole cattle, exhibit greater disease resistance than exotic breeds. *Photo credit: © Sergey Dereliev* www.dereliev-photography.com.

Box 4.4. Case examples: Interfaces with domestic animals as sources of wildlife disease

Pests des petits ruminants virus in saiga antelope, Siberian ibex and goitered gazelle

In 2016-2017, mass mortalities numbering thousands of Mongolian saiga antelope (*Saiga tatarica mongolica)*, which significantly reduced their population size, likely occurred following the introduction of 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 sheep and goats grazed on the same lands as saiga (Pruvot *et al.*, 2020).

Highly pathogenic avian influenza in wild birds

HPAI viruses originating in poultry have spread to wild bird populations and have had significant conservation impacts. The extensive interfaces between poultry and wild birds mean that infection is now readily transmitted between domestic and wild populations (CMS FAO Co-convened Scientific Task Force on Avian Influenza and Wild Birds, 2023; Wiethoelter *et al.*, 2015).

Picture 4.7. Domestic ducks grazing in a wetland – a clear wildlife-livestock interface.
The exchange of HPAI viruses between wild and domestic birds is easily facilitated by the now widespread practice of grazing large flocks of domestic ducks in natural wetlands. Protecting wetlands, including from this practice, can reduce HPAI outbreaks (Wu *et al.*, 2019). *Photo credit: Rob McInnes.*

Rabies and canine distemper in lions and wild dogs

Wild canids, and other species, are vulnerable to diseases such as rabies and canine distemper for which domestic/feral dogs may serve as a reservoir. Canine distemper virus (CDV) has a very broad host range and poses a threat to many endangered carnivore species. CDV was likely introduced into Africa with domestic dogs and has spilled into lions (*Panthera leo*) in the Serengeti, Tanzania, and African wild dogs (*Lycaon pictus*) in the Masai Mara, Kenya, causing significant infection and mortality in these species (Roelke-Parker *et al.*, 1996; Bengis *et al.*, 2002).

Picture 4.8. African wild dog – threatened by rabies and canine distemper. The conservation implications of the interface between domestic animals and wildlife are exemplified by the impact of domestic dog diseases on this species. Both rabies and canine distemper have had significant negative impacts on pack size and survival. Also see Chapter 7. *Photo credit: Canva.*

4.5 Wildlife markets, farms and other settings

In principle, any activity in which wildlife is taken from a natural setting, consumed, moved, or held in captivity, presents risks of infection transmission and zoonotic disease.

While the trade in wildlife for food, and its sale in traditional market systems, provides livelihoods and important food sources for many communities, this trade can have a significant conservation impact for some species and also presents risks of disease. Such trade systems can be the origin for outbreaks of zoonotic disease with pandemic potential, as in the case of Ebola virus disease (IPBES, 2020). Some types of activity in these food chains appear particularly high-risk, such as when, “live animals are held, slaughtered and dressed” in proximity to where meat or food is sold (WHO, OIE and UNEP, 2021), and where the trade and sale of wildlife and their products is illegal or poorly regulated (Bezerra-Santos *et al.*, 2021; WHO, OIE and UNEP 2021). Poor hygiene practices and the physiological and nutritional stress caused to wild animals in captivity in these settings contribute to increased risk of transmission both between species and to humans (Huong *et al.*, 2020; WHO, OIE and UNEP, 2021). Furthermore, any form of trade in wildlife provides opportunities for long-distance transfer of pathogens to geographical regions where they are novel, a process that has been termed ‘pathogen pollution’ (Daszak *et al.* 2000).

Wildlife farms also provide intensive production settings where wild animals are held in unnatural, commonly crowded conditions and pathogens (from whatever source, including humans, free-living wildlife or livestock) may increase in prevalence and be transmitted between wildlife and people. The farming of mink (*Neovison vison*) for fur has been identified as particularly high-risk activity in this regard (see Box 4.5) (FAO *et al.*, 2021).

As above, there are many other settings in which wild animals are held in unnatural conditions, in proximity to other wild animals and people, which present inherent risks of infection transmission within or between wild animals, and to humans. These include exotic pet centres, rehabilitation centres and other wildlife holding and/or breeding facilities (*e.g.* Snyder *et al*. 1996; Steele *et al.*, 2005; Walker *et al*. 2008). As in the case of other wildlife-livestock-human interfaces (see above section), many settings are amenable to management measures to reduce disease risks (see Chapter 7).

Picture 4.9. Wildlife-human interfaces in wildlife market systems, farming and consumption create disease risks.
Some types of activity in human food chains represent a particularly high zoonotic risk *e.g.* when live animals are held, slaughtered and dressed in proximity to where meat or food is sold and where the trade and sale of wildlife and their products is illegal or poorly regulated. *Photo credit: Axel Fassio, CIFOR.*

Box 4.5. Case example: Pandemic potential of zoonotic infections in particular wildlife settings

Highly pathogenic avian influenza virus and SARS-CoV-2 in farmed mink

Mink (*Neovison vison*) farming is practised in parts of Europe, North America and China. It has become a particular focus of concern from the perspective of zoonotic disease following outbreaks of SARS-CoV-2-associated disease, and H5N1 HPAI, on these farms. In disease outbreaks in mink on farms in the Netherlands (SARS-CoV-2) and Spain (H5N1 HPAI) there was evidence of onward, extensive mink-to-mink transmission of these viruses and, in the case of SARS-CoV-2, spillback of a novel variant to human workers (Oude Munnink *et al.* 2021; Agüero *et al.*, 2023). In these settings, mink appear well-suited to act as "mixing vessels" in which coronaviruses and influenza viruses can amplify and transform by mutation, re-assortment, or recombination into more virulent and/or transmissible variants, presenting a potential pandemic risk (Oude Munnink *et al.* 2021; Agüero *et al.*, 2023; Peacock and Barclay, 2023). The close proximity to humans presents opportunities for occupational exposure and possible onward spread (Oude Munnink *et al.* 2021; Peacock and Barclay, 2023).

Picture 4.10. Wildlife farming methods create opportunities for pathogen change and amplification, and the presence of people facilitates zoonotic risks.
Farming of wildlife species such as in this mink farm creates disease risks for wildlife and people, as has been seen recently with both avian influenza viruses and SARS-CoV-2. *Photo credit: Oikeutta Eläimille.*

4.6 Approaches promoting wildlife health and unifying health and environmental sectors

4.6.1 Wildlife health systems

Effective health systems comprise the expertise, resources and organisational structures that enable prompt disease surveillance, diagnosis and management, alongside effective disease prevention. The provision of robust and appropriately resourced health systems for wildlife will promote wildlife health and potentially reduce risks of spillover to, or from, domestic animals or people. Just as in the human and livestock health sectors, wildlife health systems should operate across scales with an emphasis on the development of robust systems at a local level (Watsa and Wildlife Disease Surveillance Focus Group, 2020). However, while health systems are often well established for humans and domestic animals, they are commonly poorly resourced or neglected for wildlife (World Bank and FAO, 2022) (see Chapter 7).

4.6.2 One Health

The One Health concept recognizes that a range of underlying societal, animal, and environmental factors can be linked to cross-sectoral disease problems (as discussed above). One Health approaches are collaborative, interdisciplinary ways of managing cross-sectoral health issues intended to achieve better health equity across these sectors. The One Health concept has now been endorsed by multiple national and international organizations and intergovernmental agreements. The COVID-19 pandemic shone a spotlight on the need for One Health approaches, and in March 2022, UNEP joined the Tripartite (FAO, WOAH and WHO), forming the Quadripartite Collaboration for One Health. An interdisciplinary OHHLEP (One Health High-Level Expert Panel) was formed in May 2021 to inform the work of the Quadripartite. This panel has defined One Health as,

"*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; see Figure 4.2).

Despite widespread acceptance of the One Health concept, historically, there has been a lack of collaboration between sectors in national and international health systems, with a common focus on wildlife as the source of zoonotic and emerging infectious diseases in humans or livestock, and a lack of recognition of the anthropogenic factors that frequently underlie health problems (Stephen *et al.*, 2023) (see above and Chapter 7). The formation of the Quadripartite and OHHLEP, working to the inclusive definition of One Health above (Figure 4.2), provides a strong framework encouraging more equitable consideration of wildlife health and ecosystem integrity in decision-making.

Figure 4.2. One Health approaches.
Adapted from the World Bank and FAO (2022).

4.6.3 Ecosystem approaches to health

Article 2 of the Convention on Biological Diversity defines an “ecosystem” as “a dynamic complex of plant, animal and micro-organism communities and their non-living environment interacting as a functional unit.” Historically, a “healthy” ecosystem has been defined as being “‘stable and sustainable’; maintaining its organisation and autonomy over time and its resilience to stress” (Rapport *et al.*, 1998). However, this definition does not recognize that many intact ecosystems in good conservation status are far from stable in their species content and ecology, rather they are dynamic and complex.

‘Ecosystem health’ is therefore challenging to define. An IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services) Workshop Report (IPBES 2020) described it as,

“A comprehensive and multiscale measure of system vigour, organization and resilience, closely linked to the idea of sustainability, which implies the ability of the system to maintain its structure (organization) and function (vigour) over time in the face of external stress (resilience)”.

As discussed above, the integrity and conservation status of ecosystems are dependent on the health of their constituent communities (Lebel, 2003; Horwitz *et al.,* 2012; Radcliffe and Jessup, 2022). Perspectives on the role biodiversity plays in emerging infectious disease, particularly zoonoses, have differed between studies. Some authors have considered areas with high biodiversity to be hotspots for and sources of zoonotic infectious agents, while others have identified a potential reduction in risks from some infectious agents in areas of high biodiversity: a so-called ‘dilution effect’ (Keesing *et al.*, 2006; Faust *et al.*, 2017; Keesing and Ostfeld, 2021). Similarly, wildlife corridors, which connect fragmented populations and facilitate gene flow, can be seen to act as routes for spread of infection but also as a means of decreasing disease risks by providing additional areas of habitat and maintaining population immunity by promoting regular exposure to pathogens. However, human-induced land-use change and associated reductions in biodiversity can allow ‘opportunistic’ hosts such as rodents to become established, increasing the chances of direct or indirect contact with people – and consequently the potential risk of spillover of certain pathogens (Gibb *et al.*, 2020). Therefore, while high biodiversity and connected habitats may have complex and context-specific associations with disease risks, it is recognized that human-induced *disruption* or *degradation* of intact ecosystems can drive disease emergence, as discussed above.

Given the links between ecosystem degradation, conservation threats and human activities that we have described in this chapter, actions to reduce human pressures on ecosystems have potential to improve wildlife health, and also to safeguard the health of humans and livestock. Ecosystem approaches to health recognize that the environment provides the context and foundation for health, and that causes of ill-health are commonly related to social, economic and cultural factors. They recognize that our actions on ecosystems can significantly affect the health of their inhabitants and their resilience and ability to adapt to change:

> “*Healthy ecosystems provide a range of ecosystem services… [and] a focus on the design, protection, and restoration of healthy ecosystems will help to sustainably provide the ecosystem services that underlie all human well-being*” (IPBES, 2020).

In this way, an ecosystem approach to health facilitates an ‘upstream’ and proactive focus on prevention of health problems (Lebel, 2003; Horwitz *et al.,* 2012). Intergovernmental processes have increasingly recognized not only One Health approaches but also, specifically, 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[13] following the Convention’s substantive work on “Healthy Wetlands, Healthy People” (Cromie *et al.*, 2012; Horwitz *et al.*, 2012).

One Health and ecosystem approaches to health offer means of enhancing the health of people, domestic animals and wildlife in concert with biodiversity conservation. These approaches align with the UN’s Sustainable Development Goals (SDGs) to “protect, restore and promote sustainable use of… ecosystems” and “ensure healthy lives and promote well-being for all” (United Nations, 2015). Full implementation of the SDGs would indeed significantly enhance health of people and wildlife.

4.6.4 Indigenous communities as custodians of natural systems

Indigenous communities are custodians of some of the most undegraded and biodiverse ecosystems remaining in the world (Riley *et al.*, 2021), but we still have much to learn from indigenous concepts of health, which have historically been overlooked. People who have grown up connected to, and learning from, nature have a unique perspective and understanding of how ecosystems function and recognize the importance of maintaining ecosystem integrity for health (Salmón, 2000; Estrada *et al.*, 2022). They can perceive subtle changes as early indicators of significant health problems in wildlife or their wider environs. For example, hunters can identify their prey losing condition, which may be an early indicator

[13] https://www.ramsar.org/sites/default/files/documents/pdf/cop11/res/cop11-res12-e.pdf

of local population stressors and declines (Kutz and Tomaselli, 2019). Environmental integrity is a key feature of many indigenous cultures and beliefs, consistent with the ethos of One Health and ecosystem approaches to health. There has been increasing recognition of the value of traditional knowledge in wildlife population monitoring and management. For example, in Northern Canada, the Tłı̨chǫ government developed a programme to monitor caribou (*Rangifer tarandus groenlandicus*) herds that were in decline, and members of the Tłı̨chǫ community work in partnership with scientific researchers and others to develop co-management strategies for caribou (Robertson, 2020).

Picture 4.11. Indigenous concepts of health have been overlooked historically. Indigenous systems tend to be holistic and sustainable, acknowledging the value of wildlife and a healthy environment. *Photo credit: Canva*.

4.7 Key messages: Key concepts in wildlife health, and the interdependence of health and environmental sectors

- → Migratory species can be affected by infectious and non-infectious diseases which can have serious implications for their health and survival, as well as associated impacts on livestock and human health.
- → Disease can negatively affect the conservation status of migratory species especially when populations are small and fragmented.
- → The environment is the setting and determinant for health across wildlife, domestic animal and human sectors.
- → Disease emergence is influenced by multiple factors, which can be synergistic or cumulative in their contribution to ill-health. These include land-use change, agricultural expansion, pollution, climate change, urbanisation and overexploitation, which are associated with unsustainable resource use and deep-rooted socio-political issues such as the increasing drive for economic wealth.
- → In this way, the usual drivers of population decline are also the drivers of disease emergence, which can, in turn, exacerbate migratory species' susceptibility to pre-existing threats.
- → Livestock-wildlife interfaces are locations where direct or indirect contact occurs between livestock and wildlife. Their area is increased through, for example, agricultural development and expansion into wild areas. They are particularly problematic for pathogen transmission between species, including potential spillover events. Whatever the original source of the pathogen, livestock remain the most common source of zoonotic infections in people.
- → Livestock frequently act as intermediate hosts for zoonoses originating from wildlife, including those with potential human pandemic risk. Transmission may also occur via invertebrate vectors.
- → Emerging zoonotic diseases can also stem from unusual interactions with wildlife. Some 'wet' or live animal markets can represent high-risk settings which have been shown to increase risks of pathogen transfer between hosts and drivers of pathogen change, increasing the likelihood of transmission between species, including to humans.
- → The legal as well as unregulated and unsustainable trade in wildlife (both live animals and animal products) can not only have negative impacts on the conservation status of migratory species but also pose risks in terms of regional and international movement of pathogens, which can then lead to emergence of infectious diseases in wildlife, domestic animals and/or humans.
- → The One Health approach aims to sustainably balance and optimize the health of people, wild and domestic animals, and ecosystems. It is an established, integrated and unifying approach to health, including to address emerging infectious diseases, and is endorsed by multiple national and international organizations and intergovernmental agreements.

5 MIGRATION, MIGRATORY CHANGE AND DISEASE

In this chapter we summarise some key concepts relating to wildlife migration, and our current understanding of health and infectious disease dynamics in relation to migration. We consider the potential consequences of migration disruption for disease and the dynamics of infectious disease, and associated knowledge gaps.

5.1 Migration: key concepts

5.1.1 CMS definition and context

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 the purpose of the CMS, 'migratory species' means,

"*the entire population or any geographically separate part of the population of any species or lower taxon of wild animals, a significant proportion of whose members cyclically and predictably cross one or more national jurisdictional boundaries"* (CMS, 1979).

This definition differs from those in the scientific literature by including some species or populations that cross jurisdictional boundaries, in addition to those that migrate to geographically separate areas.

Appendix I of the Convention represents migratory species considered to be endangered (defined as "facing a very high risk of extinction in the wild in the near future") that have been assessed as being in danger of extinction throughout all or a significant portion of their range.

"Parties that are a Range State to a migratory species listed in Appendix I should endeavour to strictly protect them by: prohibiting the taking of such species, with very restricted scope for exceptions; conserving and where appropriate restoring their habitats; preventing, removing or mitigating obstacles to their migration and controlling other factors that might endanger them."

Appendix II represent migratory species conserved through Agreements. The Appendix,

"*Covers migratory species that have an unfavourable conservation status and that require international agreements for their conservation and management, as well as those that have a conservation status which would significantly benefit from the international cooperation that could be achieved by an international agreement. The Convention encourages the Range States to species listed on Appendix II to conclude global or regional Agreements for the conservation and management of individual species or groups of related species*."

CMS acts as a framework convention from which separate instruments evolve. Agreements may vary from legally binding treaties to less formal instruments, such as Memoranda of Understanding, Action Plans or Species Initiatives covering, to the extent possible, the entire migratory range of the species concerned.

5.1.2 Taxonomic breadth of migratory species

As noted above the Convention relates to all migratory species, for example, in its obligation to take action to avoid any migratory species becoming endangered. Unsurprisingly those species listed on the Convention's appendices in effect receive the greatest conservation attention (and are the main focus of Chapter 6). There are a number of reasons why some migratory species are not currently listed on the CMS Appendices including lack of conservation attention, not being currently considered at risk, being data deficient, being present in countries that are not signatories to CMS, or a proposal for their addition may be awaiting approval by the CMS Conference of the Parties (COP).

Although still considered within the Convention's scope, some taxa such as invertebrates and amphibians, which can cross jurisdictional boundaries, are particularly poorly represented or absent from the appendices of CMS. Arguably these species, which are often hard to monitor and frequently in poor conservation status, could benefit from international conservation coordination as for the species listed on the CMS Appendices.

For example, many insects (numerous butterflies, moths, dragonflies etc.) undertake seasonal migrations for similar benefits as other taxonomic groups (see below). Research has identified that numbers of terrestrial species migrants are highest for insects, for example 4-6 billion darner dragonfly *Rhionaeschna bonariensis* with a total biomass of 4,000 tonnes, and 100-200 million monarch butterfly (*Danaus plexippus*) with a total biomass of 40-80 tonnes. The total biomass can be comparatively close to that of some migratory large mammal species, for example a biomass of 200,000 tonnes of desert locust (*Schistocerca gregaria)*, versus 280,000 tonnes of wildebeest (Holland *et al.*, 2006; Satterfield *et al.*, 2020). One study measured annual migratory insect movement with a biomass of approximately 3,200 tonnes above the United Kingdom alone: this is over seven times greater than the biomass of the approximately 30 million songbirds (415 tonnes) which migrate from the UK (Hu *et al.*, 2016). Considering the focus of this review on wildlife health, diseases of insects and other invertebrates remain poorly understood, which is of concern given the range of threats to which they are exposed, including pesticide chemicals, and their apparent marked declines in recent decades. The continuing decline of insect populations across the globe is concerning, with ramifications for ecosystem function and for numerous other species which depend on them (Hallmann *et al.*, 2017).

Like most insects, amphibians are not considered further within this review since Chapter 6 focusses on species listed in Appendices I and II. However, it should be noted that amphibians have suffered the greatest impacts of infectious disease of any taxon in recent decades, being susceptible to diseases such as chytridiomycosis and ranavirus disease. Chytridiomycosis has been a cause of population declines and extinctions of many amphibian species around the globe (Price *et al.*, 2014; Fisher and Garner, 2020) (see Box 5.1).

Box 5.1. Case example: Disease and the global amphibian crisis

Mass mortality of amphibians caused by chytridiomycosis

Population declines and mortality of amphibians in Australia and the Americas from the 1970s onwards raised alarm (Stuart *et al.*, 2004), sparking investigations into their cause. In the late 1990s a causative agent, a chytrid fungus called *Batrachochytrium dendrobatidis* (*Bd*) which impairs amphibian skin function, was identified (Berger *et al.*, 1998; Longcore *et al.*, 1999). Since its discovery, *Bd* has been detected in amphibians in numerous countries around the world and been associated with further population declines of ~500 species and extinctions of ~90 species. It is thought to have been spread around the world via anthropogenic movement of amphibians and their products, primarily for trade and research purposes. Another chytrid fungus (*Batrachochytrium salamandrivorans*, *Bs*) has since been identified as a cause of fire salamander (*Salamandra salamandra*) declines in Europe and is thought to have been spread from Asia to Europe by similar means (Martel *et al.*, 2014). These are prominent examples of how emerging infectious diseases, resulting from anthropogenic drivers, have the potential to significantly impact wildlife populations (Van Rooij *et al.*, 2015).

Picture 5.1. The fungal disease chytridiomycosis is thought to have caused many amphibian species to become extinct.
Such species include the Northern Darwin's frog (*Rhinoderma rufum*), a relative of the Southern Darwin's frog (*R. darwinii*) pictured here, Both species are (were) unique in that males incubate their young in their vocal sacs, as if pregnant (as pictured).
Batrachochytrium sp., the causal agent of chytridiomycosis, is thought to have been spread around the world through human movement of amphibians and their products.
Photo credit: Claudio Azat Soto.

5.1.3 Motivation for migration

Animals may undertake migration in order to move to better feeding and/or breeding habitats during certain times of the year (Dingle, 2014), or to evade predators during breeding or other vulnerable periods. Frequently, however, the fundamental drivers of migratory behaviour are still unclear (Altizer *et al.*, 2011). Not all animal movement is migratory, with some 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, though this is offset when the purpose is to acquire food.

5.1.4 Ecosystem benefits and services from migration

There are many benefits for ecosystems from migration, which if lost could have wider adverse consequences. Migration can move nutrients into and out of ecosystems, playing a role in nutrient cycling, shaping ecosystem structure, and benefitting ecosystem function.

In marine ecosystems, salmonoid migration from marine to freshwater environments can shift nutrients and carbon upstream (including from carcasses or eggs), in turn benefitting forest ecosystems. Disruption of sediment by the burrowing or feeding of many marine creatures (including migratory species) can release nutrients into the water, making them available for uptake elsewhere (Holmlund and Hammer, 1999). Mass migration of ungulates also provides an array of ecosystem benefits (see Section 4.2.2). Grazing by large groups of ungulates benefits grass and plant growth, by providing nutrients through excretions and letting light into the grasses; these animals can also keep the growth of other plants in check, and depending on their feeding patterns and preferences, can improve the diversity of plant species (Kauffman *et al.*, 2021). The movement of herds and the corresponding mortality of individuals along the way, across vast areas, provide ecosystems with many nutrients, through excretions and carcass decomposition.

Migration also influences food-web interactions more directly. Migratory birds and insectivorous bats may feed on insects that prey on plants, keeping this balance in check and benefitting plant health. Migratory species can also be important food sources for predators, which act as regulators of populations by removing weak or diseased individuals. Ungulate migrants, for example, are a food source for multiple carnivore and scavenger species, many of which are threatened (Subalusky *et al.*, 2017; Middleton *et al.*, 2020). Some migratory species act as 'ecosystem engineers', meaning that by maintaining, creating, or destroying parts of the environment they can indirectly or directly alter resource usability. This can be greatly beneficial to plant or animal species residing in the same habitats, creating access to more resources and nutrients (Lopez-Hoffman *et al.*, 2017).

Continuing decline in migratory species numbers could significantly alter ecosystem function and productivity. For example, it could negatively impact plant diversity; affect cycling of nutrients in soil; modify the resources available to other species; and alter fire ecology and the renewal of fire-dependent ecosystems (Middleton *et al.*, 2020; Kauffman *et al.*, 2021). The ecosystem benefits of migration are explored further in a CMS-commissioned report on Climate Change and Migratory Species (UNEP/CMS/COP14/Doc.30.4.1/Rev.3).

5.1.5 Societal benefits from migration

Migration also brings many benefits to our human societies such as:

- Biocontrol: as above, crop pests can be eaten by birds and insectivorous bats, reducing the need for reliance on polluting pesticides (Lopez-Hoffman *et al.*, 2017).

- Pollination and seed dispersal: migratory insects, birds and bats perform this function for many plants, including food plants and crops.
- Nutrient and energy transport between distant ecosystems, linking geographic regions.
- Providing food sources for indigenous communities practising subsistence hunting, increasing their supply of food for storage over winter months.
- A range of other cultural benefits by way of *e.g.* ecotourism, birdwatching, recreation, hunting, fishing, and spiritual or religious practices. Such activities can provide personal benefits, improving mental health and wellbeing, as well as economic benefits (income, jobs or funding for conservation actions) (Lopez-Hoffman *et al.*, 2017).

Declines in migratory populations could therefore negatively impact human health, wellbeing, and livelihoods.

5.1.6 Migratory routes

Although the routes and timings of animal migration vary according to taxa and individual species, 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.

5.1.6.1 Flyways

"*A flyway is the entire range of a migratory bird species (or groups of related species or distinct populations of a single species) through which it moves on an annual basis from the breeding grounds to non-breeding areas, including intermediate resting and feeding places as well as the area within which the birds migrate*" (Boere *et al.*, 2006).

These flyways can be broad-scale or more defined, narrow routes (Figure 5.1). Common migratory patterns include:

- In the northern hemisphere, frequently a breeding season in boreal regions during the northern summer, returning south to the warmer temperate regions or the tropics for the non-breeding season.
- In the southern hemisphere, frequently a summer breeding season in temperate regions of South America, Africa, or Australasia, returning north to the tropics in the winter (Kirby *et al.*, 2008).
- Some species travel very far to benefit from the southern summer.
- Some tropical migratory birds pursue the wet season, breeding north of the Tropic of Cancer, before migrating to the neotropics (between the Tropics of Cancer and Capricorn) during the non-breeding season.
- Tracking of flight patterns has also demonstrated significant, previously unrecognized East-West migration, whilst seabirds such as albatrosses and shearwaters have been shown to have extensive loop migrations around the world's oceans.

Developments in tracking technology are allowing greater insights into avian migration routes (for example, the collaborative project SEATRACK[14] is yielding data on seabird migration patterns in the North Atlantic).

Migratory birds also have different strategies with respect to congregation or dispersal, and the timing of this. For example, wildfowl may breed at low densities, then converge at staging grounds with birds from different breeding areas, spending the non-breeding season

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[14] https://seapop.no/en/seatrack/about-seatrack/

in closer proximity to these other individuals. Conversely, seabirds may breed at very high density before having less contact with conspecifics during their non-breeding season.

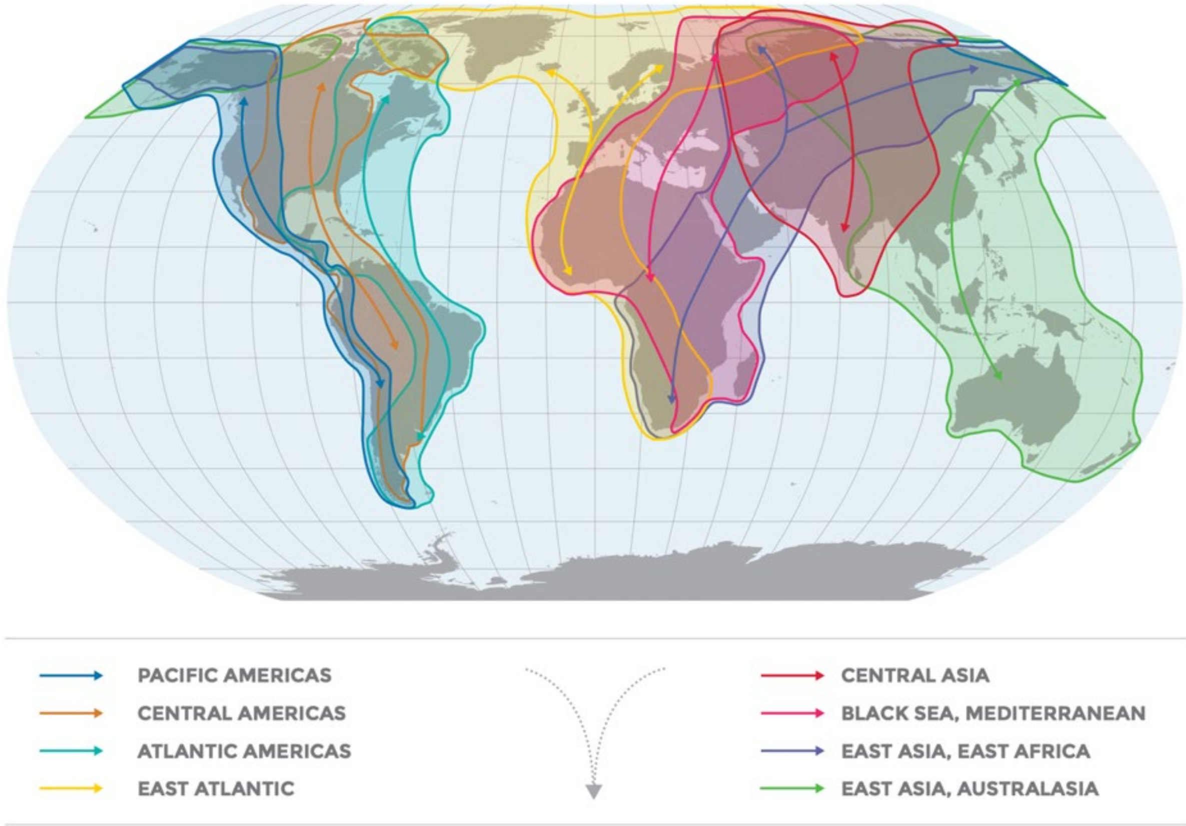

Figure 5.1. An illustration of global flyways for migratory birds.
Figure credit: Birdlife International (2018).

5.1.6.2 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. While some species may travel vast distances across the globe, other species only migrate within a small region, or do not migrate along defined routes at all (one example being the blue shark (*Prionace glauca*)).

In 2022, WWF commissioned a report to identify 'whale superhighways' using satellite tracking data from various whale species (see Figure 5.2). Although not comprehensive for all species and taxonomic groups, their findings provide an overview of general route locations. From Figures 5.2 and 5.3, it is easy to visualise how many of the whales' migratory routes overlap with shipping routes and how global transport serves as a key driver of incidental traumatic injury (ship strikes) in these large species.

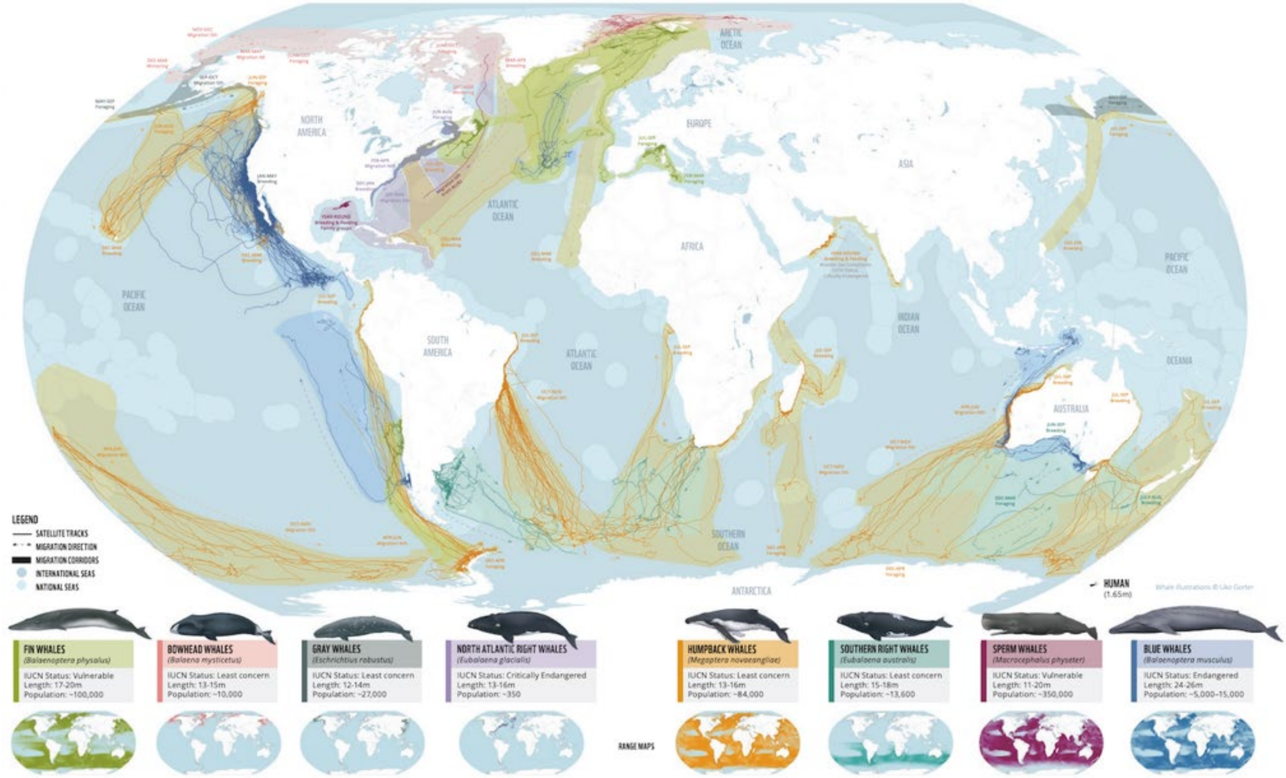

Figure 5.2. Whale migratory pathways ('superhighways') identified from satellite tracking data.
Figure credit: WWF report on "Protecting Blue corridors" (Johnson et al., 2022).

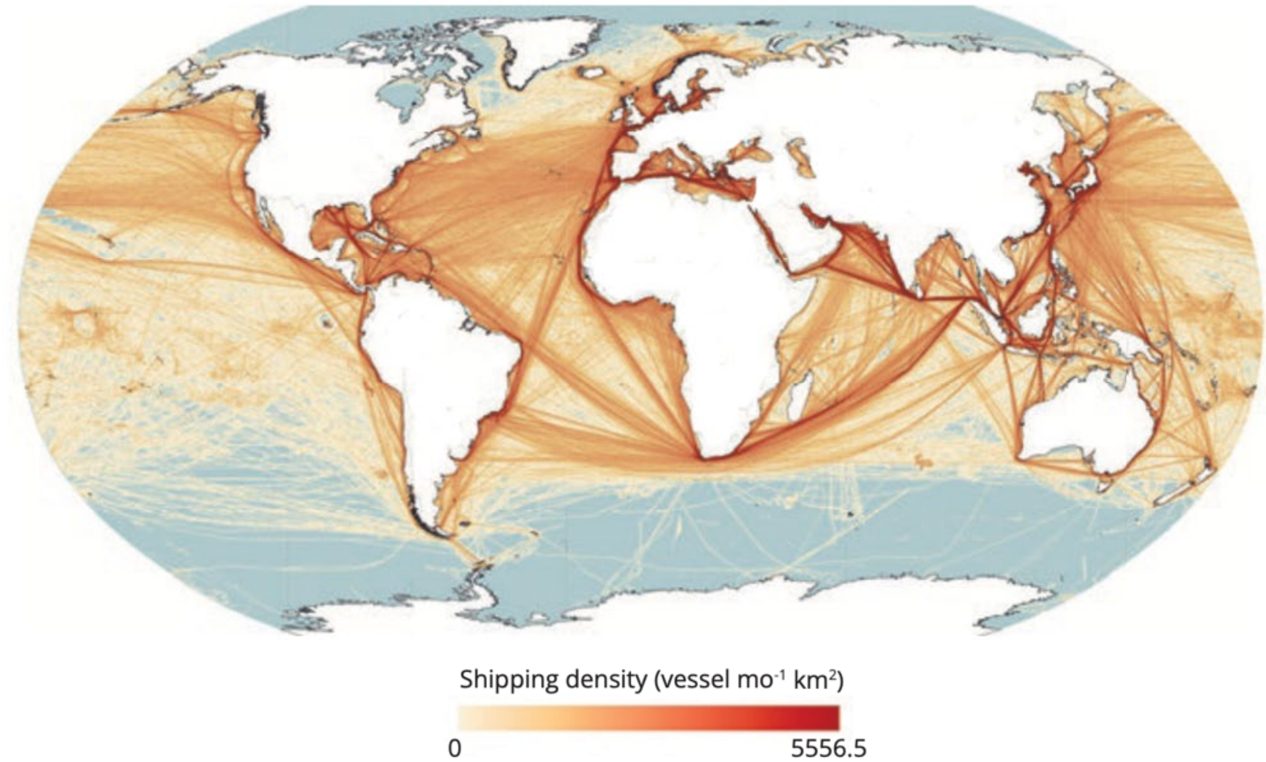

Figure 5.3. Shipping densities and routes.
Figure credit: WWF report on "Protecting Blue corridors" (Johnson et al., 2022).

For other marine taxa, as an example, Queensland's Department of Environment and Science collaborated with CMS to create an interactive "TurtleNet" Atlas[15], demonstrating turtle migration routes along with other data. Tools like this can be useful in understanding species movements and for education, as well as having the potential to assist in health research. In general, the greater understanding we have of migratory routes for all taxa, the better we can understand the threats (including those from disease) that migratory populations face, to inform mitigation measures.

5.1.7 Partial migration

As discussed above, definitions of migration vary. 'Partial migration' describes a situation when some individuals migrate within a population while others choose to remain 'resident' in their home area (Chapman *et al.*, 2011a; Dingle, 2014). Technically, even if a population has only a small percentage of animals choosing to remain resident, the population is classed as 'partially migratory'. Partial migration has been recorded across taxonomic groups: in insects, fish, amphibians, reptiles, mammals and birds (Chapman *et al.*, 2011a).

[15] https://apps.information.qld.gov.au/TurtleDistribution/

Table 5.1. Types of partial migration.
After Chapman *et al.* (2011b).

Type	Description
1. Non-breeding partial migration	Both migrants and residents breed together, but the migrants leave during winter.
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 in some years. It is thought that individuals remain resident when they are not physically capable of making the migration journey (due to *e.g.* poor condition, reduced fat stores).

Partial migration is important to keep in mind when discussing barriers to, and disruption of, migration (see Section 5.2.4 below).

5.2 Migration, migratory change and disease

5.2.1 Physiological impacts of migration

While they provide access to resources and/or means to escape unfavourable conditions, the long, arduous migratory journeys that some species undertake can come at considerable physiological expense to individuals. To warrant migratory behaviour, its benefits must therefore outweigh its costs. The physiological costs of migration vary depending on resource availability and the environmental conditions and stressors that migrants may encounter. Human-mediated activities such as habitat loss, infrastructure development and land-use change serve as stressors which can exacerbate physiological costs for the individual, resulting in poorer health outcomes from migration.

The benefits and costs of migration to the health and infection status of migratory individuals are summarised in Table 5.2 and Figure 5.4. Some of the general health benefits of migration to individuals include increased resource availability, access to more suitable habitat for *e.g.* breeding, wintering or moulting, and potential associated improvements in health and resilience to infection or disease. However, migration is a risky strategy that is also associated with high energetic and physiological costs (Alves *et al.*, 2013) such as immunosuppression and endocrine (hormonal) changes, as well as potential exposure to adverse environmental conditions and other threats such as toxicants and toxins. The timing of migration is key, with a potential for resource mismatch if animals arrive at the destination too late or too early (Table 5.2). In these ways, migration can increase animals' susceptibility to ill-health and mortality (Alerstam *et al.*, 2003; Hegemann *et al.*, 2019; Chapman *et al*., 2015) (Table 5.2).

5.2.2 Migration and infection dynamics

Given the extensive movements of migratory species and the intersections in their migratory routes, it is frequently assumed that migrants are responsible for introducing infectious agents to new areas and for spreading these from, and to, other populations of wild or domestic animals, and people. As highlighted in Chapter 4, this assumption can compromise conservation efforts for migratory species.

Migratory species certainly play a role in the spread of some pathogens, potentially carrying infectious agents across long distances and aiding in the dispersal of vectors of infectious agents (for example ectoparasites such as ticks). This can increase the geographical range of a pathogen. Well-known examples in birds include the recent, extensive spread of HPAI (highly pathogenic avian influenza) viruses in different parts of the world, and the spread of West Nile virus (WNV) in North America. It is worth highlighting, however, that in both instances this spread occurred subsequent to human activities which drove the initial introduction of these agents to these new species or locations. In the case of HPAI, wild bird-poultry interfaces in Asia led to the initial introduction of these viruses to migratory wild bird populations (Wiethoelter *et al.*, 2015), while, for WNV, intercontinental human travel is considered to have introduced the virus to the American continent (Reed *et al.*, 2003).

The act of migration can equally serve to decrease burdens of infectious agents in migratory populations and their wider ecosystems (Altizer *et al.*, 2011), and appears to be a strategy to reduce infection pressure in some migratory populations. In effect, infectious agents may be the mediators of migration and thus the migration strategies adopted by species, age classes or individuals (Wille and Klaassen, 2022). Interactions such as this are discussed further below and summarised in Figure 5.4.

Picture 5.2. Migrating red knot (*Calidris canutus*) – the act of migration can reduce infection burden.
Migration is energetically costly but can bring a range of benefits for reducing infection burden in the population and building resilience. *Photo credit: GRID-Arendal*.

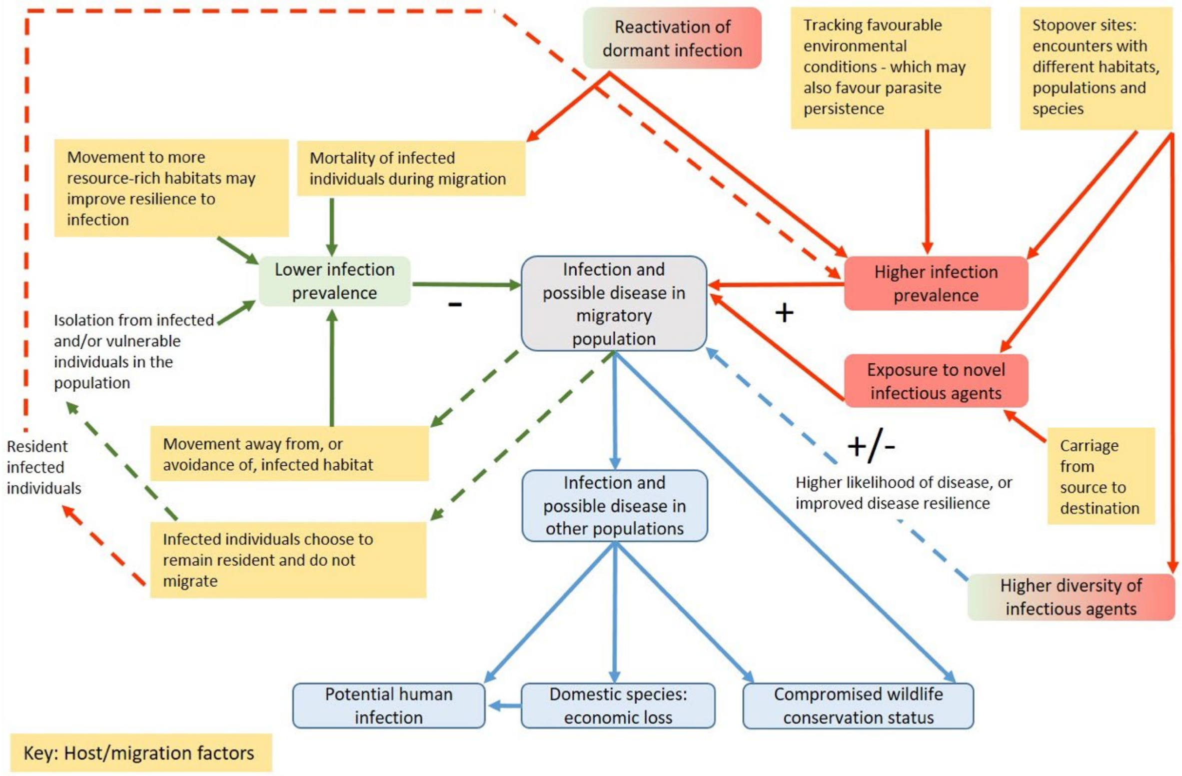

Figure 5.4. Summary of infection dynamics in relation to migratory behaviours. There are both positive and negative consequences for infection dynamics in relation to migration which are situation dependent. Anthropogenic pressures on migratory species can exacerbate the negative consequences for infection dynamics and disease occurrence.

5.2.2.1 Potential positive consequences for infection dynamics

→ Improved resources available through migration can benefit health and tolerance to infection

The better resources that animals are able to access through migration can benefit their health and fitness. In turn, this can increase their ability to overcome or eliminate an infection, a concept termed ‘migratory recovery’ (Hall *et al.*, 2022).

→ Migration can lower host and environmental burdens of infectious agents

- Animals may move away from habitats and populations at breeding or wintering sites with a high infectious agent burden as a strategy to ‘escape’ this infection pressure, especially during vulnerable life stages. This concept is called ‘migratory escape’ (Hall *et al.*, 2022) (see Box 5.2).
- They can also avoid such habitats on their migratory routes or stopover locations, termed ‘migratory avoidance’ (Hall *et al.*, 2022). For example, internal parasites such as worms (helminths) often require intermediate hosts to complete their life cycle: if the hosts migrate to areas with different environmental conditions then these parasites may struggle to adapt and survive, or the environmental part of their life cycle will be prolonged until an appropriate host is encountered (Loehle, 1995).
- Infected individuals may succumb to infectious disease during migration, thus removing infected individuals from a population. This is termed ‘migratory culling’ (Hall *et al.*, 2022).

The intensive energy costs associated with migration may also reactivate dormant infections in individuals (‘migratory relapse’; Hall *et al.*, 2022), exacerbating this effect. This may, additionally, in effect ‘remove’ genes for disease susceptibility from the population, selecting for immunocompetence and resistance to disease, leading to reduced levels of infection in the migratory population in the longer term.

- 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. This is termed ‘migratory allopatry’ (Hall *et al.*, 2022). Some individuals also demonstrate avoidance behaviour to move away from infected individuals *e.g.*, they will not share the same dens as such individuals (Narayanan *et al.*, 2020).
- Infected animals may also choose to remain resident and not migrate; delay migration; or take longer to migrate (termed ‘migratory dropout’ or ‘stalling’, Hall *et al.*, 2022). This is because infected animals often reduce their movement either as a physiological strategy to cope with infection via energy conservation, or from negative effects of infection and its physiological costs on the body. Thus, infection can lead to individuals choosing to remain resident rather than risking migration and potential mortality (Narayanan *et al.*, 2020).
- Once animals leave for migration, it can allow the environment to ‘recover’, in effect, decontaminating it. When migrating animals have left a habitat, this may leave remaining infectious agents or disease vectors (such as ticks and mites) with few or no hosts or food, so the risk of infection at these sites may decline naturally. Also, a habitat that is contaminated with faeces, for example, has time to rest and become cleansed by the elements, likewise reducing infection risk and improving habitat quality before the migrants return.

Box 5.2. Case examples: 'Migratory escape' from infection

Waders and avian malaria

Populations of waders (shorebirds) using the East Atlantic Flyway which travelled to northern and coastal environments had much lower levels of infection with avian malaria parasites relative to southern populations using tropical habitats, inland and freshwater environments. Waders utilising marine and saltwater habitats are thought to 'escape' the risk of exposure to infected mosquitos, as these habitats do not support these vectors as well as tropical and freshwater habitats (Mendes *et al.*, 2005).

Reindeer and warble flies

Reindeer (*Rangifer tarandus*) groups that migrate to different summer sites after breeding reduce their exposure to damaging warble flies (*Hypoderma tarandi)* in comparison to those that stay on or nearby their calving sites throughout the summer. It is thought this is a behavioural migratory adaptation to reduce infestation post calving, since the fly larvae emerge around the time of calving and groups that choose to migrate to distant summer grazing sites likely 'escape' the worst of the larval load (Folstad *et al.*, 1991).

Picture 5.3. Post-calving migration in reindeer may be a behavioural adaptation to reduce levels of parasitic infections.

Photo credit: © Sergey Dereliev, www.dereliev-photography.com.

→ **Migration may increase the diversity of infectious agents in the migratory population, promoting resilience to infection**

- Exposure to infection (Hoye *et al.*, 2016) and/or increased parasite diversity (Teitelbaum *et al.*, 2018) can improve animals' resilience to future infection and disease (Møller and Erritzøe, 1998), either as a consequence of an immune (antibody) response to infection, which reduces the likelihood of its recurrence, or in the longer term, evolutionary selection for increased immune gene diversity.
- Co-evolution of infectious agents with their migratory hosts can also lead these agents to be less virulent, meaning migrants may carry less harmful strains of infectious agents than resident counterparts. For example, in monarch butterflies, seasonal migrants that had the longest migratory journeys were found to carry fewer virulent strains of the protozoal parasite *Ophryocystis elektroscirrha*, and had greater resistance to infection, relative to individuals which did not migrate as far (Altizer, 2001; Altizer *et al.*, 2011).

5.2.2.2 Potential negative consequences for infection dynamics

→ **The physiological and health costs of migration can increase susceptibility to infection**

Migration can impair the health of individuals in a range of ways, increasing their susceptibility to infection through immunosuppression (Hall *et al.*, 2022; Alerstam *et al.*, 2003) (Table 5.2). In turn, this increases the likelihood of infectious agents being transmitted within or between populations.

→ **Migrants can be exposed to a broader diversity and potentially higher load of infectious agents**

- Multiple stopovers across a variable migratory landscape increase the range of infectious agents in the environment to which migrants may be exposed.
- Host aggregation at stopover, breeding or overwintering sites can also increase the chances of exposure to infectious agents, either directly or indirectly via, for example, contaminated environments.
- As above, the intensive energetic and physiological costs associated with migration can cause immunosuppression, which may reactivate dormant infections in individuals.
- Migrants follow the most favourable environmental conditions ('environmental tracking'); however, these conditions may also be beneficial for infectious agent survival and transmission, especially for those agents that persist long-term in the environment (Hall *et al.,* 2022).
- Migratory dropout or stalling (described above) can lead to increased infection prevalence in a static population through the presence of infected individuals that have chosen not to migrate, or to delay migration.
- Thus, encounters with different habitats, populations and species at stopover, breeding or wintering sites can expose migrants to a wider variety and higher load of infectious agents (Teitelbaum *et al.*, 2018). In combination with the immunosuppression associated with migration, this has potential to increase pathogen transmission rates and disease susceptibility (Poulin and Dutra, 2021).

→ **Migrants, and other populations or species that they encounter, may be exposed to novel infectious agents**

- As above, when many individuals, populations and species aggregate at the same stopover or breeding/wintering sites there is an increased chance of migrants being exposed to novel infectious agents.
- Encountering different or new habitats at stopover sites can also expose migratory animals to novel infectious agents.
- Migratory animals travelling over distances to new areas can therefore bring novel infectious agents with them and introduce them to new locations and hosts (Hall *et al.,* 2022) (see Box 5.3). The same applies to the possible movement of microbes containing genes for resistance to anti-microbial drugs – antimicrobial resistance (AMR) being a pressing public health concern (Laborda *et al*., 2022).

Box 5.3. Case example: Unusual migratory movements of animals introducing disease

Phocine distemper virus in seals

Harp seals (*Pagophilus groenlandicus*) can encounter multiple other species including harbour (*Phoca vitulina)*, hooded (*Cystophora cristata*) and grey (*Halichoerus grypus*) 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 outside their usual range, and given they can be a reservoir host for PDV, that their movement triggered outbreaks in North Sea seal populations which were naïve to this infection (Duignan *et al.,* 2014).

Picture 5.4. Unusual migratory movements can introduce novel infections to naïve populations.
An outbreak of phocine distemper in several seal species, such as this grey seal with clinical signs of disease (mucus from the nose and ears), was thought to follow introduction of virus from a reservoir host migrating outside its normal range. *Photo credit: Alan Knight/BDMLR*.

The length of migratory journeys can impact the likelihood of infection transmission. Some species may 'hop' between sites and linger *en route*, while others may 'skip' or 'jump' over longer distances without many staging sites, reaching their final destination more quickly, in effect being more likely to carry infectious agents over long distances and in a relatively shorter period of time (Warnock, 2010).

5.2.2.3 Summary

Thus, migration can have varied impacts on infection dynamics, both positive and negative, and the net effects of migration on disease dynamics will vary depending on the context. In improving the health of migratory animals and reducing their infection burden, migration can safeguard their health and reduce the likelihood of disease transmission to linked populations of wildlife, domestic animals, or people. On the other hand, migration can compromise the health of migratory animals, increasing their infection burden as well as their exposure to novel infectious agents. This could, contrarily, increase the likelihood of migratory populations introducing novel infectious agents to other populations of wildlife, domestic animals, or people. These varied interactions between migration, health and infection status are summarised in Table 5.2 and Figure 5.4.

Table 5.2. Summary of a. benefits and b. costs of migration to the health and infection status of migratory animals.

a. Benefits of migration

Benefits to general health include:

- **Access to more environmental resources**

- Ability to utilise increased resources resulting from seasonal changes.
- Avoidance of a contrasting reduction or variation in resource availability, and increasing competition for dwindling resources, relative to non-migratory residents.

- **Access to more suitable habitat**

- Ability to utilise improved habitat during seasonal flourishing.
- Access to more suitable sites for breeding, wintering or moulting.
- There may be lower predator density in the new habitat.

- **Consequent benefits for general fitness**

- Improved nutritional condition from increased resources.
- Greater genetic diversity through population connectivity.

Positive consequences for infection status include:

- **Improved fitness conferring tolerance to infection**

- The above benefits mean that individuals' ability to overcome or eliminate infection can be improved through migration (termed 'migratory recovery') (Hall *et al.*, 2022).

- **Lower host or environmental burdens of infectious agents**

This may be effected in a number of ways (see main text for further details):
- Escape from potentially high burdens of infectious agents in breeding/wintering populations and environments (termed 'migratory escape'), or avoidance of habitats associated with particular infectious agents or high infection pressure ('migratory avoidance'). The destination environment may have a lower infection pressure or no longer support survival, replication or transmission of some infectious agents.
- Mortality of infected individuals during the migration journey ('migratory culling'), which may be exacerbated by reactivation of dormant infection as a consequence of migration ('migratory relapse').
- Through migration, separation from individuals such as juveniles that are inherently more susceptible to infection and disease ('migratory allopatry').
- Separation from individuals that, as a consequence of infection, remain resident, delay their migration or take longer to migrate ('migratory dropout' or 'migratory stalling') (Hall *et al.*, 2022).
- Migration away from breeding/wintering sites also facilitates environmental recovery (decontamination).

- **Greater infectious agent diversity in the migratory population, which may confer resilience to infection**

- Migration can lead to genetic selection for immune gene (*e.g.* major histocompatibility complex (MHC)) diversity, increased immunocompetence, and tolerance or resistance to disease relative to more static populations.
- Co-evolution of infectious agents with their migratory hosts can lead them to be less virulent, so migrants can also carry less harmful strains of infectious agents than resident counterparts (see main text for an example).

b. Costs of migration

Costs to general health include:

- **Energetic and physiological costs of migration**

- Migration is an energetically costly activity. Although animals that swim or fly may exploit water currents or winds to reduce the energetic costs to an extent, and stopovers during the journey allow resource re-fuelling (Alerstam *et al.,* 2003; Alves *et al.*, 2013).
- Substantial fuel reserves are therefore required for migration and many species lay down body fat reserves pre- migration, but this may also slow their travel and increase predation risk. These effects are mitigated in some species by alterations in body composition (Landys-Cianneli *et al.*, 2003).
- Migratory exertion and migration-induced stress can lead to immunosuppression, oxidative stress and damage to tissues (Eikenaar *et al.*, 2020).

- **Exposure to adverse environmental conditions and other threats**

- Storms and windy weather can impact birds' flight, shifting them to unfamiliar locations and causing them to become disorientated, increasing their energy expenditure and mortality.
- Weather can also adversely affect open areas such as grasslands, causing terrestrial animals' migration to be impeded by ground quality, for example.
- Multiple stopovers across varied landscapes increase the likelihood of migrants being exposed to a range of threats to their health and survival, including environmental toxicants or toxins.

- **Migration timing: resource mismatch**

- If an individual takes too long to migrate they may miss beneficial resources at the destination.
- Conversely, if they arrive too early then resources may not be available, so timing is key.

- **Consequent ill-health and mortality**

- In the above ways, migration can increase animals' susceptibility to ill-health and mortality (Alerstam *et al.*, 2003).

- **Potential reduced reproductive success**

- There is some evidence of lower breeding success in migratory individuals, for example in European shags (*Phalacrocorax aristotelis*), partial migrant breeding pairs had lower breeding success than resident pairs (Grist *et al.*, 2017).

Negative consequences for infection status include:

- **Increased susceptibility to infection and disease associated with the physiological costs of migration**

  - The energetic costs of migration can cause immunosuppression via physiological trade-offs, *i.e.* diversion of resources from the immune system to other body systems (Maggini *et al.*, 2022).
  - Compromised general health also increases susceptibility to infection and disease.
  - If an individual is harbouring a silent (latent) infection, the act of migration can therefore reactivate it (termed 'migratory relapse') (Hall *et al.*, 2022).

- **Exposure of migrants to a broader diversity and potentially higher load of infectious agents**

  - As above, multiple stopovers across a variable migratory landscape may increase the range of infectious agents in the environment to which migrants are exposed.
  - Similarly, their contact other individuals, populations and species, especially through aggregations at breeding or wintering sites, increases the range and burden of infectious agents to which they are exposed either directly or indirectly via, for example, contaminated ground ('environmental sampling', Hall *et al.* 2022).
  - Tracking of favourable environmental conditions ('environmental tracking') can also lead to higher exposure rates to certain infectious agents that favour these conditions (see main text).
  - Migratory dropout or stalling (described above) can lead to increased infection prevalence in a static population through the presence of infected individuals that have chosen not to migrate, or to delay migration.
  - This increased exposure to infectious agents, and the increased diversity of agents to which migrants may be exposed, combined with increased disease susceptibility associated with migration (see above), can increase the risk of infectious disease and infectious agent transmission in the migratory population.

- **Increased exposure of migrants and linked populations to novel infectious agents**

  - As above, when multiple populations and species aggregate at the same stopover sites there is an increased chance of migrants being exposed to, and infected with, novel infectious agents.
  - Encountering different or new habitats at stopover sites can also expose migratory animals to novel infectious agents.
  - Migratory animals can therefore bring novel infectious agents with them to new or distant sites, introducing them to new locations, host populations or species (Hall *et al.*, 2022).

5.2.3 Migration disruption and its potential impacts on disease dynamics

Anthropogenic environmental pressures including climatic change are influencing migratory behaviours at a global scale (Robinson *et al.*, 2009). Various types of migratory change may result from these pressures, with some populations choosing to become more resident, and others appearing to struggle to acclimatise to the changing climate and environment around them (Bowlin *et al.*, 2010). Some broad types of migration disruption and associated changes are summarised in Table 5.3.

Table 5.3. Types of migratory change and their potential negative consequences for health and infection dynamics.

Examples of underlying disruptive processes[1]	Consequent migratory changes	Potential negative consequences
• Climate change and/or adverse weather events • Loss, fragmentation or degradation of habitat • Physical and other barriers to migration	Delays in migration	Missed resource abundance; difficult terrain on the migratory journey increasing energetic and physiological costs of migration (*e.g.* ice melt meaning terrestrial species need to swim); increased competition for resources pre- or post-migration; increased infectious agent exposure pre- or post-migration.
	Remaining resident /skipping migration	Reduced access to resources; competition and increased infectious agent burdens in the resident area as above.
	Earlier migration	Missed seasonal resources (phenological mismatch).
	Population fragmentation	Reducing population connectivity and genetic vitality.
	Altered migration range or routes	Exposure to more *e.g.* endemic infectious agents in different environments, populations or species, or novel agents; in turn, potential for increased risk of infectious disease in migrants, as well as pathogen distribution over a wider geographical area.
	Overcrowded stopover sites	Increased infectious agent burdens in hosts and environments and potential increased risk of spillover events.
	Increased physiological stress	May occur as a consequence of migratory disruption and change, leading to compromised health or immunosuppression and increased disease susceptibility.
	Loss of food and habitat, and reduced quality of habitat	Melting sea ice, increasing temperatures and rising sea levels can lead to loss of habitat and food for some species. There may also be a reduction in habitat and resource quality, *e.g.* drought affecting plant growth.
	Unsafe migratory journeys	Changing climate can impact wind patterns or ocean currents, impacting on migration routes and timings. Migratory animals may also be impeded by barriers, or encounter human activities that lead to capture, injury or mortality.
	Altered species, vector or pathogen assemblages	Climate and habitat changes may cause altered species or pathogen assemblages and also increase, or decrease, the abundance of disease vectors such as mosquitos.

[1] For further details and examples see *e.g.* Robinson *et al.* (2009).

5.2.3.1 Climate change

Climatic changes are predicted to alter habitats of migratory species, for some species, reducing suitable breeding, non-breeding and stopover sites, with consequent impacts on 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; and increased mortality during migration (Table 5.3, López-Hoffman *et al.*, 2017).

Altered migratory routes or ranges in response to climate change could expose migrants to novel infectious agents and/or cause migrants to transmit infectious agents to naïve populations, increasing the chances of infectious disease emergence. For example, the reduction or loss of sea ice that is predicated to occur in Arctic Canada through global warming could allow for increased contact between groups of previously separated species in the east and west, potentially causing some species to be exposed to novel pathogens (Post *et al.*, 2013) (see Box 5.4). In terrestrial animals, it is thought that migrating populations may deviate their route to one that is at a higher elevation or latitude, which also has the potential to cause cross-species transmission of pathogens to naïve populations (Harvell *et al.*, 2009).

Climate change will also alter the distribution and abundance of disease vectors; many disease vectors are arthropods whose distribution is largely determined by climate (see Box 5.4). The potential impacts on both migratory species and disease risks are complex and challenging to predict. For example, increasing temperatures observed in the Zambezi Valley, Zimbabwe, seem to have reduced the distribution of tsetse fly (*Glossina* sp.) populations which could reduce the risk of diseases such as trypanosomiasis in the region. Conversely, in other regions, environmental conditions could become more habitable for vectors, increasing the likelihood of disease emergence (Lord *et al.*, 2018) and leading to species being less able to avoid/escape vector-borne pathogens: a significant concern for migratory species of poor conservation status (Hall *et al.*, 2016) (see Box 5.4).

Box 5.4. Case examples: Climate change, infectious disease and migration

Phocine distemper in seals and sea lions

Sea ice loss in the Arctic may have played a role in the spread of phocine distemper virus (PDV). As discussed in the previous case example (Box 5.3), PDV has been responsible for mass mortalities of seals. From 2004-2006, PDV was found in northern sea otters (*Enhydra lutris kenyoni*) in the North Pacific in association with an unusual numbers of otter deaths. Northern sea otters' distribution overlaps with the ranges of migratory species such as fur seals (*Arctocephalus australis*), harbour seals (*Phoca vitulina*), grey seals (*Halichoerus grypus*) and Stellar sea lions (*Eumetopias jubatus*) that can act as reservoir hosts of PDV. PDV infections in these otters may therefore have been the result of cross-species transmission from such species. It has been hypothesised that the reduction in sea ice could have increased contact rates between Arctic and sub-Arctic marine mammals, leading to this cross-species transmission (VanWormer *et al.*, 2019; Goldstein *et al.*, 2009).

Spread of avian malaria due to increase in range of mosquito vectors

Avian malaria (*Plasmodium relictum*) is transmitted via mosquito vectors and is a potential pathogen in many migratory bird species. Birds in Arctic and northern regions have been thought to be protected from transmission of malaria as the climate was not suitable for the mosquito vectors. However, with warming temperatures, the region appears to now be able to support the life cycle of mosquito vectors of avian malaria (Figure 5.5). There is therefore potential for naïve migratory birds to be exposed to avian malaria, and for resultant possible negative population-level impacts (Loiseau *et al.*, 2012).

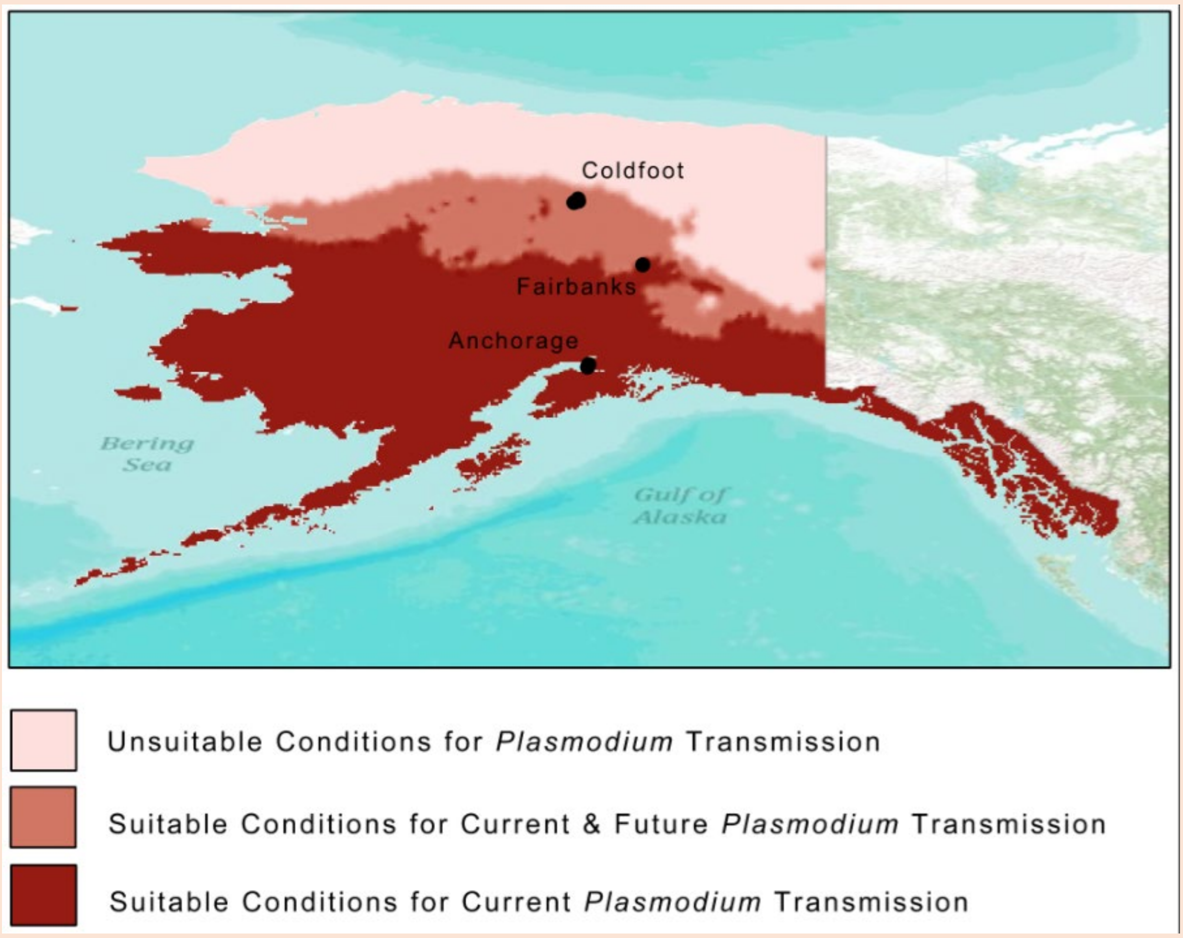

Figure 5.5. Current and predicted range of avian malaria in Alaska due to climate-related changing environmental conditions for mosquito vectors.
Figure credit: C. Loiseau (from Loiseau et al. 2012).

5.2.3.2 Habitat loss, fragmentation or degradation

Habitat loss, fragmentation or degradation as a consequence of human activities and disturbance can have a significant impact on migrants, driving alterations in migratory routes, stopover locations and the duration of migration, or encouraging populations to become more resident. Changes in land use degrade natural ecosystems and can cause stress to wildlife. There may be a reduction in resources and associated negative impacts on animal and plant health, which in turn can increase risks of disease. Habitat loss can fragment populations increasing vulnerability to disease (see Box 5.5). Moreover, habitat loss pushes wildlife to use smaller areas, with (at least temporarily) increased density and competition for resources, and increased direct and indirect contact, not only between wild animals but also, potentially, with livestock and humans in the vicinity, particularly if human activities are encroaching on the area (Plowright *et al.*, 2021) (see Box 5.5).

Box 5.5. Case examples: Habitat loss, infectious disease and migration

African wild dog and vulnerability to impact of rabies

The African wild dog (*Lycaon pictus*), which is listed on CMS Appendix II, is endangered, and through habitat fragmentation its populations are in increasing contact with people and domestic and feral animals. Rabies outbreaks (from transmission from dogs) in these small populations can lead to severe local population declines, and could potentially lead to extirpation, if the mortality rate is high. 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). This provides a good illustration of the vulnerability of small and/or fragmented populations. If a disease event occurs in an isolated group, it can be very difficult for the population to rebound, particularly in the absence of habitat (and population) connectivity.

Avian influenza viruses in wildfowl in relation to habitat loss

Migratory birds are susceptible to infection with low- and high-pathogenicity avian influenza viruses (AIVs). A recent study modelled AIV transmission in greater white-fronted geese (*Anser albifrons*) in the East Asian-Australasian Flyway under different scenarios. This study showed that crowding of geese at smaller remaining sites (as a consequence of habitat loss) was likely to increase AIV transmission and outbreak risk. It also showed, however, that migratory behaviour (migratory escape, see Section 5.2) was likely to reduce transmission rates, with higher rates of infection predicted in populations choosing to remain more resident. Ultimately, the migrating individuals might become infected, but migration served to stagger outbreaks and could in effect decrease infection burdens at overwintering locations. If the duration and distance of migration is significantly decreased due to habitat loss, then these effects might be more limited. Overall, the results suggested a potential for increased spread of AIVs in flyways with greater habitat loss. This further illustrates the importance of protecting these habitats (Yin *et al.*, 2022).

Picture 5.5. Greater white-fronted geese on migration – habitat loss can increase avian influenza risk.
Modelling suggests crowding in areas due to habitat loss can increase risk of avian influenza virus infection, but the act of migration can in effect decrease infection burdens at overwintering locations. *Photo credit: © Sergey Dereliev, www.dereliev-photography.com*.

5.2.4 Migration disruption and barriers

Physical barriers, such as fences, wind turbines, roads, buildings and other infrastructure, can disrupt migration in some populations. Migration may be disrupted when animals try to cross these barriers, or they may remain resident and choose not to migrate (Altizer *et al.*, 2011). Fencing that has been erected to section off areas, for example for livestock grazing or disease control, can significantly impact migratory mammals (Kauffman *et al.*, 2021) (see box 5.6). Changes in land-use or other human activities can also serve as barriers to migration. Wind turbines and windows are responsible for the deaths of many migratory birds and bats through collision injuries (Cusa *et al.*, 2015; O'Shea *et al.*, 2016). Additionally, light or noise pollution, and high-density urban areas, can act as barriers, disorientating or impeding the movement of migratory species (Hölker *et al.*, 2010). Such barriers can reduce access to important feeding sites or water sources, fragment populations and reduce their connectivity, and in this way lead to ill-health, reduced genetic diversity and/or population declines.

Box 5.6. Case example: Barriers to migration

Mortality as a consequence of fencing impeding wildebeest (*Connochaetes taurinus*) migration

Fencing in an important migratory area can be catastrophic for mass migratory behaviour. In a year of reduced rainfall and drought (1983), approximately 50,000 wildebeest died in the Kalahari, which was largely thought to be due to veterinary cordon fencing (against foot and mouth disease) blocking their path, meaning the animals were unable to access their usual water sources. Instead, they drank from a lake which had a significant human presence. Consequently, they were hunted, prevented from drinking and stressed by interactions with livestock farmers (Williamson *et al.*, 1988).

Picture 5.6. Barriers to migration drive ill-health.
Barriers such as physical structures and loss of habitat (by whatever means) affect health of migratory species by increasing risks of both infectious and non-infectious disease. *Photo credit: Tanya Rosen.*

5.2.5 Cumulative impacts

Given the complex interplay between migratory strategy and infection status it is possible to see how alterations in migration patterns may in turn have a significant impact on disease dynamics in migratory species (McKay and Hoye, 2016). The drivers of migratory change, and the migratory changes themselves, also have potential to act together to increase ill-health and infection burdens in migratory species, as well as transmission risks to or from these species. Emerging infectious diseases are more likely to appear in populations that are negatively affected by other threats, such as overexploitation and habitat loss (Heard *et al.*, 2013). Population declines and fragmentation further increase the likelihood and impact of adverse disease events: stochastic events such as disease outbreaks are more likely to cause local extinctions in small, isolated populations, as in the African wild dog (*Lycaon pictus*) case example (see Box 4.4 and Box 5.5) (Aguirre and Tabor, 2008). As discussed in Chapter 4, declines in one species can then have wide-ranging effects on other species and their wider ecosystems. Clearly, as anthropogenic pressures on wild animals and their habitats are expected to increase in the coming decades, there are likely to be continued, varied impacts on host migratory behaviour and infection dynamics.

5.3 Key messages: Migration, migratory change and disease

→ Migratory species are essential parts of well-functioning and resilient ecosystems. They provide a wide range of ecosystem services, from pollination and seed dispersal to multiple provisioning and regulatory services, and exceptional societal benefits.

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

→ Migration can increase the likelihood of non-infectious health problems and mortality in migratory animals as they move through different habitats. For example, they may suffer or die from anthropogenic traumatic injury; undernourishment; exposure to toxins or pollutants; or overexploitation.

→ Migratory species can host endemic, emerging or re-emerging infections including those transmitted from livestock. Consequently, migration can bring infectious agents to new areas and to naïve populations of wild and domestic species, increasing the likelihood of disease events.

→ Although migration can be associated with potential risk of long-distance movement of pathogens, migration itself can be a strategy to reduce infection burdens. For example, migration can reduce the likelihood of infection within a population by, in effect, removing individuals too unfit to successfully migrate, and with them their genes for disease susceptibility. Exposure of migratory populations to different habitats, and potentially different and diverse infectious agents, can also build their short- and long-term resilience to infectious disease.

→ Therefore, depending on the local context, migration may serve to safeguard the health of wildlife, and reduce their risk of infectious disease and infection transmission to other populations.

→ Consequently, migratory species can be viewed as both the vectors of infection and victims of disease. They can suffer indirectly if they are subject to inappropriate disease control measures (including lethal responses) or other consequences arising from negative public attitudes.

→ Human activities and climate change are profoundly influencing migratory species. Changes in migration, along with the drivers of these changes, can not only have wide-ranging ecosystem and population-level effects, but also influence infection dynamics.

→ The effects of migratory change and disruption on infection dynamics are difficult to predict, and as yet there is a lack of real-world data exploring these relationships. Nevertheless, there is potential for increased pathogen burdens to compromise the health of migratory wild animals, and to negatively impact the health of domestic animals and people.

6 KEY HEALTH ISSUES IN MIGRATORY SPECIES AND THEIR BROAD UNDERLYING CAUSES

In this chapter we identify, at a high level, key health issues in migratory species and the broad driving processes which are considered to underlie these problems.

6.1 Introduction

As discussed in Chapter 4, disease conditions are increasingly being recognized as threats to the conservation status of wild animals. In addition, infectious agents and diseases of wildlife are gaining increasing attention from a One Health perspective. The same processes which are degrading the integrity of ecosystems, and causing biodiversity declines, are recognized drivers of both infectious and non-infectious wildlife disease and of infection transmission between individuals, populations and species.

Given the growing awareness of these issues and CMS's increasing focus on wildlife health, in this chapter we aimed to elucidate infectious and non-infectious causes of disease that are important issues for the conservation of migratory species listed on the CMS Appendices, and the underlying drivers of these disease problems, through a brief expert consultation process. We also aimed to gather information on infectious agents and diseases of wildlife that are important in relation to domestic animal or human health. This was intended as a high-level overview of key health concerns, as opposed to a highly detailed review, to serve as a reference point for the CMS Working Group on Migratory Species and Health.

6.2 Methods

To determine infectious and non-infectious health issues associated with species listed in the CMS Appendices, and the drivers of these problems, we conducted a brief, high-level expert consultation exercise, for which we provide detailed methods in *Annex 1. Detailed methodology and results for Chapter 6: Expert consultation on health issues in migratory species*.

Briefly, the 657 species listed on the CMS Appendices I and II were divided into 37 taxon-based groups (Table 11.1 in Annex 1). The species were mostly grouped according to taxonomic order, however, higher- or lower-level taxonomic groupings were used in some instances given the large number of orders and varied depth of knowledge about health conditions in wild populations of different species.

A bespoke 'disease table' (spreadsheet) was constructed to capture expert opinion. This included lists of infectious and non-infectious causes of disease associated with each species group, which were drawn up through a literature search and categorised as per Table 4.2. Experts were invited to add additional agents or conditions to these lists as appropriate. They were also invited to list 'other problems' perceived to be a conservation threat to these species groups, for context. The experts were asked to score each infectious and non-infectious cause of disease to indicate its perceived importance with respect to any negative impact on biodiversity conservation, human health, or domestic animal health respectively, using a constructed scale of 5-0, where 5 = 'very high importance' and 0 = 'no importance' (see Annex 1 for further details). They were also asked to identify and score any potential future or emerging threats from this list. A median score of ≥ 3.5 out of 5 across experts was taken to indicate that an infectious or non-infectious cause of disease, or 'other problem', was considered 'highly important' with respect to any of the above negative impacts. Experts were then asked to select the drivers of the causes of disease that they considered most important, *i.e.* any factors perceived to be driving and/or increasing the impact of the disease in relation to that group of species. These drivers were considered as broad categories adapted from the IUCN (International Union for Conservation of Nature)'s Threat Classification Scheme (IUCN, 2023), as summarised Table 6.1.

We asked experts to do this exercise with a mind on those populations or species best known to them, hence some scores were illustrative of health issues relevant to a species group rather than fully representative of all populations, geographical regions or species within a group.

Table 6.1. Categorisation of drivers of wildlife disease.
That is, factors perceived to be driving or increasing the impact of a disease associated with wildlife. Adapted from the IUCN Threats Classification Scheme (IUCN, 2023).

Driver	Description
Agriculture or aquaculture	Agricultural expansion or intensification. Includes activities that lead to an increased interface between livestock and wildlife (see Chapter 4).
Habitat loss, degradation, or disturbance	Human-related settlement[1]; changing land use[1]; roads or other infrastructure; alteration, destruction, or disturbance of habitats[1], including through energy production and extractive industries; transportation and service corridors; noise disturbance; war and conflict; and recreation. Includes resultant increased proximity to human settlements and non-farmed domestic or feral species.
Overexploitation (legal or illegal taking)	Deliberate or incidental non-sustainable use of wild resources by hunting, collection, fishing or other forms of taking.
Invasive species	Invasive non-native species, other problematic species or genes[2].
Pollution	Introduction of exotic, excess or toxic materials or energy to the environment. Including chemical[3] or plastic pollution; run-offs/effluents from agriculture, forestry, industry, domestic wastewater or 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. Including droughts, temperature extremes, storms and/or flooding.
Other	*E.g.* catastrophic geological events.

[1] From human activities other than agriculture or aquaculture (categorised separately).
[2] The IUCN and CMS definitions of invasive species include invasive diseases from such species, however we consider diseases separately for the purpose of this review. [3]Includes pharmaceutical pollution.

6.3 **Results**

6.3.1 Expert recruitment

Overall, 60 experts contributed to the consultation exercise. We were able to recruit at least one expert for each species group, with a variable number of experts (up to four) contributing per group (see Table 11.1).

6.3.2 Key health issues of conservation importance in migratory species

Taking all listed migratory species together (Table 6.2), the experts considered infectious disease to be a 'highly important' conservation issue in 68% (25) of the 37 species groups. It was a particularly common concern in avian and terrestrial species, perceived as highly important in 85% (22) of these 26 groups, relative to only 27% (three) of 11 aquatic species groups. Of the different types of infectious agent, viral diseases were most frequently considered highly important: in 51% (19) of all species groups and in 62% (16) of the avian and terrestrial groups. Non-infectious causes of disease were considered a highly important issue in 76% (28) of the 37 species groups: specifically in 82% (nine) of 11 aquatic, 77% (ten) of 13 avian, and 69% (nine) of 13 terrestrial groups. Toxins and pollutants, and incidental anthropogenic trauma, were common non-infectious health concerns, considered highly important in 49% (18) and 41% (15) of all species groups respectively. 'Other problems', including diminished or suboptimal habitat, persecution, climatic and ecological problems were considered highly important issues in at least 81% (30) of all species groups (see Table 6.2).

Table 6.2. Infectious and non-infectious causes of disease in CMS-listed migratory species considered by experts as being 'highly important' conservation issues.

'Highly important' issues were defined as those given a median score of ≥ 3.5 out of 5 for their suspected or proven negative impact on biodiversity conservation at a population, species or wider ecosystem level. Scores were defined as 5 = 'very high importance' to 0 = 'no importance'. Arthropod ectoparasites, parasitoid flies and transmissible tumours were amongst the causes of disease categorised as 'other' infectious agents for the purposes of this exercise (see Table 4.2). Although not obligatory, most experts also scored 'other problems' (see Table 11.2 in Annex 1 for their categorisation), for which the median scores are shown in grey text.

A. For avian, aquatic and terrestrial taxa

				Infectious disease									Non-infectious cause of disease								Other problems
		Number of species	Number of groups	Any type	Viral	Bacterial	Protozoal	Arthropod ectoparasite	Helminth	Fungal/yeast	Other	Undetermined/unknown	Any type	Toxin or pollutant	Incidental anthropogenic trauma	Foreign body ingestion	Nutritional deficiency/disease	Anthropogenic stress/disturbance	Physiological response to extreme climate	Other environmental injury	Any type
CMS category	Avian species	385	13	85	62	31	23	0	0	0	0	0	77	62	23	15	0	8	0	8	62
	Aquatic species	164	11	27	18	0	9	0	9	0	0	0	82	55	73	18	9	9	9	0	91
	Terrestrial species	108	13	85	62	46	8	31	23	8	8	8	69	31	31	0	15	8	0	0	92
	All species	657	37	**68**	**49**	**27**	**14**	**11**	**11**	**3**	**3**	**3**	**76**	**49**	**41**	**11**	**8**	**8**	**3**	**3**	**81**

b. For higher taxonomic groups within the above categories

				Percentage of species groups in which a particular cause of disease, or problem, was scored as highly important																		
				Infectious disease									**Non-infectious cause of disease**									Other problems
		Number of species	Number of groups	Any type	Viral	Bacterial	Protozoal	Arthropod ectoparasite	Helminth	Fungal/yeast	Other	Undetermined/unknown	Any type	Toxin or pollutant	Incidental anthropogenic trauma	Foreign body ingestion	Nutritional deficiency/disease	Anthropogenic stress/disturbance	Physiological response to extreme climate	Other environmental Injury	Any type
CMS category and higher taxon	**Avian species**	385	13	85	62	31	23	0	0	0	0	0	77	62	23	15	0	8	0	8	62
	Aquatic species																				
	Aquatic mammals	93	4	50	50	0	25	0	0	0	0	0	75	75	75	25	0	25	25	0	75
	Sharks and rays	40	2	0	0	0	0	0	0	0	0	0	100	50	100	50	0	0	0	0	100
	Fish	21	3	33	0	0	0	0	33	0	0	0	67	33	67	0	0	0	0	0	100
	Reptiles	10	2	0	0	0	0	0	0	0	0	0	100	50	50	0	50	0	0	0	100
	Terrestrial species																				
	Terrestrial mammals	107	12	83	58	50	8	33	25	8	0	1	67	25	33	0	17	8	0	0	92
	Monarch butterfly	1	1	100	100	0	0	0	0	0	100	0	100	100	0	0	0	0	0	0	100
	All migratory species	657	37	68	49	27	14	11	11	3	3	3	76	49	41	11	8	8	3	3	81

6.3.2.1 Avian species

Highly pathogenic avian influenza was the foremost infectious disease considered a highly important conservation issue in the listed migratory avian species. It was scored as highly important in 62% (eight) of 13 groups: ‘waterfowl and grebes’; ‘birds of prey’; ‘waders and gulls’; ‘cranes and allies’; parrots; seabirds; penguins; and ‘pelicans and allies’ (Table 6.3). Avian cholera (caused by the bacterium *Pasteurella multocida*) was considered a highly important disease in ‘waterfowl and grebes’, seabirds, and flamingos.

Non-infectious causes of disease were also frequently considered highly important in these species, particularly toxins or pollutants, in 62% (eight) of the groups. These included a broad range of chemical toxicants, and biological toxins, such as those associated with algal blooms. Interaction with fishing gear or marine debris (such as entanglement) was considered a highly important issue in penguins, ‘waders and gulls’, ‘waterfowl and grebes’, and seabirds.

6.3.2.2 Terrestrial species

In contrast to avian species, a wide range of viral and other infectious diseases were considered highly important in the listed migratory terrestrial mammals. Viral diseases were perceived as highly important in 58% (seven) of the 12 groups, most commonly rabies, in canids (for which the African wild dog is currently the only listed species; Table 11.1), felids and elephants. Anthrax (caused by the bacterium *Bacillus anthracis*) was the most prominent perceived infectious disease issue in terrestrial mammals, considered highly important in 42% (five) of the groups: bovids, giraffes (for which the giraffe (*Giraffa camelopardalis*) is the sole representative), equids, elephants and primates. Tuberculosis (caused by *Mycobacterium tuberculosis* or *M. bovis* bacteria) was considered highly important in elephants, primates and deer; and mange mites (including *Sarcoptes* sp.) were viewed as highly important in camelids, deer and primates. In primates, for which the listed species are all great apes, a disproportionately large number of infectious diseases was considered highly important, especially owing to the potential for transmission from humans, or other wild or domestic animal species. Unknown or unrecognized infectious agents to which this group might be susceptible were also flagged as being highly important.

Incidental anthropogenic trauma was perceived as highly important in 33% (four) of the terrestrial mammal groups: most commonly wounds from or entanglement in snares or traps, in canids, felids and elephants, which are groups predominantly comprised of African species.

Migratory insects are represented solely by the monarch butterfly, in which infectious agents and pesticides were both considered highly important.

6.3.2.3 Aquatic species

In the listed migratory aquatic species, infectious disease was considered a highly important issue in three species groups, specifically: canine distemper, phocine distemper, influenza A (HPAI) viral disease and toxoplasmosis (caused by *Toxoplasma* sp. protozoa) in ‘seals and sea lions’; canine distemper and morbilliviral disease in cetaceans; and disease due to the invasive nematode *Anguillicola* (*Anguillicoloides*) *crassus* in eels (represented solely by European eel (*Anguilla anguilla*)).

Non-infectious causes of disease were by far the most common concern in aquatic species. Incidental anthropogenic trauma was perceived as a highly important issue in 73% (eight) of the 11 aquatic species groups, most notably incidental catch in fishing gear and entanglement in marine debris, which was a particular concern in ‘seals and sea lions’, cetaceans, rays, sharks, ‘sturgeons and allies’, and turtles. Toxins or pollutants were considered a highly important issue for 55% (six) of the groups, including chemical toxicants in cetaceans, sharks and crocodiles, and algal toxins in ‘seals and sea lions’, sirenians, and ‘sturgeons and allies’.

6.3.2.4 Knowledge gaps

Experts commented that there was a lack of knowledge about infectious diseases in wild-living populations of many of the listed species, including parrots (Order Psittaciformes), sharks (Infraclass Selachii), rays (Infraclass Batoidea), catfish (Order Siluriformes, solely represented by the Mekong giant catfish (*Pangasianodon gigas*)), crocodiles (Order Crocodylia), camelids (Family Camelidae), bears (Family Ursidae) and insects (Order Lepidoptera, solely represented by the monarch butterfly).

Table 6.3. Infectious and non-infectious causes of disease in CMS-listed migratory a. avian; b. i. aquatic mammal, ii. shark and ray, iii. fish, iv. reptilian; and c. i. terrestrial mammal and ii. insect species, considered by experts as having a suspected or proven 'highly important' negative conservation impact.

A highly important impact was taken to be a median score of ≥ 3.5 out of 5 across experts (scores were defined as 5 = 'very high importance' to 0 = 'no importance'). As per Tables 4.2 and 6.2, arthropod ectoparasites, parasitoid flies and transmissible tumours were categorised as causes of infectious disease. 'Other problems' considered highly important to the species' conservation status are also listed in grey text, to provide context, although these lists are not exhaustive.

A. Avian species (Class Aves; 385 species divided into 13 groups[1]; 17 expert contributors)[2]

Category	Percentage of species groups		Details	Group
Infectious agent	**85**			
Virus	62			
		62	Highly pathogenic avian influenza viruses	Waterfowl and grebes; birds of prey; waders and gulls; cranes and allies; parrots; seabirds; penguins; pelicans and allies
		8	West Nile virus	Birds of prey
Bacterium	31			
		23	*Pasteurella multocida* (avian cholera)	Waterfowl and grebes; seabirds; flamingos
		8	Camployobacter spp., *Clostridium perfringens, Coxiella burnetti, Escherichia* sp., *Klebsiella* sp., *Listeria* sp., *Pasteurella* sp., *Proteus* sp. or *Staphylococcus* sp.	Galliforms
		8	*Mycobacterium avium* (avian tuberculosis)	Flamingos
Protozoa	23			
		8	*Eimeria* sp. (coccidiosis) or *Cryptosporidium* sp.	Galliforms
		8	*Trichomonas* sp. (*Trichomonas gallinae*)	Passerines, coraciiforms and doves
Non-infectious cause of disease	**77**			
Toxin or pollutant	62		Petroleum (oil) spill events	Waterfowl and grebes; seabirds; penguins
			Algal blooms, potential algal toxicosis (including through domoic acid, brevetoxin or cyanotoxin poisoning), eutrophication and changes in water quality	Pelicans and allies; flamingos
			Chemical environmental pollutants including: herbicides or carbamates; heavy metals such as mercury, chromium, cobalt, copper, arsenic (for lead, see below); industrial chemicals; pesticides such as organophosphates	Birds of prey; storks, herons and allies; seabirds
			Lead exposure (through e.g. spent shotgun pellets, fishing tackle, bioaccumulation)	Waterfowl and grebes; storks, herons and allies
			Clostridium botulinum toxin (avian botulism)	Waterfowl and grebes
			Anticoagulant rodenticides	Birds of prey
			Strychnine, 4-aminopyridine (Avitrol), 3-chloro-p-touline (Starlicide)	Passerines, coraciiforms and doves
			Poisoning and toxicosis from water chemistry changes	Flamingos
Incidental anthropogenic trauma	23		Bycatch or entanglement (see also 'Other environmental injury', below)	Penguins; waders and gulls; waterfowl and grebes
			Accidental anthropogenic trauma e.g. collision with windmills, vehicles, windows, buildings, cranes, wire, fences, power lines and entanglements.Associated traumatic injuries	Galliforms
Foreign-body ingestion	15		Ingestion of foreign material, including plastic (plasticosis)	Storks, herons and allies; seabirds
Anthropogenic stress or disturbance	8		Nest disturbance	Waders and gulls
Other environmental injury	8		Drowning from line fishing/fishing operations	Seabirds
Other problems	62			
Environmental conditions	38		Habitat loss or degradation, including loss of migratory flyways, agricultural intensification and development, expansion of cities	Birds of prey; waders and gulls; galliforms; bustards; penguins
Climatic conditions	31		Changing marine conditions associated with climate change, including ocean acidification and related changes in the food web	Seabirds; penguins
			Flooding	Waders and gulls; flamingos
			Drought and its prolonged effects, such as lack of food or breeding opportunities, negative impacts on nesting or staging, stopover or wintering sites	Flamingos
			Extreme weather events such as heat waves and storms or flooding	Penguins
Ecological problems	31		Predation, including from invasive species	Waders and gulls; galliforms; seabirds
			Reduced food availability due to reduced fish stocks, caused by unsustainable fishing and marine ecosystem collapse / fisheries competition	Penguins

b. Aquatic species

i. Aquatic mammals (Class Mammalia; 93 species divided into four groups[1]; eight expert contributors)

Category	Percentage of species		Details	Group
Infectious agent	50			
Virus	50			
		50	Canine distemper virus	Seals and sea lions; cetaceans
		25	Phocine distemper virus or influenza A viruses	Seals and sea lions
		25	Dolphin or porpoise morbillivirus	Cetaceans
Protozoa	25			
			Toxoplasma sp. (toxoplasmosis)	Seals and sea lions
Non-infectious cause of disease	75			
Incidental anthropogenic trauma	75		Bycatch, or entanglement in marine debris (abandoned, lost or discarded fishing gear, ALDFG)	Seals and sea lions; cetaceans
			Watercraft-related trauma (e.g. boats, commercial platforms, working barges, tugs or cruise ships)	Cetaceans; sirenians
Toxin or pollutant	75		Algal blooms and toxicosis, including from brevotoxins (*Karenia brevis*) or domoic acid	Seals and sea lions; sirenians
			Persistent organic pollutants	Cetaceans
Anthropogenic stress or disturbance	25		Noise pollution, including from pleasurecraft, naval sonar or seismic surveys	Cetaceans
Physiological response to extreme climate	25		Cold stunning, including loss of thermal refuges	Sirenians
Foreign body ingestion	25		Ingestion of foreign material	Seals and sea lions
Other problems	75			
Environmental conditions	50		Habitat loss or fragmentation	Otters; sirenians
			Coastal development	Sirenians
			Forest plantations around water bodies	Otters
Climatic conditions	25		Climate change and associated loss of habitat	Otters
Ecological problems	25		Prey depletion	Cetaceans
Genetic problems	25		Reduced genetic diversity through habitat fragmentation	Otters

ii. Sharks and rays (Class Chondrichthyes; 40 species divided into two groups[1]; three expert contributors)[2]

Category	Percentage of species groups	Details	Group
Non-infectious cause of disease	100		
Incidental anthropogenic trauma	100	Bycatch, entanglement	Rays; sharks
Foreign body ingestion	50	Ingestion of foreign material, including plastic	Sharks
Toxin or pollutant	50	Paint fumes - multiple volatile organic chemicals	Sharks
Other problems	100		
Persecution	100	Gill plate trade, fin trade, medicinal trade	Rays; sharks
		Overfishing	Rays; sharks

iii. **Fishes** (Class Pisces; 21 species divided into three groups[1]; seven expert contributors)[2]

Category	Percentage of species groups	Details	Group
Infectious agent	**33**		
Helminth	33	*Anguillicola* (*Anguillicoloides*) *crassus*	Eels
Non-infectious cause of disease	**67**		
Incidental anthropogenic trauma	67	Bycatch, entanglement	Sturgeons and allies
		Trauma associated with hydropower or sluices	Eels
Toxin or pollutant	33	Algal toxicosis: *Prymnesium* sp. algae (haptophytes), which produce prymnesin toxin	Sturgeons and allies
Other problems	**100**		
Persecution	100	Poaching	Sturgeons and allies
		Overfishing, including in the dry season	Eels; catfishes
Environmental conditions	100	Habitat loss or fragmentation, including from damming or navigation barriers	Sturgeons and allies; eels; catfishes
Climatic conditions	33	Climatic extremes	Eels

iv. **Reptiles** (Class Reptilia; ten species divided into two groups[1]; four expert contributors)[2]

Category	Percentage of species groups	Agent name	Group
Non-infectious cause of disease	**100**		
Incidental anthropogenic trauma	50	Bycatch, entanglement	Turtles
Toxin or pollutant	50	Heavy metal (mercury, lead, zinc) or pesticide bioaccumulation	Crocodiles
Nutritional disease or deficiency	50	Malnutrition from habitat degradation and reduction in food sources (see also below)	Turtles
Other problems	**100**		
Environmental conditions	100	Habitat loss, including loss of prey and nesting habitats	Crocodiles
		Habitat degradation, reduction in food sources	Turtles

c. Terrestrial species

i. Terrestrial mammals (Class Mammalia; 107 species divided into 12 groups[1]; 22 expert contributors)[2,3]

Category	Percentage of species		Details	Group
Infectious agent	**83**			
Virus	58			
		25	Rabies virus	Canids; felids; elephants
		17	Canine distemper virus	Canids; felids
		17	Encephalomyocarditis virus	Elephants; primates
		8	Coronaviruses, Ebola virus, human metapneumovirus, Marburg virus, measles ('rubeola') virus, parainfluenza II virus, respiratory syncitial virus, rhinovirus C, monkeypox virus, simian immunodeficiency virus, or simian T-lymphotropic virus	Primates
		8	Cervid herpesviruses 1 and 2, deer alpha herpesviruses, or delta papilloma virus (deer fibromatosis)	Deer
		8	Peste des petitis ruminants virus, or Rift Valley fever virus	Bovids
		8	Foot and mouth disease viruses	Giraffes
		8	Canine parvovirus	Canids
		8	Elephant endotheliotropic herpesvirus	Elephants
Bacterium	50			
		42	***Bacillus anthracis*** (anthrax)	Bovids; giraffes; equids; elephants; primates
		25	***Mycobacterium tuberculosis*** and ***M. bovis*** (tuberculosis)	Elephants; primates; deer
		8	***Yersinia*** sp. (***Y. pseudotuberculosis***, ***Y. enterocolitica***; yersiniosis), ***Streptococcus pneumoniae*** (bacterial meningitis), ***Shigella*** sp. (shigellosis), or ***Streptomyces*** sp.	Primates
		8	***M. avium*** subsp. ***paratuberculosis*** (Johne's disease)	Deer
Arthropod ectoparasite	33			
		25	Mange mites (***Sarcoptes*** sp., ***Chorioptes*** sp., ***Psoroptes*** sp. or ***Demodex*** sp.)	Camelids; deer; primates
		8	Ticks	Equids
Helminth	25			
		17	***Strongyloides*** spp.	Equids; primates
		8	***Anoplocephala*** spp., ***Anoplocephaloides*** spp., ***Strongylus*** spp. or ***Parascaris equorum***	Equids
		8	***Ancylostoma duodenale***, ***Ascaris lumbricoides***, ***Echinococcus*** spp. or ***Trichuris trichura***	Primates
		8	***Fasciola*** sp. (***F. hepatica***; fascioliasis) or Dictyocaulus spp.	Deer
Fungus or Yeast	8			
		8	***Pseudogymnoascus destructans*** (white nose syndrome)	Microbats
Protozoa	8			
		8	***Cryptospridium parvum***, ***Cryptococcus*** spp. (***C. neoformans***, ***C. gatti***), ***Entamoeba histolytica*** or ***Plasmodium*** spp.	Primates
Undetermined	8	8	Unknown or unrecognised infectious agents, including from sympatric wild or domestic animals, or humans	Primates
Non-infectious cause of disease	**67**			
Incidental anthropogenic trauma	33		Wounds from, or entanglement in, snares or traps	Canids; felids; elephants
			Road traffic collisions	Canids
			Wind farm collisions	Microbats
Toxin or pollutant	25		Poisoning, including targeted (persecution; see also below)	Felids; canids
			Toxicity from polychlorinated biphenyls, botulinum toxin, heavy metals, lead, zinc, pesticides or poisonous plants (phytotoxins)	Primates
Nutritional disease or deficiency	17		Starvation or reduced body condition due to changes in prey population dynamics	Bears
			Starvation driven by habitat loss and degradation	Equids
Anthropogenic stress or disturbance	8		Constant displacement from feeding sites by farming activity	Camelids
Other problems	**92**			
Environmental conditions	58		Habitat loss or fragmentation	Deer; felids; equids; elephants; microbats
			Displacement by development	Bovids
			Overgrazing of natural feeding sties by livestock, or intensive use of water by mining companies	Camelids
Persecution	58		Poaching	Bovids; camelids; felids; elephants
			Retaliatory killings	Megabats and allied microbats; microbats; felids
			Targeted poisoning	Felids; canids
			Other forms of persecution	Canids
			Human-elephant conflict	Elephants
Climatic conditions	25		Climate change, including associated loss of habitat	Bears; deer
			Recurring droughts	Camelids
Ecological problems	17		Apparent competition with livestock and abundant exotic species; small and declining populations; dog attacks	Deer
			Novel inter- and intra-specific competion	Bears

ii. Insects (Class Insecta; one species, the monarch butterfly (*Danaus plexippus*), Order Lepidoptera; one expert contributor)[2]

Category	Details
Infectious agent	
Virus	Baculoviruses (nucleopolyhedrosis viruses)
Other	Natural parasitoid flies (tachinids or others)
Non-infectious cause of disease	
Toxin or pollutant	Pesticides such as glycophosphate
Other problems	
Ecological problems	Arthropod predators, including invasive species. E.g. Formicidae ants, invasive fire ants, *Polistes* wasps, spiders, mantids, and a diverse group of other insect predators
	Reduced nectar sources to fuel adult migration
	Milkweed reduction due to agriculture (herbicide use) and climate change (see also below)
Climatic conditions	Climate change-related reduction in milkweed (food source and host plant)

[1] See this link[16] for listed species, and Table 11.1 in Annex 1 for details of species groups and number of expert contributors.
[2] N.B. Experts noted a lack of information about disease conditions in wild-living taxa from these groups.
[3] An important taxonomic ambiguity was noted for the species listed on CMS Appendix I as the Bactrian camel (*Camelus bactrianus*). In Mongolia, this is considered a domesticated species and wild camels are instead considered a distinct species, the wild camel (*Camelus ferus*) (Jemmett *et al.*, 2023).

[16] https://www.cms.int/en/species/appendix-i-ii-cms

6.3.3 Disease concerns for human and domestic animal health

Expert opinion on infectious agents and non-infectious conditions of importance to human health (those considered to have the potential to cause an epidemic or serious, widespread health impact in humans) and domestic animal health and human livelihoods, in association with CMS-listed migratory species, are presented in Table 11.4 in Annex 1.

6.3.3.1 Avian species

Highly pathogenic avian influenza viruses were considered a highly important concern for human and/or domestic animal health in multiple avian species groups: 'birds of prey'; 'waders (shorebirds) and gulls'; 'waterfowl and grebes'; galliforms; cranes; parrots; and penguins. West Nile virus was also considered a highly important human health issue in association with 'waterfowl and grebes' and 'passerines, coraciforms and doves' (specifically passerines). This zoonotic pathogen emerged in the Americas two decades ago and has since been spreading across the Americas (Hadfield *et al.* 2019) and Europe (Bakonyi and Haussig, 2020). It is spread between animals and humans via mosquitos, which acquire the virus by feeding on infected avian hosts (Campbell *et al*., 2002). *Salmonella* spp. infections in this species group were considered a highly important issue for domestic animal health.

Lead was highlighted as a highly important concern for human health in association with 'waterfowl and grebes', given that people can consume waterfowl that may have embedded shotgun pellets in their tissues or because these birds may have ingested lead, for example, in spent shotgun pellets or fishing tackle (see Box 6.2).

6.3.3.2 Aquatic species

Highly pathogenic avian influenza viruses in 'seals and sea lions' were considered a highly important concern with respect to human and domestic animal health. West Nile virus was considered a highly important human health issue in the context of its association with crocodiles of CMS-listed species, albeit in farmed animals. *Mycobacterium pinnipedi* in 'seals and sea lions', and *Nitzschia sturionis*, a parasite of sturgeons, were highlighted as important concerns with respect to human livelihoods or domestic animal health.

Heavy metals in 'seals and sea lions' and 'contaminants' in eels were also considered highly important health concerns for humans, bearing in mind these species may be consumed.

6.3.3.3 Terrestrial species

The expert contributors highlighted multiple zoonotic viruses of bats as being important human health concerns (*e.g.* Johnson *et al*., 2020). These included certain types of coronavirus carried by the Yangochiroptera (microbats) and Yinpterochiroptera ('megabats and allied microbats'). The sarbecoviruses, a subgenus of coronaviruses that include SARS-CoV and SARS-CoV-2, are endemic in *Rhinolophus* bats and have severe pandemic potential in humans; while some coronaviruses pose a low zoonotic risk, the zoonotic potential of other coronaviruses endemic in a range of bat species remains unknown. In the Yinpterochiroptera specifically, a number of other viruses were also considered highly important concerns for human health: multiple lyssaviruses; Marburg and Ebola virus (filoviruses); Nipah virus; and henipaviruses. Filoviruses and henipaviruses were also considered highly important issues for domestic animal health and human livelihoods. The experts emphasised that poaching of bats for consumption as wild meat and, paradoxically, retaliatory killing of bats owing to their perceived threat to human health, are both causes and drivers of zoonotic disease, including emerging infectious diseases. These activities increase the likelihood of human exposure to zoonotic pathogens carried by bats. For example, multiple studies have explicitly linked the consumption of bats to spillover of Ebola virus to humans (Tumelty *et al*., 2023).

A broad range of pathogens was considered highly important with respect to other terrestrial migratory mammals. The following pathogens were considered highly important concerns for human and/or domestic animal health in association with multiple species groups: rabies virus in bovids, felids, canids, equids and elephants; FMD virus in bovids, giraffes and elephants; *Bacillus anthracis* in bovids, deer, giraffes and equids; *Brucella* sp. in bovids, deer and canids; and *Mycobacteria* spp. in deer and elephants. Further details are provided in Table 11.4 (it should be noted that for some species groups, expert scores may have reflected the general risk posed by an agent or condition as opposed to the risk associated with that particular species group).

6.3.4 Potential future or emerging disease issues

Table 11.4 also details causes of disease that experts considered to be potential future or emerging threats, whether from a conservation, human or domestic animal health perspective. These included HPAI viruses in 69% (9 of 13) of avian species groups. In many of these groups HPAI was already considered a highly important conservation issue (Section 6.3.2.1); 'passerines, coraciforms and doves' were considered to have been largely unaffected to date, but it was considered a highly important concern for this group in future, given the markedly broad range of avian taxa already affected to date. Algal toxins were also considered to present a potentially greater threat to a number of species groups in future, including 'waders and gulls', sirenians and turtles.

6.3.5 Drivers of key diseases in migratory species

The processes considered by experts as driving the above key disease issues in the listed migratory species are summarised in Table 6.4. Habitat loss, degradation or disturbance was frequently considered a driver of infectious disease across avian, terrestrial and aquatic species (in 43% of 489 table entries for priority infectious agents across species groups). Climate change or severe weather events, and agriculture or aquaculture, were also commonly perceived drivers of infectious diseases in avian and terrestrial species (see Table 6.4).

In the case of avian influenza, agriculture or aquaculture was considered a key driver (in 81% of 16 relevant table entries). Habitat loss, degradation or disturbance, and climate change or severe weather events, were also commonly viewed as drivers of this disease, as were 'other' factors, including aggregation of birds at feeding stations; the time of year (phenological stage), with higher losses observed during the breeding season in some species; as well as the rapidly changing nature of the virus and its subtypes, including its infectivity and pathogenicity in different species. Table 6.4 also illustrates how, for many infectious diseases, experts considered there to be multiple drivers at play.

The perceived drivers of non-infectious diseases from toxins and pollutants, and from incidental anthropogenic trauma, are also summarised in Table 6.4. As would be expected, experts commonly considered pollution to be the driver of toxin- or pollutant-related disease, particularly in avian and aquatic species (77% of 53, and 57% of 56, relevant table entries respectively). Legal or illegal taking was a commonly perceived driver of this issue in terrestrial species (in 44% of 17 relevant table entries). Habitat loss, degradation or disturbance, agriculture or aquaculture, and legal or illegal taking, were all commonly perceived drivers of incidental anthropogenic trauma (in 38%, 30% and 30% of 73 relevant table entries, respectively).

Table 6.4. Expert opinion on the drivers of the following key health issues in migratory species: a. i. all infectious agents considered most important across species groups, and ii. avian influenza virus; and b. i. toxins and pollutants, and ii. incidental anthropogenic trauma.
'Entries' refer to any completed rows in the disease table (Picture 11.1) that represented a particular infectious or non-infectious cause of disease for which drivers were marked (experts were asked to mark the drivers of their top-rated causes of disease).

a. Infectious agents

i. All types of infectious agent (those considered most important)

CMS category	Number of entries	Percentage of entries for which factor was considered a driver							
		Agriculture or aquaculture	Habitat loss, degradation or disturbance	Legal or illegal taking	Invasive species	Pollution	Climate change or severe weather events	Other	Undetermined/ unknown
Avian species	148	30	51	5	5	4	32	11	9
Terrestrial species	203	41	49	25	25	16	42	6	7
Aquatic species	138	10	25	0	4	14	14	2	19
All relevant migratory species	**489**	**29**	**43**	**12**	**13**	**12**	**31**	**7**	**11**

ii. Avian influenza virus

CMS category	Number of entries	Percentage of entries for which factor was considered a driver							
		Agriculture or aquaculture	Habitat loss, degradation or disturbance	Legal or illegal taking	Invasive species	Pollution	Climate change or severe weather events	Other	Undetermined/ unknown
Avian species	15	87	53	7	0	0	40	27	0
Aquatic mammals: seals & sea lions	1	0	100	0	0	0	100	0	0
All relevant migratory species	**16**	**81**	**56**	**6**	**0**	**0**	**44**	**25**	**0**

b. Non-infectious causes of disease

i. Toxins and pollutants

CMS category	Number of entries	Percentage of entries for which factor was considered a driver							
		Agriculture or aquaculture	Habitat loss, degradation or disturbance	Legal or illegal taking	Invasive species	Pollution	Climate change or severe weather events	Other	Undetermined/ unknown
Avian species	53	32	40	4	0	77	23	2	0
Terrestrial species	17	33	22	44	6	28	22	0	6
Aquatic species	56	36	29	4	4	57	38	2	0
All relevant migratory species	**126**	**34**	**32**	**9**	**2**	**61**	**29**	**2**	**1**

ii. Incidental anthropogenic trauma

CMS category	Number of entries	Percentage of entries for which factor was considered a driver							
		Agriculture or aquaculture	Habitat loss, degradation or disturbance	Legal or illegal taking	Invasive species	Pollution	Climate change or severe weather events	Other	Undetermined/ unknown
Avian species	16	19	50	25	0	19	13	0	0
Terrestrial species	15	27	47	27	0	0	7	0	0
Aquatic species	42	36	31	33	2	14	7	14	0
All relevant migratory species	**73**	**30**	**38**	**30**	**1**	**12**	**8**	**8**	**0**

6.4 Case studies: drivers of health problems

Using information gathered from the experts consulted for this review, the following section presents some case studies illustrating how human activities are driving important disease issues in CMS-listed wildlife species. Figure 6.4 provides a pictorial summary of some of these disease issues.

Box 6.1. Driver of disease: Habitat loss, degradation and disturbance

Parasite burdens in monarch butterflies

Some populations of monarch butterfly (*Danaus plexippus*) are remaining resident in North America and breeding there year-round, rather than migrating to Mexico to breed. This is thought to be due to increased abundance of non-native tropical milkweed in the southern United States acting as a supplementary food source. Migration usually reduces burdens of the protozoal parasite *Ophryocystis elektroscirrha* (OE) in the monarch butterflies: they are thought to 'escape' such a high parasite burden in their non-breeding habitat (see further information in Chapter 5). By remaining resident, their parasite burdens are up to nine times higher than their migratory counterparts (Satterfield *et al.*, 2016).

Picture 6.1. Migration reduces parasite burdens in monarch butterflies due to 'migratory escape' from infectious agents.
Non-native plants are encouraging the insects to remain resident which is leading to increased disease burden. *Photo credit: Canva.*

Noise disturbance and cetacean strandings

Cetacean strandings, particularly of beaked whale species, appear to correlate to anthropogenic noise in the oceans. There have been multiple strandings connected to underwater human activities such as seismic surveys and military exercises (Weilgart, 2007). Marine noise from shipping traffic, which is predicted to continue to rise, also appears to be impacting many marine species. This is a difficult area of study due to gaps in basic understanding of the normal behaviours of many marine animals, and difficulties in researching noise events.

Beyond cetacean strandings and the demise of individuals, marine noise pollution can also have more subtle impacts on their normal day-to-day functioning. It is thought that increased noise can cause stress, which may lead them to move from usual habitats, and make them less able to hear 'natural' noises essential for finding prey or communication, due to masking by the anthropogenic noise. Many species alter their vocalisation patterns when there is increased noise, and change their behaviour such as stopping foraging, moving away from the location of the *e.g.* ship, or diving for longer periods. Communication range often decreases due to noise masking vocalisations. If individuals are exposed to chronic levels of noise, this could lead to disruption of normal activities, increased energy expenditure, lower general health, and potentially impact on reproduction success. Very loud noise can also cause temporary or permanent hearing impairment (Erbe *et al.*, 2019).

Picture 6.2. Multiple negative health impacts are created by marine noise. Marine noise can affect health of species such as this sperm whale (*Physeter microcephalus)* by driving them from favoured habitat, creating stress and affecting communication. *Photo credit: Canva.*

Box 6.2. Driver of disease: Pollution

Plasticosis in seabirds

The newly coined non-infectious disease termed 'plasticosis' describes the fibrotic changes in seabirds' stomachs and gastrointestinal tracts that result from plastic ingestion (Figure 6.1). Charlton-Howard *et al.* (2023) described this scar formation and fibrosis in flesh-footed shearwaters (*Ardenna carpeneipes*), and it is likely to affect numerous other seabird species. The condition was identified even in association with only small amounts of plastic. These internal changes can result in nutrient deficiencies, organ failure and potentially lead to mortality.

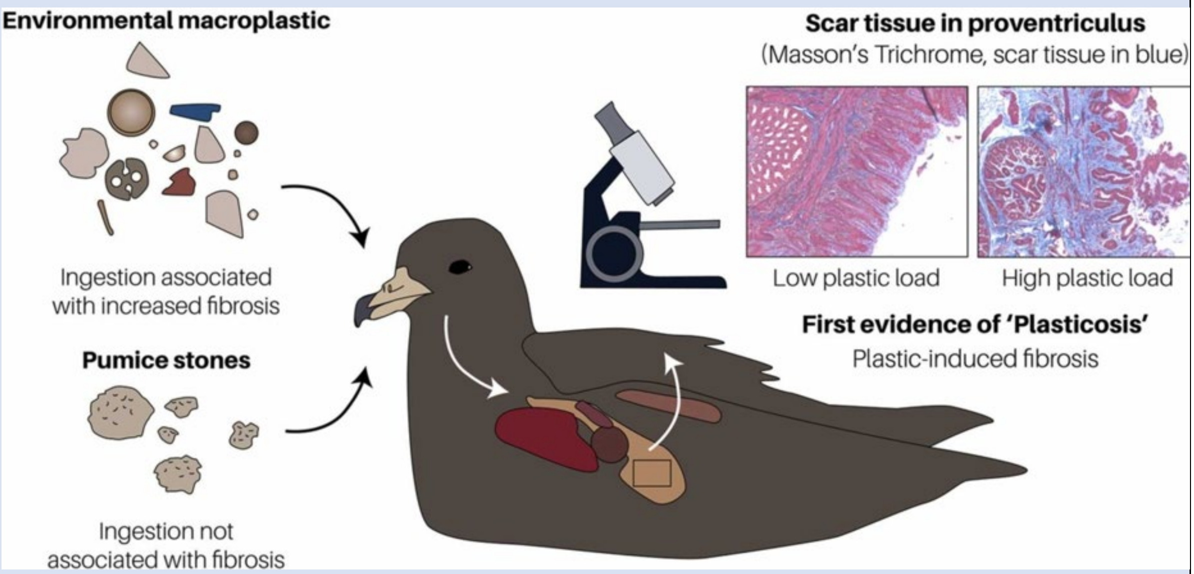

Figure 6.1. Plasticosis – a newly recognized wildlife disease.
Ingestion of environmental pieces of plastic is now known to create physical changes to the gut of seabirds such as shearwaters creating nutritional deficits and consequent ill-health or mortality. *Figure credit: Hayley Charlton-Howard/Adrift Lab.*

Pharmaceutical pollution

Pharmaceutical pollution is a significant problem worldwide, with use of veterinary and medicinal drugs increasing. Their discharge into the environment can impact many species both in aquatic and terrestrial environments, and can result in antibiotic-resistant organisms, hormonal and behavioural changes (endocrine disruption), immunosuppression and bioaccumulation (Klimaszyk and Rzymski, 2018); there are numerous reports of such impacts on fish species.

'*Gyps*' vultures have been a focus of attention due to pharmaceutical pollution from diclofenac and some other non-steroidal anti-inflammatory drugs (NSAIDS). The sudden and alarming decline of numerous vultures in the '*Gyps*' family on the Indian subcontinent prompted one of the most intensive wildlife disease investigations of recent times with a presumptive diagnosis of an infectious agent being at play. Eventually, secondary poisoning from diclofenac, owing to its use in domesticated animals, was identified as the cause (Oaks *et al.,* 2004). Vultures scavenging on treated livestock carcasses ingest the diclofenac residues. The drug accumulates in their kidneys leading to uric acid crystal formation in multiple organs (visceral gout), ultimately causing death. Once diclofenac was identified as the cause, it was eventually banned for veterinary use within many of the vultures' range states and some populations have since recovered. However, their declines were not without wider impacts. The loss of this main scavenging species across the Indian subcontinent resulted in an increased scavenging role for feral dogs (*Canis familiaris*) in some areas. The increased numbers of feral dogs led to greater incidence of dog bites and rabies virus infections in humans. Vultures help to remove diseased livestock carcasses (*e.g.* infected with diseases such as anthrax, brucellosis etc.), so disposal of such carcasses was impacted. Lastly, the increased presence of rats (*Rattus* spp.) at sites where carcasses are disposed of can increase the transmission risk of certain diseases which can impact humans, such as bubonic plague (Swan *et al.*, 2006).

This case example demonstrates the potentially severe impact of pharmaceutical pollution on wildlife populations and possible resultant downstream effects. Moreover, knowing now that diclofenac and the NSAID meloxicam can also affect '*Aquila*' eagles highlights the need for safety testing of new pharmaceuticals, risk assessment and restrictions on licensing of their use[17].

Lead poisoning from ammunition sources

Hunting with lead ammunition creates a One Health issue due to the extreme toxicity of the heavy metal and the multiple routes by which wildlife, humans, livestock and companion animals are subsequently exposed. Birds consuming lead shot from the environment mistaking them for grit or seeds, and raptors and scavengers (avian and mammalian) consuming shot or bullet fragments in their prey, may be poisoned to death. Birds may also be affected sub-clinically with impacts to mobility, ability to find food and evade predation, negative impacts to immunocompetence and reduced breeding success (ECHA, 2022). Unsurprisingly, a widely used powerful toxicant which affects both births and deaths has population level impacts for some species. Green *et al.* (2022) describes the European populations of raptors which are in effect supressed by the use of lead ammunition and essentially missing from ecosystems.

Humans are exposed to lead when consuming the lead in shot game which can cause IQ deficits in children due to neurotoxicity and chronic kidney disease and other negative health impacts in those regularly consuming such food. Poultry and cattle are prone to ingesting shot when feeding on land previously shot over, and dogs, particularly those in hunting households, are exposed via their food. The transition to non-toxic alternatives has been embraced by progressive hunters in some countries such as Denmark and has been slow where industry and other stakeholder resistance is strong (Arnemo *et al.*, 2019).

[17] MOU on the Conservation of Migratory Birds of Prey in Africa and Eurasia: Non-steroidal anti-inflammatory drugs and vultures. Available at: https://www.cms.int/raptors/en/page/non-steroidal-anti-inflammatory-drugs-and-vultures

Figure 6.2. The One Health issue of lead poisoning from ammunition sources. The figure illustrates some of the pathways by which people, wildlife and companion animals are exposed to neurotoxic lead from ammunition. Soil and plant contamination from degraded lead ammunition, particularly in areas of high usage, provides other pathways of exposure for people, livestock and wider ecological systems. *Figure credit: WWT.*

Box 6.3. Driver of disease: Aquaculture and agriculture

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

Highly pathogenic avian influenza (HPAI) in wild birds provides an example of the global One Health consequences of 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 (as well as human health). Mutations of such viruses when in dense domestic bird rearing settings – facilitated by mixing of domestic and wild birds - can allow emergence of HPAI viruses, which can cause high losses to poultry. The emergence of 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 (Sonnberg *et al.*, 2013). 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. A perception of migratory wild birds as vectors of disease led to 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 some wet market settings, practices such as grazing of domestic ducks in natural wetlands continue to provide ample opportunity for viral exchange. Spillover and spillback, and re-assortment with other avian influenza 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 happened in approximately 2021 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 and now to Antarctica in what is an on-going dynamic situation with potential for further spread into southern oceanic seabird breeding colonies. There are particular fears for albatross and penguin populations[18].

The rapid expansion of the poultry industry in the last few decades, often in the absence of adequate biosecurity and insufficient risk assessment with conservation authorities to inform land planning, 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 the virus has not acquired the ability to easily spread to and between humans. However, it has a propensity to infect mammals such as sealions and other carnivores[19] and mammal-to-mammal transmission has occurred in mink farm settings (Agüero *et al.*, 2023). 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. What is clear is that prevention of escape of livestock diseases to the wild is both cost effective and the obvious One Health approach (Kuiken and Cromie, 2022; CMS FAO Co-convened Scientific Task Force on Avian Influenza and Wild Birds, 2023).

Picture 6.3. The impact of highly pathogenic avian influenza.
Different tern species, such as these in the UK, are affected by H5N1 HPAI which is now circulating globally in wild birds and threatening Antarctic breeding colonies of seabirds.
Photo credit: Ibrahim Alfarwi/RSPB.

[18] https://www.fao.org/animal-health/situation-updates/global-aiv-with-zoonotic-potential/en
[19] See https://www.woah.org/en/disease/avian-influenza/#ui-id-2

Box 6.4. Driver of disease: Climate change

Septicaemia in saiga antelope

Saiga antelope (*Saiga tatarica tatarica*) have experienced multiple mass mortality events in recent years. In 2015, climate irregularities of increased specific humidity and higher low mean temperature are thought to have been a driver of haemorrhagic septicaemia caused by *Pasteurella multocida* Type B, which was implicated in the death of over 20,000 individuals. These specific climatic conditions that suit bacterial growth occur within a narrow climatic window, thus have not happened every year. Deaths from *P. multocida* septicaemia occurred during the calving season, when animals were likely to have been under greater physiological stress. So far, populations have recovered from these events owing to the species' specific life history trait of a high reproductive rate. Concerns remain, however, as human developments shrink saigas' migratory corridors and they face other continued pressures including poaching and increased livestock encroachment into their habitats. Together, there is potential for these threats to diminish populations to the degree that they are unable to bounce back (Kock *et al.*, 2018).

Starvation in polar bears

Polar bears (*Ursus maritimus*) rely on the sea ice for their survival. They move slowly, looking to ambush seals at their breathing holes: a hunting method which results in relatively low energy expenditure for high energy, blubber-rich food rewards. Increasing temperatures due to climate change are leading to sea ice reduction and break up which can move polar bears further from their usual feeding grounds. This results in increased energy expenditure, since the bears need to look further afield for food and cover an increased distance, spending more time swimming. Overall, this reduces their chances of catching seals; while energy-rich cetaceans or walruses also become harder to catch. Polar bears feeding on land must eat far more food to meet their energy demands, and if they have diminished access to marine prey they are at higher risk of starvation (Pagano and Williams, 2021).

Picture 6.4. Climate change is reducing sea ice and resulting in poor health and starvation of polar bears.
Relatively low-energy hunting practices of waiting by breathing holes for high-energy prey species (marine mammals such as seals) are being replaced by foraging over larger distances including by swimming for lower-energy foodstuffs. *Photo credit: Canva.*

Box 6.5. Driver of disease: Overexploitation (legal and illegal taking)

Deaths and injuries in African mammals from indiscriminate snaring

The demand for wild meat can relate to subsistence hunting and food security, as well as supply of wild meat markets and the wildlife trade. Snaring, as a type of harvest, is a significant problem in parts of Africa with indiscriminate, unsustainable wild meat poaching representing a significant threat to many species of wildlife. Wire snares may be put out to catch herbivores, but unintentionally snare larger or more endangered species such as African elephants (*Loxodonta africana*), lions (*Panthera leo*) or African wild dogs (*Lycaon pictus)*. Some individuals will succumb from their entrapment or injuries, while some will escape with wounds that compromise their health in the longer term (Becker *et al.*, 2013).

Picture 6.5. Wire snares are a common and inexpensive method for illegal hunting of wildlife.
This photograph shows a snare that has become embedded within the bone of a wild antelope with subsequent new bone growth around it. Although the animal clearly did not die at the time of snaring, the snare will have caused significant pain and suffering, most likely ultimately resulting in the death of this animal. *Photo credit: Anna Tolan.*

Ghost-gear entanglement

Historically fishing gear was made from natural materials such as hemp and cotton, which degraded and decomposed relatively quickly, thus not posing a significant threat to marine life. However, more recent and advanced synthetic materials such as nylon, which are much hardier, do not break as easily and can last for decades. Fishing equipment made from these materials that gets lost, discarded or breaks ends up persisting for prolonged periods in the marine environment and contributing to 'ghost fishing'. These gears are indiscriminate in the wildlife species they capture, with entanglement in all species causing a detriment to the health of that individual and leading to consequences such as traumatic wounds, starvation, drowning and death. Animals such as seals and sea lions, cetaceans, sharks, rays, sawfish, wedgefish, guitarfish and marine turtles are often found entangled in ghost gear. They may be attracted to the gear because floating material can host smaller prey species which use it for shelter, or because they are inquisitive and explore the material (Stelfox *et al.*, 2016).

Picture 6.6. The problem of ghost fishing gear.
Entanglement in ghost-gear is responsible for mortality of marine mammals, turtles, bony fish and cartilaginous fish such as this scalloped hammerhead shark (*Sphyrna lewini*).
Photo credit: Toby Matthews/Ocean Image Bank.

Box 6.6. Driver of disease: Invasive non-native species

Introduced parasite of European eels

The invasive nematode *Anguillicola crassus,* now an established parasite of European eels (*Anguilla anguilla*), was unintentionally introduced to Europe in the 1980s following the return of *A. anguilla* specimens after their aquaculture alongside the Japanese eel (*Anguilla japonica*) in Asian farms (Currie *et al.*, 2020). It causes damage to the swimbladder of an eel, which impacts buoyancy control and compromises swimming ability (due to the rupturing of fibrotic scars originating from swimbladder wall penetration by larval nematodes, weakness from infection and energy costs associated with infection). This can result in migratory failure, with infected eels being unable to complete their journey to the Sargasso Sea for spawning (Palstra *et al.*, 2007). The nematode appears to be one of the causes of European eel population collapse, alongside other threats which include changing climate and ocean conditions, overexploitation, and construction of barriers to migration, such as dams (Barry *et al.*, 2014).

Picture 6.7. Introduction of infectious agents from non-native species is a typical driver of disease emergence.
Farmed eels were the source of an exotic nematode involved in population decline of European eels. *Photo credit: Derek Evans.*

Figure 6.3. Examples of important health issues in migratory species and their anthropogenic drivers.

6.5 Discussion

6.5.1 Main findings

There was expert consensus that both infectious and non-infectious diseases are 'highly important' conservation issues for many wildlife taxa listed on CMS Appendices I and II. The establishment of a CMS Working Group on Migratory Species and Health is therefore very timely, as is the updated resolution on wildlife health and migratory species (Resolution 12.6(Rev.COP.14)) and other recent, high-level initiatives that incorporate wildlife in broader health fora, notably the One Health High-Level Expert Panel and the Quadripartite for One Health.

6.5.1.1 Infectious diseases

Infectious diseases were considered a highly important conservation issue in 68% of the species groups and a particularly key concern in avian and terrestrial taxa (85% of those groups). Again, this affirms the importance of CMS's enhanced focus on infectious disease in migratory species.

The role of wild birds as a reservoir and source of HPAI viruses in domestic species and humans is well recognized. However, importantly, this consultation highlighted the potential or confirmed threat that HPAI poses to the conservation status of a large, taxonomically diverse range of migratory avian species: it was considered a highly important conservation issue in 62% of avian species groups (Tables 6.2 and 6.3). Other infectious diseases were also considered highly important conservation concerns across multiple species groups, such as: anthrax, tuberculosis, rabies and mange in migratory terrestrial mammals; canine distemper in migratory marine mammals; and avian cholera in migratory birds. CMS-listed primate and galliform species (the latter represented only by the common quail (*Coturnix coturnix coturnix*)) were considered at risk from a markedly broad range of infectious agents: in primates, this was especially owing to their proximity to human settlements. Aside from mammals and birds, the experts highlighted infectious disease issues of conservation importance in the European eel and monarch butterfly (see Boxes 6.6 and 6.1). It is important for Contracting Parties to take note of these infectious disease problems and act on the recommendations contained in this report relating to their mitigation, which echo recommendations in the new CMS Resolution on Avian Influenza adopted at COP14 and the updated resolution on wildlife health and migratory species (Resolution 12.6(Rev.COP.14)).

Picture 6.8. Lowland gorillas (*Gorilla gorilla*) are at risk of disease due to habitat loss and degradation, disturbance and contact with people.
Photo credit: Michael Kock.

The most prominent broad underlying drivers of priority infectious disease issues were judged to be habitat loss, degradation or disturbance (our definition of which encompassed multiple types of anthropogenic activity as per Table 6.1); climate change; and agriculture/aquaculture, respectively marked as drivers in 43%, 31% and 29% of expert inputs. These results reiterate the key messages of previous chapters, that factors underlying declines in migratory species are, concurrently, driving disease emergence in these populations. Contracting Parties should appreciate the links between these driving processes and disease issues. While an important driver of disease, habitat loss, fragmentation and degradation is one of the foremost conservation threats to migratory species (UNEP-WCMC, 2023). It is tackled through multiple CMS resolutions and instruments (Agreements, MOUs, Action Plans and other species initiatives). The CMS Resolution 12.21 on Climate Change and Migratory Species includes a Programme of Work on Climate Change and Migratory Species. In acting on the recommendations of these CMS instruments, Contracting Parties will be increasing the resilience of natural systems to disease emergence. Experts frequently considered there to be multiple important drivers of infectious disease issues, which appear to act synergistically and cumulatively in driving disease emergence. In turn, disease events may exacerbate endangered species' precarious conservation status, increasing their vulnerability to other threats.

In the case of avian influenza, 'agriculture or aquaculture' was perceived as a key driver (81% of expert inputs), alongside other factors. HPAI viruses are now well established in wild bird populations, particularly waterbirds, however, as discussed above, HPAI subtypes in wild birds largely originated from domestic poultry, in particular domestic-wild birds interfaces associated with poultry production systems in Asia (see Box 6.3 and Chapter 4). The CMS-FAO Co-Convened Scientific Task Force on Avian Influenza and Wild Birds has repeatedly called for better biosecurity and good cross sectoral working to achieve One Health outcomes. The new Quadripartite for One Health is very welcome, as there is a pressing need for further high-level recognition of these links between some agricultural practices and the emergence and spread of pathogens such as HPAI, and of the benefits that more sustainable and biosecure farming practices will have for wildlife, domestic animal and, ultimately, human health.

6.5.1.2 Non-infectious conditions

Toxicants, toxins and pollutants were considered a highly important conservation concern in many migratory taxa, especially avian and aquatic species (in 62% and 55% of species groups respectively). In both groups, these included a broad range of chemical toxicants including oil spills, pesticides and heavy metals such as lead ammunition, as well as biological toxins. Algal toxins, associated with algal blooms, were a prominent issue and may be an increasing, emerging threat to migratory species. Our expert consultation lacked sufficient detail to explore the drivers of this problem in depth, however, pollution and climate change have been cited as important underlying factors in mortality events linked to algal toxins (see *e.g.* Gobler, 2020; IGB, 2022).

Incidental anthropogenic trauma was also considered a highly important conservation issue across multiple taxa, most notably in aquatic species (73% of aquatic species groups), where injury from interaction with fishing gear or marine debris was considered particularly impactful (see Box 6.5). The variety of existing CMS instruments relevant to toxic and traumatic threats are summarised below.

6.5.2 CMS instruments key to reducing disease issues and their drivers

These findings reinforce the importance of Contracting Parties implementing existing CMS instruments. As mentioned above, the Resolution 12.6(Rev.COP.14) on Wildlife Disease and the new Resolution on Highly Pathogenic Avian Influenza adopted at COP14 are of key importance in tackling primarily infectious, but also non-infectious, disease threats to migratory wildlife. The CMS-FAO Co-Convened Scientific Task Force on Avian Influenza and Wild Birds has been a valuable initiative for providing both situation updates and guidance on measures to tackle this disease in wild birds and reduce risks to poultry and people. Since its establishment in 2005 it has in effect represented the wildlife perspective of this One Health issue.

Resolution 11.15(Rev.COP.13) on Preventing Poisoning of Migratory Birds is the Convention's main existing instrument addressing toxic substances of anthropogenic origin threatening migratory avian species. The provisions of this resolution adopt the CMS Guidelines to Prevent the Risk of Poisoning to Migratory Birds, which include recommendations to prevent risks from insecticides, rodenticides, poison baits, veterinary pharmaceuticals and lead ammunition and fishing weights. There is a particular focus on tackling poisoning within the CMS Multi-species Action Plan to Conserve African-Eurasian

Vultures, and the wider work of the Raptors MOU. To support its implementation of actions on lead ammunition, the resolution mandates the Preventing Poisoning Working Group and an Intergovernmental Task Force on Phasing Out the Use of Lead Ammunition and Lead Fishing Weights. Resolution 11.15(Rev.COP.13) also includes reference to a number of additional tools and initiatives within and outside the CMS Family.

For migratory aquatic species and seabirds, threats associated with ingestion of marine debris, including microplastics, are addressed in the Resolution 12.20 on Management of Marine Debris, which includes references to relevant initiatives and tools of a number of other international fora. Resolution 7.3(Rev.COP.12) on Oil Pollution and Migratory Species also addresses, to some extent, the threat from oil pollution to migratory species. For aquatic, specifically marine, species, a range of CMS instruments address incidental capture in fisheries and marine debris. These include the CMS Resolutions 12.20 on Management of Marine Debris and 12.22 on Bycatch with CMS Technical Series Publication No. 38 and No. 43, as well as, for example, work undertaken by the Agreement on the Conservation of Albatrosses and Petrels (ACAP), the Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area (ACCOBAMS), the Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas (ASCOBANS) and the CMS Sharks MOU. Incidental capture of aquatic avian species is addressed to some extent under CMS instruments such as ACAP and the Agreement on the Conservation of African-Eurasian Migratory Waterbirds (AEWA), the latter Agreement having been at the forefront of restriction of lead shot.

The issues of barriers to migration and trauma caused by infrastructure are addressed in several instruments including CMS Technical Series Publication No. 41 (for mammals in Central Asia) and No. 29 (mitigating risks from power infrastructure for birds in the African Eurasian region).

Multiple other CMS instruments address the underlying drivers of infectious and non-infectious disease threats to migratory species (see Figures 6.3 and 7.1 for illustrations of disease issues and their drivers). As per above, habitat loss is addressed through several CMS resolutions and many CMS instruments. Relevant forms of disturbance are also addressed, for example via the Resolution 12.14 on the Adverse Impact of Anthropogenic Noise on Cetaceans and other Migratory Species and CMS Technical Series Publication No. 46; Resolution 13.5 on Light Pollution Guidelines for Wildlife; and Resolution 12.16 on Recreational In-water Interaction with Aquatic Mammals. The impact of agriculture on migratory species' health is to some extent addressed through Resolution 11.15 on Preventing Poisoning of Migratory Birds, while Resolution 13.6 on Insect Decline and its Threat to Migratory Insectivorous Animal Population is also relevant, and an accompanying CMS review of insect declines (UNEP/CMS/COP14/Doc.30.4.2/Rev.1) includes an exploration of the drivers of decline such as agriculture; EUROBATS (the Agreement on Conservation of European Bat Populations) also has a specific resolution on this subject.

Overexploitation (legal and illegal taking) is the foremost threat to the conservation status of migratory species (UNEP-WCMC, 2023), and is also a recognized driver of disease issues of conservation and zoonotic concern (*e.g.* Tumelty *et al*., 2023). Relevant CMS resolutions include Resolution 12.15 on Aquatic Wild Meat, Resolution 11.16(Rev.COP.13) on The Prevention of Illegal Killing, Taking and Trade of Migratory Birds, and the aforementioned Resolution 12.22 on Bycatch, along with many other instruments. CMS Resolution 11.28 on Future CMS Activities related to Invasive Alien Species acknowledges that invasive alien species can exert their impact on migratory species through the transmission of diseases. This resolution also makes reference to several other CMS instruments with provisions to address the impacts of invasive alien species. As per above, climate change is addressed through CMS Resolution 12.21 on Climate Change and Migratory Species.

It should be noted that responses to mass mortality events in migratory species are considered under Resolution 10.2 on Modus Operandi for Conservation Emergencies. This establishes a mechanism for intervention which, to the best of our knowledge, has been fully activated only once thus far, in the case of mass saiga antelope (*Saiga tatarica tatarica*) mortality in Kazakhstan (see Box 6.4). Also, Resolution. 7.3(Rev.COP.12) on Oil Pollution and Migratory Species refers to preparedness for emergency responses to oil spill events.

Picture 6.9. Policy initiatives, such as that of CMS, are needed to address the harms of marine noise.
CMS Resolution 12.14 on the Adverse Impact of Anthropogenic Noise on Cetaceans and other Migratory Species provides a set of actions aimed at reducing the impacts of noise on the health of marine mammals. *Photo credit: Aaron Crowe.*

6.5.3 Challenges in detecting and understanding disease problems in migratory species

Our literature search and the expert consultation highlighted some important challenges relating to detection and understanding of disease processes in migratory wild animals.

There was a lack of information regarding pathogens and diseases of many CMS-listed species (Section 6.3.2.4). For these groups, much (if any) of the available literature concerned their captive or farmed counterparts. It is therefore possible that diseases of potential conservation significance in these species were, and remain, overlooked. Also, other studies have highlighted a geographic bias in reporting of wildlife disease events (Machalaba *et al.,* 2020b). These problems reflect a lack of health monitoring and surveillance in many taxa and geographic regions associated with poorly resourced wildlife health systems (Section 4.6.1). This precludes our ability to understand which infectious agents and disease conditions are associated with wildlife species and their impacts on these populations.

We asked the experts to score infections and non-infectious causes of disease according to their perceived proven or suspected importance for biodiversity conservation. We did not require them to justify their score or clarify the extent to which an infectious or non-infectious cause of disease had been proven to negatively impact species within a particular group, which would be desirable in a more detailed future study. A key element in deciding whether to invest efforts to address a disease problem should be an evaluation of its significance for the long-term conservation of a migratory species. However, to answer this question, in the first instance, countries need to have wildlife veterinary pathology expertise and associated laboratory facilities to enable wildlife diseases to be detected and diagnosed. Moreover, wildlife disease surveillance needs to be conducted long-term, in concert with population monitoring programmes, so that associations between the temporal and geographic patterns of disease can be analysed relative to population and demographic trends, to determine population-level impacts. Even in the case of amphibian chytridiomycosis (Box 5.1), which is likely to have been the most impactful wildlife disease problem in history, the cause of disease, and its negative impacts on amphibian populations, only began to be realised several decades into the disease's emergence, once it had likely caused amphibian population declines across a wide geographic area and had been spread between continents via anthropogenic movements.

While some diseases, such as HPAI or anthrax, can cause dramatic mortality events, as we have discussed, the negative impacts of other diseases on wildlife can be more easily overlooked. For example, the first outbreaks of chytridiomycosis in Australian frogs are likely to have killed many individuals, but "dead frogs were rarely discovered and those found were discovered only through intensive monitoring" (Preece *et al.*, 2017), since these species are less 'visible' and more cryptic than many mammals and birds. Also, as we have discussed, some diseases can cause less dramatic, ongoing 'background' mortality and/or have more subtle physiological effects while still exerting an impact at a population level. Diseases such as this, for example lead poisoning (see Box 6.2) are more likely to be overlooked in the absence of wildlife disease surveillance programmes (Preece *et al.*, 2017).

As discussed in Chapter 4, infectious disease represents a complex interplay between hosts, their environment and infectious agents. There is potential for some infectious agents and non-infectious disease conditions to act synergistically to cause disease, as discussed in Chapter 4. The saiga antelope case study (Box 6.4) illustrates how environmental and host factors can influence disease occurrence: *Pasteurella multocida* has the potential to cause mass mortalities under particular host and environmental conditions. Such complex interactions between infectious agents, hosts, the environment, and drivers of environmental and population change, are likely to be important considerations with respect to disease emergence in migratory species. However, these relationships can be challenging to unpick and multidisciplinary expertise is required to elucidate them.

It is also important to recognize that disease threats are not static, but can emerge, re-emerge or lessen over time. As per above, there is a paucity of knowledge about infectious agents in many wild-living species, and even when novel infectious agents are detected, their pathogenicity in a particular species is frequently unclear. The expert consultation highlighted the potential for ‘unknown’ or currently unrecognized pathogens to become conservation threats in future: this was a particular concern for the CMS-listed primates. Given the intense and evolving pressures on ecosystems, it seems inevitable that novel pathogens and disease conditions will continue to emerge in migratory species into the future.

Picture 6.10. Mass mortality events in saiga antelope (*Saiga tatarica tatarica*) illustrate the complexity of some wildlife diseases.
Changes in environmental and host factors resulted in silent infection with the bacteria *Pasteurella multocida* becoming overt disease, with significant mortality**.** *Photo credit: P. Romanow.*

6.5.4 Other limitations of this review

The expert consultation was always intended as a high-level, pilot exercise as opposed to a detailed review of disease issues in all migratory species. It was very time-bound, and the task was complex, hence there were inevitably limitations in the study design which would need to be considered carefully should the study be repeated or built on in future.

The size of the species groups varied greatly, ranging from one species (for Class Insecta, orders Galliformes, Anguilliformes and Siluriformes, and families Giraffidae and Canidae) to 103 species (in the 'birds of prey' group combining species from the orders Accipitriformes, Falconiformes, Strigiformes and Cathartiformes) (see Table 11.1). The majority of species were grouped according to their taxonomic order. However, the mammalian orders Chiroptera, Carnivora and Artiodactyla were subdivided based on the diversity of their known infectious agents, while some avian orders were grouped together given their large number. Ultimately, this meant there were fewer avian groups than mammal groups, despite avian species being most numerous on the CMS Appendices. Rays (Infraclass Batoidea) and shark orders (Infraclass Selachii) were also grouped together given a lack of available data on diseases in wild-living populations. In any future iteration of the study, each species should perhaps be considered separately, which would require a longer study timeframe, or, for example, a proportionate number of species from each taxonomic order could be considered in depth.

Experts had to be enlisted at short notice, therefore only a proportion of those we contacted were able to contribute to the consultation and many of those who did had limited time for the task. Despite the international experience of many, most experts were from Europe and North America, with relatively few from South America, Asia, Australasia, Oceania and Africa. Also we only had time to enlist a small number per species group (for 13 groups, just one expert). Experts approached the scoring in different ways: some scores were representative of a species group as a whole, while some were given with a particular population, species or geographic region in mind. Although we were able to secure scores for all species groups, given the diversity of species in some groups, a number of species were ultimately not represented in the consultation. For these reasons, the results represent an illustrative snapshot of disease issues affecting migratory species as opposed to a comprehensive analysis; our approach to summarising the data through mean scores across experts was also somewhat crude. Any future iteration of this study should ensure that (as above), all, or a representative breadth, of species are represented, and that all relevant geographic regions are included, given some species have large geographic ranges and the presence or importance of a particular disease issue will vary by region and in different parts of a species' migratory range.

As discussed in the previous section, in future it would be useful to glean more information on the nature and extent of a disease's impact on the conservation status of species within a group. Scores reflected the propensity of disease to cause declines in one or some populations or species within a species group, however, infectious agents can impact different populations or species very variably. For example, some bat species or populations in North America appear to be more tolerant of the fungal disease 'white nose syndrome' than others. Other negative effects of disease, such loss of genetic diversity, or indirect effects that result from perceived public health risk such as persecution of wildlife were not factored into the scores: the expert contributors noted the problem of retaliatory killing of bats out of fear of public health risk, but scored the conservation impact of this separately to the impact of zoonotic viruses (Table 11.4 in Annex 1). Through the ‘One to Watch’ column we attempted to give experts an opportunity to highlight any infectious agents that, in association with a particular species group, might pose a potential or future conservation threat to another species group. However, the way(s) in which a condition is considered a potential future threat should be better articulated and differentiated in a future study. We did not give experts the opportunity to give a range of scores (noting the varying impacts of disease across populations or species), or to express their level of uncertainty, which would have increased the complexity of analysis but should also be considered in future. Most experts were wildlife veterinarians and health specialists; experts from other disciplines may have given different and possibly lower scores in some instances. The importance of disease *relative* to other types of problem was also not explored. Experts were asked to list ‘other problems’ and most, but not all, experts also attributed scores to these problems, hence they are included in Tables 6.2, 6.3 and 11.4 for context. The UNEP-WCMC report on the State of the World’s Migratory Species (UNEP-WCMC, 2023) provides a robust analysis of these broader threats.

We also asked experts to score the importance of infectious agents and non-infectious causes of disease from the perspective of their ‘Risk of epidemic and/or serious, widespread health impact in people’ and ‘Negative impact on human livelihoods or economics’, as a consequence of their presence in that particular species group. However, in some cases, it appeared that experts gave scores reflecting the general importance of an agent or condition, as opposed to its importance in association with the species group. For this reason, we have not attempted to summarise these results in this chapter, but instead present the scores for each species group in turn in Annex 1 (Table 11.4). Should the study be repeated in future, and be less time-bound, introductory workshops for experts could be held to ensure scores are more standardised. A Delphi-like approach, allowing consultation and potentially improved consensus between experts, might also be appropriate and possibly allow some of the other aforementioned challenges to be addressed.

The approach to identifying drivers of disease problems could also be refined in future. We used broad categories of driver, some of which encompassed many different types of problem (Table 6.1), and we asked experts to mark the drivers of their top-rated disease issues only, using a tick box. A ‘yes’ / ‘no’ response would have provided better-quality data, albeit making the table longer to complete. In a future study, it might be better for the drivers to be considered in a separate step, once a shortlist of priority disease conditions for a species or species group has been established. It would also be useful to gauge how robust the links have been shown to be between a proposed driver and disease condition. As per above, the links between drivers and disease emergence are challenging to elucidate, however an increasing number of studies are providing robust evidence to support the complex causal linkages between, for example, the disturbance or loss of habitat and infectious disease emergence. As discussed above, our methodology meant there was little scope to highlight synergistic effects between infectious agents and disease conditions, meaning the results were likely biased towards ‘primary’ pathogens as opposed to commensal pathogens (such as in saiga). Diseases causing undramatic, ‘background’ mortality or subtle, ‘bottom up’ effects on population demographics might also have been overlooked or underscored.

6.5.5 Recommendations to the Working Group on Migratory Species and Health

This review is intended as an initial starting point for the CMS Working Group on Migratory Species and Health, which is well positioned to explore some of the above topics, issues and knowledge gaps in more depth.

Despite the limitations described above, the disease table we created has the potential to be refined and updated in future and evolve into a living reference platform for the Working Group or possibly a wider audience. We have identified experts familiar with the health of migratory wildlife from across the spectrum of CMS-listed species, who the Working Group may wish to engage further. And we have collated their detailed inputs on disease conditions associated with these migratory species groups, including some key references.

As per above, this study of disease concerns in migratory species could potentially be repeated with a view to encompassing a more comprehensive or representative range of migratory species, and all relevant geographic regions, provided the limitations outlined above are considered and surmounted. The information from experts could also be supplemented with species-specific reviews of the IUCN Red List of Threatened Species (several 'Threat' categories are relevant, *e.g.*, related to infection and pollution) and the WOAH's World Animal Health Information System (WAHIS) voluntary reporting system for wildlife (*e.g.* Machalaba *et al.,* 2020b). This would potentially provide valuable information for risk analyses and conservation action planning for threatened migratory species. A review focusing on a particular disease problem, such as HPAI, and its impacts and drivers, would also be valuable. As above, algal toxins appear to be a potentially emerging (or perhaps overlooked) threat to migratory species and are a topic worthy of further attention from CMS.

The Working Group might also wish to better capture the diseases that, through their association with migratory species, pose a risk to the health of domestic animals and/or humans. Certainly, it would be worthwhile exploring the drivers of key disease issues in more depth, whether for a range of diseases, a key disease condition, or by way of a detailed review of a specific driver and the evidence surrounding its links to disease in migratory wildlife. This review has highlighted some key perceived drivers of diseases of conservation importance which would be worthy of review, including agriculture/aquaculture. Drivers that would likely be perceived as more important in the context of zoonotic or pandemic risk, such as overexploitation, were not well captured in this study and could also be explored in more depth. Again, there is potential synergy with other high-level analyses, such as recent IUCN (Kock and Caceres-Escobar, 2022) and WOAH (Stephen, 2021) reviews focusing on the role of wildlife trade in human disease emergence, both of which highlighted a notable lack of scientific data on this topic.

From a more practical perspective, a review of established wildlife health systems, including approaches to wildlife disease surveillance (*e.g.* Stephen *et al*., 2018; Lawson *et al.*, 2021) would be of value to Contracting Parties. These should include, if possible, an exploration of their economic costs. Similarly, a review of case-studies of preventative One Health and ecosystem approaches, including, if possible, their efficacy, and/or of specific management measures to reduce or manage risks from key disease threats, would be informative and could assist in development of specific recommendations or Modus Operandi.

A number of CMS instruments mentioned in Section 6.5.2 may be vehicles by which to implement the recommendations of this and future reviews.

6.6 Key messages: Health issues in migratory species and their broad underlying causes

→ A pilot consultation of 60 experts identified infectious and non-infectious diseases of conservation concern in migratory species listed in CMS Appendices I and II.

→ Infectious disease was viewed as a 'highly important' conservation issue in the majority of species groups. It was a particular concern in avian and terrestrial species (85% of these species groups).

→ While the role of wild birds as a reservoir and source of HPAI viruses in domestic species and humans is well recognized, importantly, this consultation highlighted that HPAI is a notable issue in a large, taxonomically diverse range of migratory avian species: 'waterfowl and grebes'; 'birds of prey'; 'waders and gulls'; 'cranes and allies'; parrots; seabirds; penguins; and 'pelicans and allies'.

→ Other infectious diseases were considered highly important conservation concerns across multiple species groups. These included anthrax, tuberculosis, rabies and mange in migratory terrestrial mammals; canine distemper in migratory marine mammals; and avian cholera in migratory birds.

→ Experts viewed the most prominent underlying drivers of priority infectious disease issues to be habitat loss, degradation or disturbance; climate change; and agriculture/aquaculture. The latter was considered a particularly important driver of HPAI. Frequently, multiple drivers were considered important.

→ Chemical toxicants, biological toxins, such as those produced by algal blooms, and pollutants were also considered a highly important non-infectious issue, particularly in avian and aquatic migratory species (62% and 55% of species groups respectively).

→ Incidental anthropogenic trauma was considered a highly important issue in a broad range of taxa and especially aquatic species (73% of aquatic species groups), which are commonly affected by injury from interaction with fishing gear and marine debris.

→ The consultation exercise highlighted some common challenges associated with the detection and understanding of disease processes in migratory wild animals, including a notable lack of knowledge about infectious agents and diseases of many migratory species groups.

→ Even in better-studied species such as primates, there remains the potential for currently unknown or unrecognized pathogens to become a future threat.

→ This chapter provides information for the CMS Working Group on Migratory Species and Health to draw from and resources to take forward in future.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary of key messages

This expansive review has shown that migratory species from across the taxonomic spectrum are at risk from infectious disease, as well as, in particular, poisoning and anthropogenic trauma, and how preventative One Health approaches are required to address these issues. Chapter 4 described how drivers of population decline are, concurrently, responsible for disease emergence, and how intensive production systems and activities that create interfaces between wildlife, livestock and/or people generate infectious disease risks. Chapter 5 described how migration can act as a strategy for improving wildlife health but may also result in long-distance movement of pathogens, including those originally acquired from livestock. Further research is needed to improve our understanding of how migratory change may alter the infection and disease status of migratory populations. In Chapter 6, an expert consultation identified key infectious and non-infectious disease issues in migratory species and the importance of human drivers in their emergence (Figure 7.1). It also highlighted that HPAI poses risks to the conservation status of a broad taxonomic range of migratory avian species. However, our knowledge of infectious agents and diseases of many migratory wildlife taxa remains poor, which is compromising our ability to recognize and respond to novel wildlife health problems when they emerge.

7.2 Shortcomings in existing approaches to wildlife health

As highlighted in the previous chapter, understanding of the infectious agents and diseases associated with wildlife populations is frequently poor – a situation exacerbated by poorly resourced wildlife health systems (Chapter 4). There are significant gaps in national and organizational prevention, contingency and response planning for wildlife disease threats. In many countries, wildlife health systems are absent or hindered by logistical and resource difficulties, inadequate surveillance and diagnostic facilities, ineffective and inefficient wildlife veterinary capability, and lack of capacity for sample storage. Compounding this are the regulations in transporting wildlife samples from threatened (CITES-listed) species which can delay sample analysis and thus responses to disease outbreaks (Machalaba *et al.*, 2020a). Even in relatively rich countries, voluntary reporting systems for wildlife disease or mortality incidents are frequently inadequate and ineffective, which can result in unnecessary burdens of disease for wild animals, domestic animals and humans. There is a clear need for improved global systems for wildlife disease reporting to aid international preparedness and responses.

Reactive types of management dominate the funding and expenditure in wildlife health. Often, however, there has been a lack of robust scientific evidence to support the efficacy of interventions undertaken in the name of disease control. Approaches have frequently been adapted directly from the management of disease in domestic animal populations, but some disease control measures directed at wildlife, such as habitat manipulation, population dispersal or mass depopulation (culling), can be damaging to these populations and the wider environment (Gortazar *et al.*, 2015). It is very challenging to control wildlife diseases once they have emerged due to their epidemiological complexity and the ecological context within which they operate. Vaccination is receiving increasing attention as a means of disease management. It has been effective in some specific wildlife disease situations, for example in the control of rabies (Knobel *et al.*, 2008), however, high levels of complexity and cost limit its applicability to wildlife disease scenarios (Artois *et al.*, 2011).

Some forms of reactive management can also lead to negative conservation outcomes. For example, in the early days of H5N1 HPAI emergence in wild birds, there was reactive killing of wild birds and destruction of nests and some wetland habitats. In the recent COVID-19 pandemic, wildlife was quickly blamed as the source of the virus with some reports of bats being targeted as a result of fear-based responses (MacFarlane and Rocha, 2020). Although coronaviruses were not considered a direct conservation threat to bats, the association of bats with these (and other) zoonotic viruses has made them a target for retaliatory killing or culling, which our experts considered may become an increasing threat in future. The experts also noted that, paradoxically, retaliatory killing of bats increases the risk of humans being exposed to such zoonotic pathogens. Even where actions to cull wildlife are taken as part of more formalised disease control responses, they may still lack a sound evidence base, be inappropriate and may also exacerbate disease risks (Carter *et al.*, 2009; Bielby *et al.*, 2016). Reactive management may not only be ineffective and detrimental to wildlife and the environment, but much more economically costly than preventative approaches (Dobson *et al.*, 2020). These responses can fail to understand the root causes of disease and the interconnectedness of health in animals, the ecosystem, and people (IPBES, 2020).

Despite widespread acceptance of the value of One Health approaches, wildlife has historically remained the 'poor relation' in decision-making about health (Chapter 4). Also, a perception of wildlife disease as a matter for agriculture rather than wildlife conservation has also led to a reluctance for environment sections of government to lead on wildlife and ecosystem health issues. There is a need for better integration of health systems across sectors, joined-up working with environment departments, and equitable provision of resources.

7.3 Recommendations

The following recommendations are intended for CMS Contracting Parties and those with responsibilities for health and/or wildlife. They may also inform the contributions of the CMS Working Group on Migratory Species and Health to the OHHLEP and other relevant initiatives.

7.3.1 Tackling key drivers of disease emergence

It is important to recognize the commonalities between the drivers of both migratory species population decline and disease emergence. Disease prevention, including prevention of the emergence or re-emergence of pandemic threats, is a further reason for urgent enhanced actions to address the drivers of wildlife population decline. Such actions include climate change mitigation and adaptation; reducing habitat loss, fragmentation and degradation (including by habitat protection); limiting pollution; reducing overexploitation of wildlife; preventing the spread of invasive non-native species; and addressing high-risk agricultural and aquacultural practices. In addressing these drivers of disease emergence, resilience to disease can be improved across health sectors (IPBES, 2020; UNEP and ILRI, 2020).

There should be a focus on ensuring effective protection of well-connected natural habitat and minimizing fragmentation to reduce 'edge effects' where transmission of infections could occur. Governments and intergovernmental bodies should promote sustainable agricultural practices that are less damaging to natural ecosystems and take measures to reduce human-wildlife conflict (Machalaba *et al.*, 2020a; Kock and Caceres-Escobar, 2022). There will be benefits in reducing dependence on intensive livestock production systems that present particular threats to human and wildlife health; allied to this, there are growing calls for reduced consumption of animal protein from such systems.

Climate change mitigation and adaptation, and habitat protection, are vital in safeguarding our migratory species. Although the relationships are complex and not yet well elucidated, migration disruption and change (in addition to the drivers of such change) has the potential to influence infection dynamics and increase pathogen burdens in migratory wild animals with the potential for negative impacts on the health of domestic animals and people.

Those involved in biodiversity conservation and sustainable livelihoods, including indigenous communities, should be recognized for, and actively supported in, their contribution to health across all sectors. Health promotion and harm reduction approaches also have potential application to One Health settings. They are well-established in the human health sector as means of promoting collaboration between public and private sectors to safeguard human health and health systems (Gallagher *et al*., 2021).

In summary, preventative approaches such as these, and those outlined in the following sections, are key. They are likely to be more cost effective than addressing human, animal and ecosystem health problems once they occur (Dobson *et al.*, 2020), and will have better outcomes in the broader contexts of sustainable agriculture, socio-economic development, environment protection, sustainability and complex patterns of global change (Cromie *et al.*, 2012). Preventative One Health approaches should be a key feature of any future pandemic instrument being negotiated under the auspices of WHO. They will help to fulfil the UN's Sustainable Development Goals of enhancing the health of people, animals and the environment worldwide (United Nations, 2015).

Figure 7.1. Summary of infectious and non-infectious threats to the health of migratory species, and the drivers of these threats.

Picture 7.1. CMS support for One Health.
A wide range of CMS instruments, if implemented fully, would address health concerns – and would represent preventative One Health actions. *Photo credit: Aydin Bahramlouian/CMS.*

7.3.2 Filling knowledge gaps and prioritisation

In line with Article II.3.a) of the Convention on Migratory Species, Contracting Parties should promote, cooperate in and support research relating to migratory species in the context of disease, both at a national level and by supporting the work of the CMS Working Group on Migratory Species and Health and other high-level initiatives. Efforts should be made to address the significant gaps in our knowledge of the epidemiology and drivers of diseases of migratory species, with a focus on priority disease threats and species with a poor conservation status. Although it can be challenging to elucidate the wider drivers of disease, rigorous surveillance and interdisciplinary working will help to elucidate the wider determinants of health problems.

7.3.3 Enabling frameworks for health

Governments should protect and promote the health of migratory populations by strengthening wildlife health systems (Chapter 4 and Figure 7.2) and instituting national wildlife health strategies. The important role that wildlife health systems play in successful One Health approaches should be noted, and these systems should be integrated with human and domestic animal health systems within a One Health framework. Governments should use One Health approaches to promote equitable decision-making about health management, appreciating that promoting the health of wildlife reduces risks to humans and their interests as well as bringing conservation benefits. Ecological and population monitoring should be integrated into wildlife surveillance systems so that the epidemiology and impacts of disease can be better understood. Rather than seeing animal health as the sole responsibility of agriculture ministries, environment sections of government need to engage in wildlife health and recognize their roles in promoting resilience of ecosystems and health outcomes across sectors, including in human pandemic prevention. There should be more substantive funding of wildlife health systems and environmental sectors of government to facilitate One Health approaches. Governments and international bodies should also institute appropriate organizational structures and communication to facilitate multisectoral and transdisciplinary collaboration to prevent and respond to wildlife health threats.

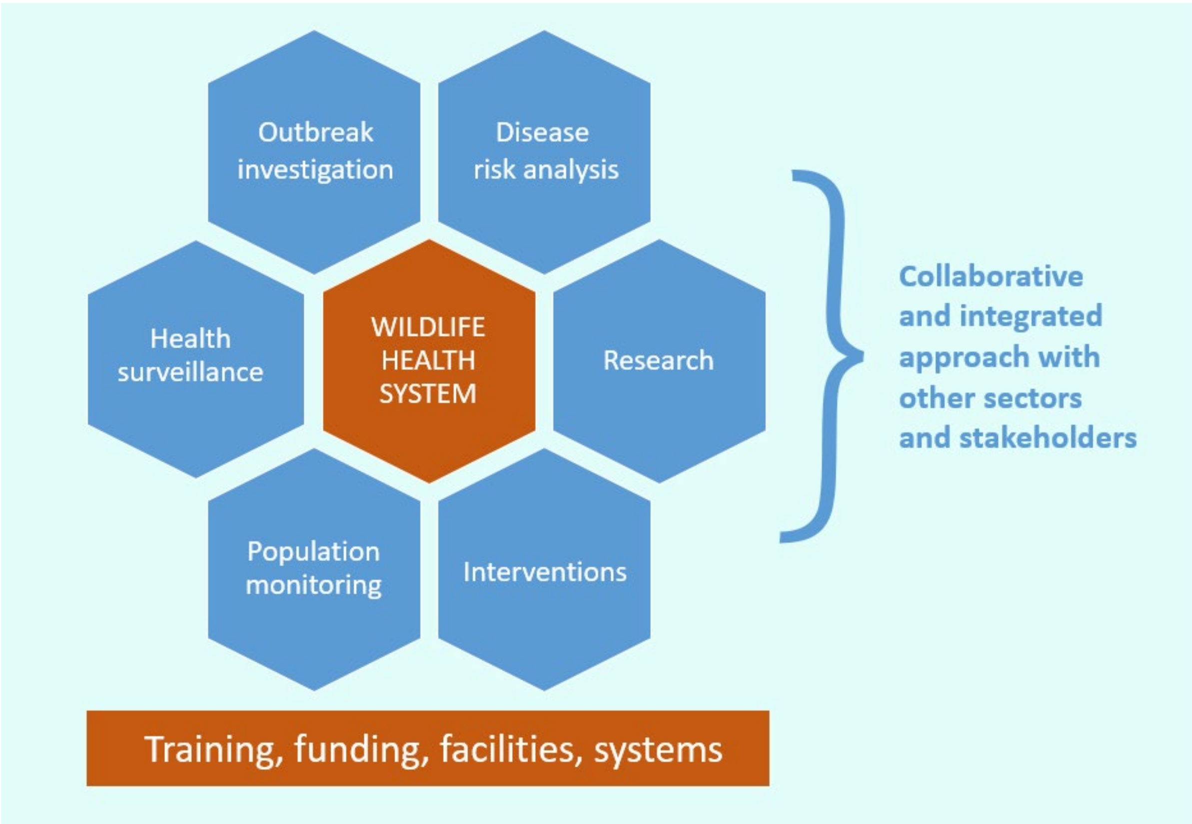

Figure 7.2. Wildlife health systems: creating and enabling robust wildlife health systems is a foundation for One Health approaches.

7.3.4 Improving institutional preparedness, planning and response

As part of wildlife health systems, robust wildlife health surveillance programmes with conservation (in parallel with livestock protection) as a key goal, are required to support risk analyses, contingency planning and early warning systems (Pruvot *et al.*, 2023; Figure 7.3). Thorough investigations of wildlife disease events are needed to help inform epidemiological understanding and assist in future disease planning to minimize impacts across health sectors. Improvements are needed in wildlife diagnostics, including increased capacity in testing facilities (Machalaba *et al.*, 2020a). Additionally, it is important for international instruments to prevent delays in diagnosis and research by facilitating transport of diagnostic and research specimens across national boundaries.

Governments, their agencies, and all those with responsibility for managing wildlife are encouraged to carry out contingency planning during times without outbreaks, ensuring that all relevant stakeholders are involved. This will not only help prevent wildlife health problems occurring but minimize the adverse impacts of disease outbreaks and facilitate prompt and appropriate responses in emergency situations, guarding against inappropriate control measures such as lethal responses.

Where resources are limited, efforts can be targeted to areas where disease risks are considered greatest. Critical control points may be identified where risks of disease transmission, spillover and emergence are high and resources targeted accordingly. This requires capacity to identify these risks, via data collection and analysis (such as surveillance systems), and to collate these findings into useful, practical, and realistic policy/programmes for prevention and response (World Bank and FAO, 2022). Substantial investment into the development of preventative disease control measures such as these is much needed.

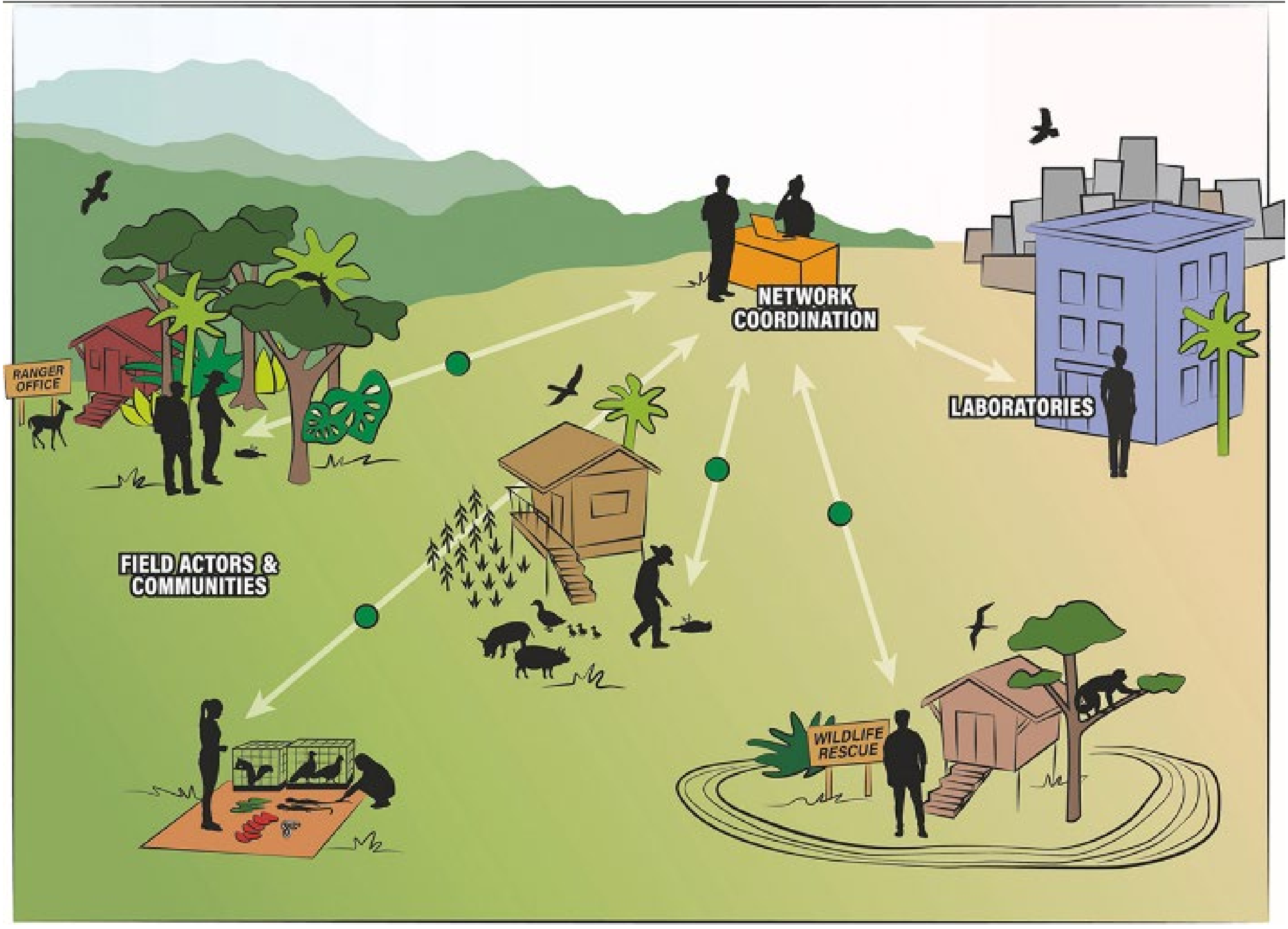

Figure 7.3. Wildlife health surveillance programmes provide an early warning of problems for wildlife as well as livestock and people (including pandemic risk). Initiatives such as the WCS WildHealthNet[20] aim to build capacity for such programmes and detect and share information about wildlife health at large scale and in real time. *Figure credit: Pruvot* et al*. (2023).*

7.3.5 Improving reporting and information sharing

Disease information and reporting systems for wildlife are essential for early warning as well as other aspects of disease control. These systems require further improvement at national and global levels. There should be rapid reporting and inclusion of contextual epidemiological and environmental information, to improve understanding of disease events and to enable early warning and risk analyses for management decision-making. Timely information and data sharing on wildlife health issues between nations is encouraged (Machalaba *et al.*, 2020a,b).

7.3.6 Information sources for wildlife health

Guidance on managing wildlife health and responding to diseases is available (see examples in Appendix 1) and those with responsibilities for wildlife are encouraged to use it

[20] https://oneworldonehealth.wcs.org/Initiatives/WildHealthNet.aspx

and adapt it for national and specific settings. However, as per Section 6.5.5, there is scope for further international guidance on preventative and constructive disease risk management approaches. Species conservation and habitat action plans should also include provisions to prevent, monitor, manage and/or respond to disease issues.

7.3.7 Managing interfaces and infectious diseases

Given the importance of agriculture in infection transmission and disease emergence, governments should make every effort to better manage livestock to reduce these risks, and health and environmental agencies should work more closely with the food production sector. Recommended measures to reduce risks of disease include use of less intensive productions systems and vaccination of livestock and other domestic animals. Since livestock-wildlife interfaces are particularly problematic for infectious agent transmission and emergence, we also recommend improvements in farm biosecurity and better planning of the location of production systems, for example, preventing encroachment of farmed poultry on natural wetlands. Also, indigenous breeds of livestock can be more resilient to disease and pose a lower risk in terms of pathogen transmission.

Efforts should also be made to improve food safety and enhance biosecurity practices in markets and the wildlife trade, and to reduce or otherwise manage practices in live animal market systems that pose a high risk of pathogen transfer and are drivers of pathogen change. Governments and intergovernmental bodies should also work to prevent additional sources of pathogen introduction to wildlife and their environment, for example, by regulating plant and animal trade, preventing incursion of non-native species, reducing feral animal populations and ensuring there are appropriate controls on releases of animals for game, conservation or other purposes.

Measures such as these have the potential to significantly reduce the risk of disease emergence and zoonotic disease transmission (World Bank and FAO, 2022). Robust risk analyses can be valuable in helping 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.*, 2020a; Kock and Caceres-Escobar, 2022).

7.3.8 Tackling non-infectious disease

Measures to minimize non-infectious causes of wildlife mortality should also be prioritised. Action should be taken to reduce and mitigate pollutants and poisons, particularly where regulatory restriction and/or enforcement is required to prevent release or use of pollutants and poisons at source. Measures should also be taken to mitigate human-induced injury of wildlife from infrastructure and other developments and activities, and to remove physical barriers to migration. When planning changes to land use or altering or fragmenting natural habitats, the stressful effects of these activities on wildlife and the negative impacts on their health and resilience to other diseases should be recognized. Non-infectious and, where appropriate, infectious disease risks to wildlife should be considered in environmental impact assessments alongside the standard risks to humans and livestock (Machalaba *et al.*, 2020a; World Bank and FAO, 2022).

8 GLOSSARY AND ABBREVIATIONS

8.1 Glossary

Burden of infection	The proportion of a population (animal or human) which has a particular health condition or disease at a specific point in time.
Dead-end host	A host which is infected by a particular infectious agent but not able to transmit it to other hosts.
Disease	Impairment of normal functions due to the presence of an infectious agent or other, non-infectious impairment.
Ecosystem health	*“A comprehensive and multiscale measure of system vigour, organization and resilience, closely linked to the idea of sustainability, which implies the ability of the system to maintain its structure (organization) and function (vigour) over time in the face of external stress (resilience)”* IPBES (2020).
Emerging infectious disease	An infectious disease that has recently appeared in a population or is rapidly increasing in incidence or geographic range (Morse, 2004).
Endemic	The continual and ‘normal’ presence of an infectious agent or disease within a population and/or area.
Environmental sampling	Exposure of animals to novel infectious agents when they encounter different habitats at stopover sites or new sites, which can increase their infectious agent burden.
Environmental tracking	The act of some migratory animals to follow optimal environmental conditions (seasonal climates etc.), however these conditions may also facilitate infectious agent survival and transmission (especially if the agent can survive in the environment).
Host aggregation	Many different animals, and of different species, often stop and congregate at the same stopover sites. This increases their risk of exposure to novel infectious agents.
Host animal/individual	An individual animal of interest, particularly an infected individual.
Immunosuppression	A compromised immune response in a host, which can increase its vulnerability to infectious disease. Immunosuppression can result from the exertion and stress of migration.
Infection	The presence of an infectious agent in an individual. An individual host can be ‘infected’ with an agent, but this may or may not cause ‘disease’ in the host.
Infectious	An ability for an agent to be transmitted from an infected individual to another individual.

Infectious agent	A parasite (infectious organism) or other agent that is transmissible between hosts, either directly (via *e.g.* contact or aerosol) or indirectly (via *e.g.* food or a vector species) (see Table 4.2; WHO, 2020).
Infectious disease	Disease resulting from an infectious agent.
Migratory allopatry	Behaviour of migrants to isolate themselves from certain vulnerable individuals in the population (*e.g.* juveniles) which reduces both their own exposure to infectious agents and also that of immunologically naïve, vulnerable individuals.
Migratory avoidance	Behaviour of migrants to 'avoid' certain areas on their migratory routes or stopover locations that may be associated with a higher risk of infectious agent exposure.
Migratory culling	Through the act of migration, infected individuals can be removed from the migratory population through mortality.
Migratory dropout and stalling	The behaviour of infected animals to delay migration or take longer to migrate (stalling), or to choose to remain resident and not migrate (dropout). They can die during migration (migratory culling) or can be exposed to more agents during their delay or residency thus increasing infectious agent exposure.
Migratory escape	The behaviour of migratory animals to move away from habitats with high parasite burden in certain seasons which enables them to 'escape' these infectious agents.
Migratory recovery	The act of migrating to habitats with better resources which improves individuals' health and their chance of fighting and removing infection.
Migratory relapse	Reactivation of silent infection in individuals as a consequence of "migration preparation or initiation" (Hall *et al.,* 2022). This can serve to reduce infection burden in a population by removing infected individuals (migratory culling) or increase it through transmission of infection to other individuals.
Non-infectious disease	A health impairment other than that caused by an infectious agent. This includes disease resulting from human-related toxicants or natural toxins; trauma; anthropogenic stress; physical extremes (heat, cold); nutritional deficiency or imbalance; genetic disorders or degenerative (*e.g.* age-related) conditions (see Table 4.2 for more detail).
One Health	"A*n 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).
Pathogen	An infectious agent that has potential to cause disease.
Parasite	An infectious organism, which may be a microparasite, *e.g.* virus, bacterium, protozoan or fungus, or microparasite, such as a helminth (parasitic worm).
Population	A groups of individuals of the same species living in the same, defined area.
Reservoir	A host population, species or environment that serves as a persistent source of an infectious agent to other populations of animals or humans in the same locality.
Silent infection	An infection that causes no, or subclinical, disease.
Spillover	Here, defined as transmission of an infectious agent from a host population or community (which may or may not be a reservoir), where its prevalence may be relatively high, to a new host, usually crossing a species barrier.
Subclinical disease	A low-grade disease that is not outwardly (clinically) detectable.
Target host/population	The host or population of interest.
Transmitter	A host which is infectious to other hosts, *i.e.* serves to transmit an infection on to other individuals, whether of the same or a different species.
Vector	An organism (frequently an arthropod) responsible for transmitting an infectious agent from one host to another.
Virulence	The degree to which an infectious agent is harmful to the host.
Wildlife corridor	An area of habitat which acts as a route for wildlife to move through, connecting fragmented populations that have been separated by human activities or barriers (such as fences).
Wildlife health	Here defined 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).
Wildlife-livestock interface	The physical space in which some form of contact or shared use of resources occurs between wildlife and livestock populations.
Zoonosis	Here, defined as an infection transmissible between humans and animals; 'zoonotic' is the adjective of this[21].

[21] Noting that the WHO (2020) defines a zoonosis more specifically as, "Any disease or infection that is naturally transmissible from vertebrate animals to humans".

8.2 Abbreviations

ACAP	Agreement on the Conservation of Albatrosses and Petrels
ACCOBAMS	Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area
AEWA	Agreement on the Conservation of African-Eurasian Migratory Waterbirds
AMR	Antimicrobial resistance
ASCOBANS	Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas
CDV	Canine distemper virus
CITES	Convention on International Trade in Endangered Species of Wild Fauna and Flora
CMS	Convention on the Conservation of Migratory Species of Wild Animals
EUROBATS	Agreement on the Conservation of Populations of European Bats
FAO	Food and Agriculture Organization of the United Nations
FMD	Foot and mouth disease
HPAI	Highly pathogenic avian influenza
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IUCN	International Union for Conservation of Nature
NSAIDs	Non-steroidal anti-inflammatory drugs
OHHLEP	One Health High-Level Expert Panel
PDV	Phocine distemper virus
PPRV	Peste des petits ruminants virus
SARS-Cov-2	Severe acute respiratory syndrome coronavirus 2
UN	United Nations
UNEP	United Nations Environment Programme
WAHIS	World Animal Health Information System
WHO	World Health Organization
WNV	West Nile virus
WOAH	World Organization for Animal Health (formerly Office International des Epizooties, OIE)

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Yin, S. *et al.* (2022) 'Habitat loss exacerbates pathogen spread: An agent-based model of avian influenza infection in migratory waterfowl', *PLOS Computational Biology*, 18(8), p. e1009577. Available at: https://doi.org/10.1371/journal.pcbi.1009577.

10 APPENDIX 1. ONE HEALTH AND WILDLIFE HEALTH GUIDANCE

10.1 One Health toolkits and guidance

For extensive resources on One Health tools and toolkits:

https://www.onehealthcommission.org/en/resources__services/one_health_tools__toolkits/

WOAH One Health Resources:

https://www.woah.org/en/what-we-do/global-initiatives/one-health/

Quadripartite Joint Plan of Action (2022 – 2026):

https://www.unep.org/resources/publication/one-health-joint-plan-action-2022-2026

One Health theory of change - One Health High Level Expert Panel (OHHLEP):

https://www.who.int/publications/m/item/one-health-theory-of-change

Integrated Approaches to Health: A handbook for the evaluation of One Health:

https://www.wageningenacademic.com/doi/book/10.3920/978-90-8686-875-9

One Health Core Competencies:

https://www.cabidigitallibrary.org/doi/10.1079/cabionehealth.2023.0002

One Health Workforce Academies:

https://onehealthworkforceacademies.org/faculty-resources/

Drawing light from the pandemic: A new strategy for health and sustainable development:

https://www.who.int/europe/publications/m/item/drawing-light-from-the-pandemic--a-new-strategy-for-health-and-sustainable-development

10.2 Wildlife health management and systems – overviews and specific guidance

WOAH Wildlife Health website: https://www.woah.org/en/what-we-do/animal-health-and-welfare/wildlife-health/

WOAH Terrestrial Code Online Access: https://www.woah.org/en/what-we-do/standards/codes-and-manuals/terrestrial-code-online-access/

FAO website: https://www.fao.org/one-health/en, https://www.fao.org/animal-health/areas-of-work/wildlife/en

One Health High Level Expert Panel (OHHLEP) white paper on zoonotic spillover prevention: https://www.who.int/publications/m/item/prevention-of-zoonotic-spillover

Recommendations in: United Nations Environment Programme (UNEP) and International Livestock Research Institute (ILRI) (2020). Preventing the Next Pandemic: Zoonotic diseases and how to break the chain of transmission. Nairobi, Kenya:

https://www.unep.org/resources/report/preventing-future-zoonotic-disease-outbreaks-protecting-environment-animals-and

IUCN Wildlife Health Specialist Group. Publications and Tools and Resources: http://www.iucn-whsg.org/about

Ramsar Wetland Disease Manual. Guidelines for Assessment, Monitoring and Management of Animal Disease in Wetlands. Ramsar Technical Report No. 7. Cromie, R.L., R. Lee, R. J. Delahay, J. L. Newth, M.F. O'Brien, H. A. Fairlamb, J.P. Reeves and D.A. Stroud. (2012). Ramsar Convention Secretariat, Gland, Switzerland: https://www.wwt.org.uk/uploads/documents/Ramsar_Wetland_Disease_Manual.pdf

Wildlife Health Australia – see resource centre: https://wildlifehealthaustralia.com.au/About-Us/Who-We-Are

Proposed attributes of national wildlife health programmes. Stephen, C., Sleeman, J., Nguyen, N., Zimmer, P., Duff, J. P., Gavier-Widén, D. and Uhart, M. (2018). Revue Scientifique et Technique-Office International des Epizooties, 37(3): https://www.wildlifedisease.org/PersonifyEbusiness/Portals/0/Resources/Publications/Reports%20from%20the%20Field/November%202018.pdf

USGS Field Manual of Wildlife Diseases: https://www.usgs.gov/centers/nwhc/science/field-manual-wildlife-diseases

USGS Index of Wildlife Disease Information, Resources: https://www.usgs.gov/centers/nwhc/science/index-wildlife-disease-information-resources

10.3 Contingency planning and risk analysis

FAO Manual No. 25: Good Emergency Management Practice: The Essentials. A guide to preparing for animal health emergencies (2021): https://www.fao.org/documents/card/en/c/cb3833en/ Available in multiple languages.

IUCN/OIE Guidelines for Wildlife Disease Risk Analysis: https://portals.iucn.org/library/sites/library/files/documents/2014-006.pdf

IUCN/OIE Manual of Procedures for Wildlife Disease Risk Analysis: https://portals.iucn.org/library/sites/library/files/documents/2014-007.pdf

10.4 Surveillance and reporting

WOAH WAHIS interactive database of outbreaks: https://wahis.woah.org/#/home

WOAH Training manual on surveillance and international reporting of diseases in wild animals: https://www.woah.org/app/uploads/2021/03/a-training-manual-wildlife-2.pdf

WOAH Guidelines for Wildlife Disease Surveillance: An Overview, 2015: http://www.oie.int/fileadmin/Home/eng/Internationa_Standard_Setting/docs/pdf/WGWildlife/OIE_Guidance_Wildlife_Surveillance_Feb2015.pdf

How to Start Up a National Wildlife Health Surveillance Programme. Lawson, B., Neimanis, A., Lavazza, A., López-Olvera, J.R., Tavernier, P., Billinis, C., Duff, J.P., Mladenov, D.T., Rijks, J.M., Savić, S., *et al.* Animals. (2021); 11(9):2543: https://doi.org/10.3390/ani11092543

Supporting the development of sustainable wildlife health surveillance networks in Southeast Asia. Pruvot, M., Denstedt, E., Latinne, A., Porco, A., Montecino-Latorre, D., Khammavong, K., and Fine, A. E. (2023). WildHealthNet: Science of The Total Environment, 863, 160748: https://www.sciencedirect.com/science/article/pii/S0048969722078512

10.5 Capacity building

Capacity development for wildlife health management in low and middle income countries. Leighton, F.A., Valeix, S., Wall, R., and Polachek, L. (2012). A Workshop Work Book. Wildlife Disease Association, Lawrence, KS USA: https://www.cwhc-rcsf.ca/docs/technical_reports/Capacity_Development_for_Wildlife_Health_Management_in_Low_and_Middle_Income_Countries.pdf

10.6 Responding to highly pathogenic avian influenza

For extensive guidance on dealing with highly pathogenic avian influenza see the 2023 statement from the CMS-FAO Co-convened Scientific Task Force on Avian Influenza and Wild Birds (2023). H5N1 High pathogenicity avian influenza in wild birds - Unprecedented conservation impacts and urgent needs. https://www.cms.int/sites/default/files/publication/avian_influenza_2023_aug.pdf

11 ANNEX 1. DETAILED METHODS AND RESULTS FOR CHAPTER 6: EXPERT CONSULTATION ON HEALTH ISSUES IN MIGRATORY SPECIES

11.1 Detailed methods

11.1.1 Species groups

The 657 species listed on the CMS Appendices I and II were categorised into 37 groups, to keep the exercise as straightforward as possible for the research team and expert contributors in the short project timescale. Species were mostly grouped by taxonomic order, however, higher- or lower-level taxonomic groupings were used in some instances, given the number of orders to consider and the varied amount of published literature and expert knowledge regarding health conditions in different wild-living populations. The species groups are summarised in Table 11.1.

11.1.2 Expert recruitment

The core research team recruited experts from their contact networks with knowledge of health conditions in wild-living populations of the relevant species groups. To engage additional experts we used 'snowball recruitment', and for a minority of groups we contacted authors of relevant scientific papers. Initially, we aimed to recruit at least two experts per species group, but were unable to secure this number for all groups within the timescale. The number of experts ultimately varied across species groups based on experts' availability.

11.1.3 Disease table and scoring

As described in the main text, this exercise was necessarily high-level given the short timeframe for the review, and this was communicated to the experts. The experts were asked to complete a bespoke 'disease table' (spreadsheet), either online or as a Microsoft Excel file according to their preference, for one or more species groups with which they were familiar. We asked them to take note of the CMS-listed species in their particular group(s). Although the importance, and perceived drivers, of different disease conditions might vary greatly between the populations and geographic regions encompassed by each species group, we asked experts to score the causes of disease, and mark drivers, with a mind on those populations, species or geographic regions best known to them. Each expert completed a separate ('clean') table. They were provided with detailed instructions and two worked examples (see Picture 11.1) to help them complete it.

From our own expert knowledge and a brief review of the literature, we identified infectious agents and non-infectious conditions (as categorised in Table 4.2) associated with each species group, as well as 'other problems' perceived to be a threat to their conservation status (as categorised in Table 11.2), and listed these in the disease table. Extra lines were provided in the table for expert contributors to add any additional agents/conditions they considered relevant.

Table 11.1. Grouping of species for the purposes of the expert consultation, and number of expert contributors per species group

CMS category, taxonomic listing and species grouping	Number of species (number of groups)[1]	Number of expert contributors
AVIAN SPECIES		
Class Aves		
Orders Accipitriformes, Falconiformes, Strigiformes and Cathartiformes: 'birds of prey'	103	2
Order Charadriiformes: 'waders (shorebirds) and gulls'	98	1
Orders Anseriformes and Podicipediformes: 'waterfowl and grebes'	57	1
Orders Procellariiformes, Gaviiformes and Suliformes: 'seabirds'	42	1
Orders Passeriformes, Coraciiformes and Columbiformes: 'passerines, coraciiforms and doves'	26	1
Order Gruiformes: 'cranes and allies'	20	1
Order Ciconiiformes: 'storks, herons and allies'	19	2
Order Otidiformes: bustards	6	1
Order Pelecaniformes: 'pelicans and allies'	5	1
Order Phoenicopteriformes: flamingos	4	3
Order Psittaciformes: parrots	2	1
Order Sphenisciformes: penguins	2	3
Order Galliformes: galliforms. Common quail (*Coturnix coturnix coturnix*)	1	1
Subtotal (Avian Species)	*385 (13)*	*17*[2]
AQUATIC SPECIES		
Class Mammalia		
Order Cetacea: cetaceans	81	4
Order Carnivora		
Families Otariidae and Phocidae (suborder Pinnipedia): 'seals and sea lions'	6	2
Family Mustelidae: otters	2	1
Order Sirenia: sirenians	4	4
Subtotal	*93 (4)*	*8*[2]
Class Chondrichthyes		
Orders Myliobatiformes and Rhinopristiformes: rays	21	2
Orders Carcharhiniformes, Lamniformes, Orectolobiformes, Squaliformes and Squatiniformes: sharks	19	2
Subtotal	*40 (2)*	*3*[2]
Class Pisces		
Order Acipenseriformes: 'sturgeons and allies'	19	4
Order Anguilliformes: eels. European eel (*Anguilla anguilla*)	1	2
Order Siluriformes: catfishes. Mekong giant catfish (*Pangasianodon gigas*)	1	1
Subtotal	*21 (3)*	*7*
Class Reptilia		
Order Testudinata: turtles	8	3
Order Crocodylia: crocodiles	2	2
Subtotal	*10 (2)*	*4*[2]
Subtotal (Aquatic Species)	*164 (11)*	*20*[2]

TERRESTRIAL SPECIES		
Class Mammalia		
Order Chiroptera		
Suborder Yangochiroptera[3]: 'microbats'	50	4
Suborder Yinpterochiroptera[3]: 'megabats and allied microbats'	7	3
Order Artiodactyla		
Family Bovidae: bovids	21	2
Family Cervidae: deer	3	1
Family Camelidae: camelids	2	3
Family Giraffidae: giraffes. Giraffe (*Giraffa camelopardalis*)	1	2
Order Carnivora		
Family Felidae: felids	5	3
Family Ursidae: bears	2	2
Family Canidae: canids. African wild dog (*Lycaon pictus*)	1	3
Order Primates: primates	7	3
Order Perissodactyla: equids	5	3
Order Proboscidea: elephants	3	2
Subtotal	*107 (12)*	*22*[2]
Class Insecta		
Order Lepidoptera: Monarch butterfly (*Danaus plexippus*)	*1 (1)*	*1*
Subtotal (Terrestrial Species)	*108 (13)*	*23*[2]
Total (all species listed on CMS Appendices I and II)	***657 (37)***	***60***[2]

[1] Species are listed on the CMS website (see https://www.cms.int/en/species). Species were listed as per the CMS website listing in April 2023.

[2] Some experts contributed scores for multiple groups.

[3] Although CMS does not currently use the terms Yangochiroptera and Yinpterochiroptera, our experts recommended that bats were considered separately under these two suborders for the purposes of this review.

Table 11.2. Categorisation of 'other problems', that is perceived threats to migratory species other than those categorised as causes of disease.
(See Table 4.2 for categorisation of causes of disease.)

Main category[1]	Definition
Persecution	Targeted legal or illegal taking[2].
Environmental conditions	Diminished or suboptimal habitat, including altered ecosystem function. Such problems could be expected to impact wildlife health through *e.g.*, undernourishment or reduced 'wellbeing'.
Climatic conditions	Adverse weather or climatic extremes, including drought, extreme heat, fire, storms, flooding, extreme winter weather or unseasonable/variable weather. Such problems could be expected to impact health through undernourishment, reduced 'wellbeing' or possible *e.g.*, burn injury.
Ecological problems	Including predation, inter/intraspecies aggression or competition, or animal disturbance.
Genetic problems	Genetic conditions with no suspected health impact, such as hybridisation.

[1] Categories adapted from Beckmann *et al.* (2022).
[2] Particularly relating to physical or traumatic taking as opposed to poisoning, which was categorised as a non-infectious cause of disease (as per Table 4.2).

There were two main sections in the table for experts to fill in. These were:

- **Scoring: proven/suspected importance**

The intention for this section was for experts to score the listed causes of infectious and non-infectious disease, to identify the most important ones. Experts were asked to score each agent or condition from 5-0, where 5 = very high importance and 0 = no importance, as per Table 11.3.

Table 11.3. Scoring system for the expert consultation exercise

Score	Description
5	Very high importance
4	High importance
3	Medium importance
2	Low importance
1	Very low importance
0	No importance

The experts were asked to attribute scores to each listed cause of disease, for each of the following impacts in turn:

1. The negative impact on biodiversity conservation, at a population, species and/or wider ecosystem level[22];
2. The potential for an epidemic and/or serious, widespread health impact on people, specifically as a consequence of the condition in that particular species group;
3. And the negative impact on human livelihoods and economics, owing to a negative impact on the health of domestic animals[23], as a consequence of the condition in that species group.

The experts were also asked to identify potential future threats in the same manner, namely agents or conditions that could potentially have an adverse impact on any of the above three criteria in future; or that could potentially be transmitted from that species group to other wild-living species and then become an important issue.

- **Drivers**

The intention of this section was to identify the suspected or confirmed drivers of disease issues that experts considered most important. Drivers were considered as broad categories as per Table 6.1, and experts were asked to mark the drivers of at least their 'top five' causes of disease.[24]

Additional columns were included in the spreadsheet, giving experts an opportunity to comment on select disease concerns and/or provide key references, as appropriate.

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[22] This was not defined in any more detail. Responses therefore reflected negative impacts on survival, population size or species persistence in one or more populations or species within a species group as a whole. Losses of genetic diversity, or risks to conservation status of these or other species through indirect effects such as persecution, did not appear to be captured directly in these scores (for further discussion see Section 6.5.4).

[23] Negative impacts on human livelihoods and economics could also result from the impacts of disease on wild-living populations (whether of the species of interest, or other species), for example impacts on fish stocks. This appeared to be implicit in the expert scores for relevant groups, but was not explicit in our instructions.

[24] Experts were asked to tick the categories of driver applicable to a minimum of their 'top five' causes of disease. However, these 'driver' columns were completed to a varying extent, with some experts marking the drivers for fewer, and some for many more, rows than this. With this 'tick box' system we were unable to distinguish rows where drivers had deliberately not been ticked, *i.e.* causes of disease for which drivers were not considered relevant, from rows where the drivers columns had been overlooked or the cause of disease was not considered important enough to merit the drivers being filled in.

Picture 11.1. A worked example provided to experts to help inform their scoring of a. different causes of disease, and b. marking of drivers, in the disease table.
In this case, for the Order Charadriiformes.

a. Scoring the importance of causes of disease.

Taxonomic details as per CMS listing		Proximate threat to health		Scoring - proven/suspected importance (5-0, 5 = very high, 0 = none)			
Class, Order	No. of species represented (see Species List for details)	Potential threat*	Category	Negative impact on biodiversity conservation*	Risk of epidemic and/or serious, widespread health impact in people*	Negative impact on human livelihoods or economics*	Ones to watch: possible future threats (5-0, 5 = very high)*
EXAMPLE 2: Order Charadriiformes							
Class Aves 1. Order Charadriiformes	**98**	**Infectious**	**Category***				
		Avian influenza viruses - particularly Highly Pathogenic strains	Virus	5	4	5	5
		Avian paramyxoviruses (APMVs) including Newcastle Disease virus (APMV-1)	Virus	1	1	2	1
		Infectious bursal disease virus	Virus	0	0	0	0
		Avian poxvirus	Virus	2	0	0	1
		Salmonella sp	Bacterium	2	2	2	1
		Erysipelothrix spp	Bacterium	0	0	0	0
		Camplyobacter spp	Bacterium	1	1	2	1
		Chlamydia sp	Bacterium	1	1	1	1
		Yersinia sp	Bacterium	0	0	0	0
		Mycoplasma sp	Bacterium	0	0	0	1
		Mycobacterium avium complex	Bacterium	2	1	1	1
		Klebsiella pneumoniae	Bacterium	0	0	0	0
		Aspergillosus (A.fumigatus)	Fungus or Yeast	0	0	0	0
		Eimeria spp (~~renal~~ coccidiosis)	Protozoa	2	0	0	1
		Cestodes, trematodes & acanthocephalans - various spp	Helminth	0	0	0	0
		Nematodes - various including Capillaria spp	Helminth	0	0	0	0
		Trematodes (Cyclocoelum spp)	Helminth	0	0	0	0
		Ectoparasites including lice, mites & others	Arthropod ectoparasite	0	0	0	0
		Coronavirus	Virus	2	2	0	2
		Circovirus, reovirus & various other viruses	Virus	2	2	0	3

b. Marking the drivers of top-rated causes of disease. (This was part of the same table shown in Picture 11.1. a., above.)

Taxonomic details as per CMS listing		Proximate threat to health	Drivers: please mark for at least the top 5 threats identified in previous column*								
Class, Order	No. of species represented (see Species List for details)	Potential threat*	Top 5 Threats*	Agriculture or aquaculture	Other habitat loss, degradation or disturbance	Harvesting or persecution (overexploitation)	Invasive species	Pollution	Climate change or severe weather	Other*	Undetermined / unknown
EXAMPLE 2: Order Charadriiformes											
Class Aves 1. Order Charadriiformes	**98**	**Infectious**									
		Avian influenza viruses - particularly Highly Pathogenic strains	1st (highest) of Top 5	☑	☑	☐	☐	☐	☐	☐	☐
		Avian paramyxoviruses (APMVs) including Newcastle Disease virus (APMV-1)		☐	☐	☐	☐	☐	☐	☐	☐
		Infectious bursal disease virus		☐	☐	☐	☐	☐	☐	☐	☐
		Avian poxvirus		☐	☐	☐	☐	☐	☐	☐	☐
		Salmonella sp		☐	☐	☐	☐	☐	☐	☐	☐
		Erysipelothrix spp		☐	☐	☐	☐	☐	☐	☐	☐
		Camplyobacter spp		☐	☐	☐	☐	☐	☐	☐	☐
		Chlamydia sp		☐	☐	☐	☐	☐	☐	☐	☐
		Yersinia sp		☐	☐	☐	☐	☐	☐	☐	☐
		Mycoplasma sp		☐	☐	☐	☐	☐	☐	☐	☐
		Mycobacterium avium complex		☐	☐	☐	☐	☐	☐	☐	☐
		Klebsiella pneumoniae		☐	☐	☐	☐	☐	☐	☐	☐
		Aspergillosus (A.fumigatus)		☐	☐	☐	☐	☐	☐	☐	☐
		Eimeria spp (~~renal~~ coccidiosis)		☐	☐	☐	☐	☐	☐	☐	☐
		Cestodes, trematodes & acanthocephalans - various spp		☐	☐	☐	☐	☐	☐	☐	☐
		Nematodes - various including Capillaria spp		☐	☐	☐	☐	☐	☐	☐	☐
		Trematodes (Cyclocoelum spp)		☐	☐	☐	☐	☐	☐	☐	☐
		Ectoparasites including lice, mites & others		☐	☐	☐	☐	☐	☐	☐	☐
		Coronavirus		☐	☐	☐	☐	☐	☐	☐	☐
		Circovirus, reovirus & various other viruses		☐	☐	☐	☐	☐	☐	☐	☐
		[illegible]									

11.1.4 Data collation and analysis

Experts' responses were then collated and analysed. For species groups with more than one expert contributor, a median score was calculated for each identified infectious or non-infectious cause of disease. Median scores of ≥ 3.5 out of 5 were considered indicative of a 'highly important' cause of disease.

To identify the most important, perceived drivers of select causes of disease for each group, the number of rows in the table representing a particular agent or condition for which a particular driver was ticked, as a proportion of all rows for which drivers were marked for that agent or condition, was calculated.

11.2 Detailed results

Table 11.4 gives the detailed results from the expert consultation exercise, for each species group in turn.

Table 11.4. Expert scores for the perceived importance of different causes of disease with respect to biodiversity conservation, human health and human livelihoods, listed by species group.

Scores are from 5 to 0, where 5 = 'very high importance' and 0 = 'no importance'. For groups with more than one expert contributor, the scores are a median value across experts with the exception of causes of disease marked with an asterisk, which were scored by one expert only. Only causes of disease with median scores of ≥ 2.5 out of 5, defined as being of 'medium' or greater importance, are included here[25]. Where relevant, 'other problems' are also listed in light grey text for context, but are not exhaustive.

a. Avian species (Class Aves)

i. Orders Accipitriformes, Falconiformes, Strigiformes and Cathartiformes ('birds of prey'): 103 species; two expert contributors.

Causes of disease considered of medium or greater importance (scoring ≥ 2.5 in any category)			Median score				Key references provided by experts
Infectious agent, non-infectious condition or other problem	Subcategory (as per Tables 4.2 and 11.2)	Agent/ detailed condition (an asterisk indicates a score from one expert only)	Negative impact on biodiversity conservation	Potential for an epidemic and/or serious, widespread impact in people	Negative impact on domestic animal health and human livelihoods	Potential future threat ('one to watch')	
Infectious	Virus	Avian influenza viruses, particularly Highly Pathogenic strains	4.5	4	4.5	4.5	
Non-infectious	Toxin, pollution or eutrophication	Anticoagulant rodenticides	4	0	1.5	3	
Non-infectious	Toxin, pollution or eutrophication	Organophosphates, carbamates	4	1.5	1.5	3.5	
Infectious	Virus	West Nile virus (e.g. red-tailed hawks, Coopers hawks, goshawks, golden eagles, owls)	3.5	2.5	2.5	3	
Non-infectious	Toxin, pollution or eutrophication	Chemical poisoning*	3	3	3	4	
Non-infectious	Toxin, pollution or eutrophication	Chromium (essential element at potentially toxic concentrations to raptors)*	3	2	3	0	
Non-infectious	Toxin, pollution or eutrophication	Cobalt (essential element at potentially toxic concentrations to raptors)*	3	2	3		
Non-infectious	Toxin, pollution or eutrophication	Copper (essential element at potentially toxic concentrations to raptors)*	3	2	3	2	
Non-infectious	Toxin, pollution or eutrophication	Lead	3	1.5	1.5	2.5	
Non-infectious	Toxin, pollution or eutrophication	Mercury	3	1.5	1.5	2.5	
Non-infectious	Toxin, pollution or eutrophication	Selenium (essential element at potentially toxic concentrations to raptors)*	3	2	3		
Non-infectious	Incidental anthropogenic trauma	Accidental anthropogenic trauma e.g. collision with windmills, vehicles on roads, windows. Associated traumatic injuries e.g. eyes, spine	2.5	0	1.5	5	doi.org/10.3356/JRR-16-100.1
Other problems	Environmental conditions	Habitat loss/degradation*	5	0	1.5	5	
Other problems	Persecution	Persecution*	3	0	0.5	4	

[25] Experts were asked to score the importance of each infectious agent or non-infectious condition to human and domestic animal health as a result of its presence in the particular species group under consideration. However, scores for some groups appeared to reflect the general risk posed by an agent or condition, as opposed to the specific risk from that species group.

ii. Order Charadriiformes (‘waders (shorebirds) and gulls'): 98 species; one expert contributor.

Causes of disease considered of medium or greater importance (scoring ≥ 2.5 in any category)			Median score				Key references provided by experts
Infectious agent, non-infectious condition or other problem	Subcategory (as per Tables 4.2 and 11.2)	Agent/ detailed condition (an asterisk indicates a score from one expert only)	Negative impact on biodiversity conservation	Potential for an epidemic and/or serious, widespread impact in people	Negative impact on domestic animal health and human livelihoods	Potential future threat ('one to watch')	
Infectious	Virus	Avian influenza viruses - particularly Highly Pathogenic strains	5	4	5	5	Sutherland et al (2012). A horizon scanning assessment of current and potential future threats to migratory shorebirds. Ibis 154:663-679. https://doi.org/10.1111/j.1474-919X.2012.01261.x.
Non-infectious	Incidental anthropogenic trauma	Bycatch (incidental offtake)	5	0	0	4	
Non-infectious	Anthropogenic stress or disturbance	Nest disturbance	4	0	0	4	
Non-infectious	Toxin, pollution or eutrophication	Algal blooms - reducing quality of feeding areas and potential for direct toxicity	3	0	0	4	
Non-infectious	Toxin, pollution or eutrophication	Avian botulism	3	1	0	4	
Non-infectious	Toxin, pollution or eutrophication	Chemical pollutants: pesticides, heavy metals, industrial chemicals, petroleum products (oil spills)	3	0	0	3	
Non-infectious	Toxin, pollution or eutrophication	Eutrophication and changes in water quality	3	0	0	4	As above
Infectious	Virus	Coronavirus	2	2	0	3	
Non-infectious	Toxin, pollution or eutrophication	Microplastic or nanosilver pollution	2	0	0	3	As above
Non-infectious	Incidental anthropogenic trauma	Collisions e.g. road traffic, wind turbines, or entanglements	2	0	0	3	
Infectious	Protozoa	Avian malaria (*Haemoproteus* sp, *Plasmodium* sp)	1	0	0	3	
Other problems	Environmental conditions	Habitat degradation due to agricultural practices, wetland drainage and other developments - at wintering, breeding & stopover sites	5	0	0	5	
Other problems	Environmental conditions	Habitat loss due to agricultural intensification and development - at wintering, breeding & stopover sites	5	0	0	5	As above
Other problems	Ecological problems	Predation (particularly of nests & pre-fledged young)	5	0	0	5	
Other problems	Environmental conditions	Flooding of breeding sites	4	0	0	5	
Other problems	Climatic conditions	Other adverse weather associated with climate change	2	0	0	3	
Other problems	Environmental conditions	Afforestation of upland breeding habitats	1	0	0	3	
Other problems	Climatic conditions	Changing marine conditions associated with climate change, including ocean acidification and associated changes in the food web	1	0	0	4	

iii. Orders Anseriformes and Podicipediformes (‘waterfowl and grebes’): 57 species; one expert contributor.

Causes of disease considered of medium or greater importance (scoring ≥ 2.5 in any category)			Median score				Key references provided by experts
Infectious agent, non-infectious condition or other problem	Subcategory (as per Tables 4.2 and 11.2)	Agent/ detailed condition (an asterisk indicates a score from one expert only)	Negative impact on biodiversity conservation	Potential for an epidemic and/or serious, widespread impact in people	Negative impact on domestic animal health and human livelihoods	Potential future threat ('one to watch')	
Non-infectious	Toxin, pollution or eutrophication	Avian botulism (*Clostridium botulinum* toxin)	5	1	1	3	
Non-infectious	Toxin, pollution or eutrophication	Lead exposure (spent shotgun pellets, fishing tackle)	5	5	1	1	
Infectious	Virus	Avian influenza viruses, particularly Highly Pathogenic strains	5	5	5	5	
Infectious	Bacterium	Avian Cholera (*P.multocida)*	4	1	0	1	
Non-infectious	Toxin, pollution or eutrophication	Petroleum (oil spills)	4	1	0	1	
Non-infectious	Incidental anthropogenic trauma	Entanglement	4	0	0		https://www.wwt.org.uk/uploads/documents/1341561509_RWDM4DiseaseFactsheetsAvianbotulism.pdf
Infectious	Bacterium	Mycobacterium avium complex (avian tuberculosis)	3	1	2		
Non-infectious	Foreign body ingestion	Foreign body ingestion, including plastic	3	0	0		
Non-infectious	Toxin, pollution or eutrophication	Algal blooms including red tides (*Gymnodinium breve*); blue-green cyanobacteria	3	1	0		https://echa.europa.eu/documents/10162/16a7626e-8073-7f72-9303-948b60494831
Non-infectious	Undetermined	Emaciation and cachexia - unknown cause (e.g. stranded grebes)	3	0	0		
Infectious	Bacterium	Salmonellosis (*S. typhimurium, S. paratyphi*)	1	2	4		
Infectious	Bacterium	*Camplobacter* spp.	0	2	3		
Infectious	Bacterium	Chlamydiosis (*Chlamydia psittaci)*	1	2	3		
Infectious	Virus	Avian paramyxoviruses: APMV-1 (Newcastle disease)	1	1	3		https://www.wwt.org.uk/uploads/documents/1341561570_RWDM4DiseaseFactsheetsDuckvirusenteritis.pdf
Infectious	Virus	Bornaviruses: avian bornavirus	0	3	1		https://www.wwt.org.uk/uploads/documents/1341561742_RWDM4DiseaseFactsheetsWestNilevirusdisease.pdf
Infectious	Virus	Duck viral enteritis virus / anatid herpesvirus-1 (duck viral enteritis, duck plague)	1	0	3	1	
Infectious	Virus	West Nile virus	1	4	1	3	

iv. Orders Procellariiformes, Gaviiformes and Suliformes ('seabirds'): 42 species; one expert contributor.

Causes of disease considered of medium or greater importance (scoring ≥ 2.5 in any category)			Median score				Key references provided by experts
Infectious agent, non-infectious condition or other problem	Subcategory (as per Tables 4.2 and 11.2)	Agent/ detailed condition (an asterisk indicates a score from one expert only)	Negative impact on biodiversity conservation	Potential for an epidemic and/or serious, widespread impact in people	Negative impact on domestic animal health and human livelihoods	Potential future threat ('one to watch')	
Infectious	Virus	Avian influenza particularly Highly Pathogenic strains (Suliformes, Gaviiformes, Procellariiformes)	5	3	2	5	Dias et al. (2019) Threats to seabirds: a global assessment. Biological Conservation 237, 525-537. https://doi.org/10.1016/j.biocon.2019.06.033 Vanstreels et al. (2023) Health and diseases. In Young and VanderWerf (eds.), Conservation of Marine Birds. pp 131-176
Non-infectious	Incidental anthropogenic trauma	Drowning from line fishing/fishing operations (albatross)	5	0	0		
Infectious	Bacterium	Avian cholera (*P. multocida*) (Procellariiformes - petrels)	4	2	2		
Non-infectious	Foreign body ingestion	Plastic ingestion/plasticosis, foreign body, starvation	4	0	0	5	
Non-infectious	Toxin, pollution or eutrophication	Mercury toxicity (methylmercury)	4	0	0	5	
Non-infectious	Toxin, pollution or eutrophication	Oil spill events	4	0	0	4	
Infectious	Virus	Adenoviral infection (Procellariiformes)	3	1	1		
Infectious	Virus	Gaviid herpesvirus -1 (Gaviiformes)	3	0	0		
Infectious	Virus	Puffinosis (shearwaters)	3	1	0		
Non-infectious	Incidental anthropogenic trauma	Entanglement	3	0	0	3	
Non-infectious	Toxin, pollution or eutrophication	Avian botulism type E	3	0	0		
Non-infectious	Toxin, pollution or eutrophication	Biotoxins	3	0	0	3	
Non-infectious	Toxin, pollution or eutrophication	Lead poisoning	3	0	0		
Non-infectious	Undetermined	Emaciation and cachexia - unknown cause	3	0	0	3	
Other problems	Ecological problems	Predation of chicks and adults by invasive species (rats and cats)	5	0	0		
Other problems	Environmental conditions	Changing marine conditions associated with climate change, including ocean acidification and associated changes in the food web	4	0	0	4	
Other problems	Genetic problems	Hybridism (Pterodroma)	3	0	0		

v. Orders Passeriformes, Coraciiformes and Columbiformes ('passerines, coraciiforms and doves'): 26 species; one expert contributor.

Causes of disease considered of medium or greater importance (scoring ≥ 2.5 in any category)			Median score				Key references provided by experts
Infectious agent, non-infectious condition or other problem	Subcategory (as per Tables 4.2 and 11.2)	Agent/ detailed condition (an asterisk indicates a score from one expert only)	Negative impact on biodiversity conservation	Potential for an epidemic and/or serious, widespread impact in people	Negative impact on domestic animal health and human livelihoods	Potential future threat ('one to watch')	
Non-infectious	Toxin, pollution or eutrophication	Strychnine, 4-aminopyridine (Avitrol), 3-chloro-p-touline (Starlicide), pesticides e.g. organophosphates	4	1	1		
Infectious	Protozoa	*Trichomonas* spp. (*T. gallinae*) (Passeriformes, Columbiformes)	4	0	1		
Infectious	Bacterium	Avian chlamydiosis (*Chlamydia psittaci*) (Passerines, Columbiformes)	3	3	3		
Infectious	Bacterium	Salmonellosis: *S.typhimurium* (Passerines, Columbiformes)	3	3	3		
Infectious	Virus	Avian influenza: LPAI; HPAI (passerines)	3	2	3	5	
Infectious	Virus	Avian pox (Avipoxvirus) (passerines)	3	0	1		
Infectious	Virus	Newcastle disease - Avian paramyxovirus type 1 (APMV-1) (passerines, Columbiformes); APMV-2 and 3 affect passerines	3	0	2	1	
Infectious	Virus	Paramyxovirus (paramyxovirus type 1) - Columbiformes	3	0	2		
Infectious	Virus	Pigeon circovirus inf (Columbiformes)	3	0	2	3	
Infectious	Virus	West Nile Virus (WNV) (flavivirus) (passerines)	3	4	1	4	
Non-infectious	Incidental anthropogenic trauma	Trauma (collisions)	3	0	0		
Infectious	Fungus or Yeast	*Cryptococcus* (Columbiformes)	1	3	0		
Infectious	Fungus or Yeast	*Histoplasma* (Columbiformes)	1	3	0		

vi. Order Gruiformes (‘cranes and allies’): 20 species; one expert contributor.

Causes of disease considered of medium or greater importance (scoring ≥ 2.5 in any category)			Median score				Key references provided by experts
Infectious agent, non-infectious condition or other problem	Subcategory (as per Tables 4.2 and 11.2)	Agent/ detailed condition (an asterisk indicates a score from one expert only)	Negative impact on biodiversity conservation	Potential for an epidemic and/or serious, widespread impact in people	Negative impact on domestic animal health and human livelihoods	Potential future threat ('one to watch')	
Infectious	Virus	Avian influenza particularly Highly Pathogenic strains	5	3	5	5	
Infectious	Protozoa	*Eimeria* sp (*E. reichenowi*)	3	0	0	3	
Non-infectious	Incidental anthropogenic trauma	Power line, fencing or vehicle collision	3	0	0	4	
Non-infectious	Toxin, pollution or eutrophication	Organophosphates, anti-cholinersterade pesticide poisoning	3	2	2	5	
Non-infectious	Anthropogenic stress or disturbance	Disturbance, esp. at nesting areas, staging/stopover or winter sites	2	0	0	3	
Non-infectious	Foreign body ingestion	Foreign body, plasticosis	2	0	0	3	
Non-infectious	Toxin, pollution or eutrophication	Botulism (*Clostridium botulinum*)	2	0	0	3	
Non-infectious	Toxin, pollution or eutrophication	Lead poisoning	2	0	0	3	
Non-infectious	Toxin, pollution or eutrophication	Oil spills	1	0	3	2	
Other problems	Persecution	Illegal harvest (either domestic/international trade or hunting)	3	0	0	5	
Other problems	Environmental conditions	Water resource development, changing hydrology, etc.	2	0	0	4	
Other problems	Climatic conditions	Prolonged drought effects (nesting, staging, stopover or wintering sites)	2	0	0	4	
Other problems	Environmental conditions	Change of agricultural systems	1	1	0	3	

vii. Order Ciconiiformes ('storks, herons and allies'): 19 species; two expert contributors.

Causes of disease considered of medium or greater importance (scoring ≥ 2.5 in any category)			Median score				Key references provided by experts
Infectious agent, non-infectious condition or other problem	Subcategory (as per Tables 4.2 and 11.2)	Agent/ detailed condition (an asterisk indicates a score from one expert only)	Negative impact on biodiversity conservation	Potential for an epidemic and/or serious, widespread impact in people	Negative impact on domestic animal health and human livelihoods	Potential future threat ('one to watch')	
Non-infectious	Foreign body ingestion	Foreign body, plastic*	5	n/a	n/a	5	
Non-infectious	Toxin, pollution or eutrophication	Environmental pollutants: lead*	5	n/a	n/a	5	
Non-infectious	Toxin, pollution or eutrophication	Environmental pollutants: mercury, other heavy metals, arsenic, organophosphates and carbate pesticides*	5	n/a	n/a	5	
Infectious	Virus	Avian influenza*	3	2	2	2	
Infectious	Arthropod ectoparasite	Lice*	2	0	3	2	
Non-infectious	Incidental anthropogenic trauma	Trauma, entanglement*	2	n/a	n/a	3	

viii. Order Otidiformes (bustards): six species; one expert contributor.

Causes of disease considered of medium or greater importance (scoring ≥ 2.5 in any category)			Median score				Key references provided by experts
Infectious agent, non-infectious condition or other problem	Subcategory (as per Tables 4.2 and 11.2)	Agent/ detailed condition (an asterisk indicates a score from one expert only)	Negative impact on biodiversity conservation	Potential for an epidemic and/or serious, widespread impact in people	Negative impact on domestic animal health and human livelihoods	Potential future threat ('one to watch')	
Non-infectious	Nutritional disease or deficiency	Starvation caused by decline of prey species (invertebrates)	4	0	0	4	
Non-infectious	Incidental anthropogenic trauma	Trauma - collisions	3	0	0	4	
Non-infectious	Toxin, pollution or eutrophication	Pesticides, herbicides and chemicals	3	0	0	4	
Other problems	Persecution	Persecution / shooting on migration /trapping illegal trade	3	0	0	4	
Infectious	Virus	Avian influenza	3	2	0	3	
Infectious	Virus	Avipox	2	0	0	3	
Other problems	Ecological problems	Reintroduced captive-bred birds, may cause e.g. disease introduction into wild populations	3	1	1	4	
Other problems	Genetic problems	Genetic pollution of wild populations from reintroduced captive bred birds	3	0	0	4	
Other problems	Environmental conditions	Habitat loss/degradation and loss of migratory flyways due to development	n/a	n/a	n/a	4	

ix. Order Pelecaniformes (‘pelicans and allies’): five species; one expert contributor.

Causes of disease considered of medium or greater importance (scoring ≥ 2.5 in any category)			Median score				Key references provided by experts
Infectious agent, non-infectious condition or other problem	Subcategory (as per Tables 4.2 and 11.2)	Agent/ detailed condition (an asterisk indicates a score from one expert only)	Negative impact on biodiversity conservation	Potential for an epidemic and/or serious, widespread impact in people	Negative impact on domestic animal health and human livelihoods	Potential future threat ('one to watch')	
Infectious	Virus	Avian influenza including Highly Pathogenic strains	5	3	0	4	
Non-infectious	Toxin, pollution or eutrophication	Marine toxins: domoic acid, brevotoxins	5	0	0	3	
Infectious	Virus	Newcastle disease	3	0	0	2	
Non-infectious	Toxin, pollution or eutrophication	Botulism (*Clostridium botulinum*)	3	0	0	3	
Non-infectious	Foreign body ingestion	Foreign body, plastic ingestion	2	0	0	3	
Non-infectious	Incidental anthropogenic trauma	Entanglement from fishing operations, plastic	2	0	0	3	
Non-infectious	Toxin, pollution or eutrophication	Oil spill events	2	0	0	3	

x. Order Phoenicopteriformes (flamingos): four species; three expert contributors.

Causes of disease considered of medium or greater importance (scoring ≥ 2.5 in any category)			Median score				Key references provided by experts
Infectious agent, non-infectious condition or other problem	Subcategory (as per Tables 4.2 and 11.2)	Agent/ detailed condition (an asterisk indicates a score from one expert only)	Negative impact on biodiversity conservation	Potential for an epidemic and/or serious, widespread impact in people	Negative impact on domestic animal health and human livelihoods	Potential future threat ('one to watch')	
Non-infectious	Toxin, pollution or eutrophication	Poisoning and toxicosis from water chemistry changes	4	1.5	2.5	4.5	https://link.springer.com/article/10.1007/s10661-021-09340-3
Infectious	Bacterium	*Pasturella multocida* (Avian cholera)	5	n/a	n/a		
Infectious	Bacterium	*Mycobacterium avium* serovar I	5	n/a	n/a		
Non-infectious	Incidental anthropogenic trauma	Collision trauma: fractures; luxations; soft tissue injuries	3	0	0.5	3	https://www.birdlife.org/wp-content/uploads/2022/10/Electrocutions-Collisions-Birds-Best-Mitigation-Practices-NABU.pdf
Non-infectious	Toxin, pollution or eutrophication	Cyanobacteria toxins	4	2	4	4	
Infectious	Virus	Avian influenza (Highly Pathogenic)	3	3	3		
Non-infectious	Toxin, pollution or eutrophication	Lead poisoning (from ingestion of lead shot)	3	1	1	3	
Non-infectious	Toxin, pollution or eutrophication	Blue green algae & other algal species imbalance, from dam flooding, reduces food sources*	3	0	0	3	
Non-infectious	Toxin, pollution or eutrophication	Poisoning by PCBs, DDT and DDE*	3	0	0	2	Dissertation - Investigation into the Ecological and Toxicological Constraints on a Population of Lesser Flamingos (Phoeniconaias minor) at Kamfers Dam in Kimberley, South Africa. L Hill, 2016
Non-infectious	Toxin, pollution or eutrophication	Botulism (*Clostridium botulinum*)*	2	1	0	3	
Other problems	Climatic conditions	Reduced food availability and no breeding due to drought	4.5	0	1	3	
Other problems	Climatic conditions	Dam flooding - causes algal imbalance, reducing food resources, and prevents breeding on mudflats*	4	0	0	4	
Other problems	Persecution	Predation	2	0	0	3	
Other problems	Environmental conditions	Proposed residential developments*	2	0	0	5	
Other problems	Persecution	Hunting with dogs	2	0	0	3	

xi. Order Psittaciformes (parrots): two species; one expert contributor.

Causes of disease considered of medium or greater importance (scoring ≥ 2.5 in any category)			Median score				Key references provided by experts
Infectious agent, non-infectious condition or other problem	Subcategory (as per Tables 4.2 and 11.2)	Agent/ detailed condition (an asterisk indicates a score from one expert only)	Negative impact on biodiversity conservation	Potential for an epidemic and/or serious, widespread impact in people	Negative impact on domestic animal health and human livelihoods	Potential future threat ('one to watch')	
Infectious	Virus	Avian influenza including Highly Pathogenic strains	4	2	4	4	

xii. Order Sphenisciformes (penguins): two species; three expert contributors.

Causes of disease considered of medium or greater importance (scoring ≥ 2.5 in any category)			Median score				Key references provided by experts
Infectious agent, non-infectious condition or other problem	Subcategory (as per Tables 4.2 and 11.2)	Agent/ detailed condition (an asterisk indicates a score from one expert only)	Negative impact on biodiversity conservation	Potential for an epidemic and/or serious, widespread impact in people	Negative impact on domestic animal health and human livelihoods	Potential future threat ('one to watch')	
Infectious	Virus	Avian influenza (Highly Pathogenic)	5	3	4	5	https://doi.org/10.1155/2023/2708458, https://doi.org/10.7589/2019-03-067, https://www.fao.org/3/ca1209en/CA1209EN.pdf, https://doi.org/10.1101/2023.03.03.531008, http://www.sernapesca.cl/noticias/sernapesca-informa-que-se-amplian-especies-marinas-afectadas-por-influenza-aviar-huillin General references: Vanstreels et al. (2023) Health and diseases. In Young and VanderWerf (eds.), Conservation of Marine Birds. pp 131-176 Parsons and Vanstreels. 2016. Southern African seabird colony disease risk assessment - December 2016. Southern African Foundation for the Conservation of Coastal Birds, Cape Town, South Africa
Non-infectious	Incidental anthropogenic trauma	Fisheries by-catch*	4	1	1	3	https://conbio.onlinelibrary.wiley.com/doi/10.1111/cobi.12349; https://www.frontiersin.org/articles/10.3389/fmars.2019.00248/full
Non-infectious	Toxin, pollution or eutrophication	Oil spills - mainly African	4	1	2	3	https://conbio.onlinelibrary.wiley.com/doi/10.1111/cobi.12349; https://www.frontiersin.org/articles/10.3389/fmars.2019.00248/full
Infectious	Bacterium	*Pasteurella multocida*	3	0.5	2	2	https://doi.org/10.2307/1521458, https://doi.org/10.2989/AJMS.2007.29.1.9.74, https://doi.org/10.1371/journal.pone.0197291, https://doi.org/10.7589/0090-3558-42.2.259, https://doi.org/10.7589/0090-3558-26.2.283
Infectious	Protozoa	*Cryptosporidium sp.**	3	1	1	2	https://doi.org/10.3354/dao03504
Infectious	Protozoa	*Plasmodium* (avian malaria - usually *P. relictum* & *P. elongatum*)	3	0	1	3	https://doi.org/10.7589/2017-06-146, https://doi.org/10.7589/2018-05-134, https://doi.org/10.1017/S0031182016000251, https://doi.org/10.1080/03079457.2016.1149145, https://doi.org/10.2989/18142320509504087
Infectious	Virus	Herpesvirus*	3	0	0	4	https://doi.org/10.1111/tbed.12064, https://doi.org/10.4102/ojvr.v83i1.1147, https://doi.org/10.1016/j.vetmic.2010.05.006, https://doi.org/10.1111/tbed.14037, https://doi.org/10.1590/S1516-89132012000400008
Infectious	Bacterium	Relapsing fever *Borrelia*	2.5	1.5	0.5	1	https://doi.org/10.7589/2017-06-146, https://doi.org/10.7589/2018-05-134, https://doi.org/10.1007/s00300-017-2171-7, https://doi.org/10.1007/s00436-011-2602-2, https://doi.org/10.1017/S0031182016000251
Infectious	Fungus or Yeast	Aspergillosis (*A. fumigatus*)	2	1	1	2.5	https://doi.org/10.1136/vr.150.16.513, https://doi.org/10.2307/20094516, https://doi.org/10.3390/antibiotics12030584, https://doi.org/10.1021/acsomega.0c04983, https://doi.org/10.1093/mmy/myad008
Infectious	Helminth	*Cardiocephaloides physalus**	3	0	0	1	
Infectious	Virus	Avian pox	2	0	0	3	https://doi.org/10.7589/0090-3558-48.3.790, https://doi.org/10.1080/03079457.2013.849794, https://doi.org/10.1099/0022-1317-79-7-1637, https://doi.org/10.1371/journal.pone.0205126, https://doi.org/10.1017/S0954102017000347
Non-infectious	Incidental anthropogenic trauma	Dynamite fishing - only Humboldt*	2	0	0	3	
Non-infectious	Incidental anthropogenic trauma	Entanglement	2	0	0	3	https://www.frontiersin.org/articles/10.3389/fmars.2019.00248/full
Non-infectious	Toxin, pollution or eutrophication	Harmful algal blooms	1	1	1	3	

Causes of disease considered of medium or greater importance (scoring ≥ 2.5 in any category)			Median score				Key references provided by experts
Infectious agent, non-infectious condition or other problem	**Subcategory (as per Tables 4.2 and 11.2)**	**Agent/ detailed condition (an asterisk indicates a score from one expert only)**	**Negative impact on biodiversity conservation**	**Potential for an epidemic and/or serious, widespread impact in people**	**Negative impact on domestic animal health and human livelihoods**	**Potential future threat ('one to watch')**	
Other problems	Environmental conditions	Habitat loss due to development in foraging areas (new harbours and increased marine activity)*	5	0	0		
Other problems	Ecological problems	Reduced food availability due to reduced fish stocks which are caused by unsustainable fishing and marine ecosystem collapse / fisheries competition / overexploitation of fisheries resources - mostly African	5	1	3	5	https://conbio.onlinelibrary.wiley.com/doi/10.1111/cobi.12349; https://www.frontiersin.org/articles/10.3389/fmars.2019.00248/full
Other problems	Environmental conditions	Changing marine conditions associated with climate change, including ocean acidification and associated changes in the food web*	4	0	4		
Other problems	Climatic conditions	Extreme weather events (heat waves, storms, etc.) - both species; (mainly flooding and overheating affecting nests and bereeding)	3.5	0	3	5	
Other problems	Ecological problems	Predation	2	0	0	3.5	
Non-infectious	**Anthropogenic stress or disturbance**	**Disturbance from guano harvesting - only Humboldt***	3	0	0	3	

xiii. Order Galliformes (common quail (*Coturnix coturnix coturnix*)): one expert contributor.

Causes of disease considered of medium or greater importance (scoring ≥ 2.5 in any category)			Median score				Key references provided by experts
Infectious agent, non-infectious condition or other problem	Subcategory (as per Tables 4.2 and 11.2)	Agent/ detailed condition (an asterisk indicates a score from one expert only)	Negative impact on biodiversity conservation	Potential for an epidemic and/or serious, widespread impact in people	Negative impact on domestic animal health and human livelihoods	Potential future threat ('one to watch')	
Infectious	Bacterium	*Camployobacter*	5	4	3		
Infectious	Bacterium	*Clostridium perfringens*	5	4	3		
Infectious	Bacterium	*Coxiella burnetti*	5	4	3		
Infectious	Bacterium	*Escherichia*	5	4	3		
Infectious	Bacterium	*Klebsiella*	5	4	3		
Infectious	Bacterium	*Listeria*	5	4	3		
Infectious	Bacterium	*Pasteurella*	5	4	3		
Infectious	Bacterium	*Proteus*	5	4	3		
Infectious	Bacterium	*Staphylococcus*	5	4	3		
Non-infectious	Incidental anthropogenic trauma	Collisions with buildings, cranes, wire, fences and entanglements	5	5	0		
Infectious	Protozoa	Coccidiosis (*Eimeria*)	4	n/a	3		
Infectious	Protozoa	*Cryptosporidium*	4	n/a	3		
Infectious	Bacterium	Avian TB (Mycobacteria)	3	4	3		
Infectious	Bacterium	Chlamydiosis	3	0	3		
Infectious	Bacterium	Salmonellosis	3	4	3		
Infectious	Helminth	*Ascaridia* sp, *Heterakis gallinarium*	3	n/a	3		
Infectious	Helminth	*Capillaria* spp; *Gongylonema* sp; *Dispharynx nasuta* ; *Tetrameres americana* , *T.fissipina* . Cyrnea colini; *Cheliospirura spinosa*	3	n/a	3		
Infectious	Virus	Avian influenza including Highly Pathogenic strains	3	5	3		
Infectious	Virus	Avian poxvirus	3	0	3		
Infectious	Virus	Herpesviruses	3	5	3		
Infectious	Virus	Newcastle disease	3	0	3		
Infectious	Virus	Phleboviruses	3	5	3		
Non-infectious	Toxin, pollution or eutrophication	Chemical pollutants: pesticides, heavy metals, industrial chemical	3	5	1		
Infectious	Arthropod ectoparasite	*Ornithonyssus sylvarium* (northern fowl mite)	2	0	3		
Infectious	Fungus or Yeast	Aspergillosis (*A. flavusin*)	2	2	3		
Infectious	Arthropod ectoparasite	Lice	1	0	3		
Infectious	Helminth	Nematodes, *Syngamus trachea*	1	n/a	3		
Infectious	Helminth	Tapeworms; flukes	1	n/a	3		
Infectious	Arthropod ectoparasite	Sticktight fleas (*Echidnophaga gallinacean*)	0	0	3		
Other problems	Ecological problems	Domestic and feral cat predation	5	5	2		
Other problems	Environmental conditions	Cities expansion	5	5	2		
Other problems	Environmental conditions	Habitat loss/degradation	2	5	0		
Other problems	Persecution	Overexploitation	2	3	0		

b. Aquatic species

i. Class Mammalia

1. Order Cetacea (cetaceans): 81 species; four expert contributors.

Causes of disease considered of medium or greater importance (scoring ≥ 2.5 in any category)			Median score				Key references provided by experts
Infectious agent, non-infectious condition or other problem	Subcategory (as per Tables 4.2 and 11.2)	Agent/ detailed condition (an asterisk indicates a score from one expert only)	Negative impact on biodiversity conservation	Potential for an epidemic and/or serious, widespread impact in people	Negative impact on domestic animal health and human livelihoods	Potential future threat ('one to watch')	
Non-infectious	Incidental anthropogenic trauma	Bycatch, entanglement (marine debris, ALDFG)	5	1	2	4.5	https://doi.org/10.1016/j.marpolbul.2016.06.034
Non-infectious	Toxin, pollution or eutrophication	Persistent organic pollutants (PCBs, PFAs, BDEs etc)	4.5	3	2.5	3.5	Jepson et al. (2016) PCB pollution continues to impact populations of orcas and other dolphins in European waters. Sci. Rep. 6, 18573. Williams et al. (2020) Levels of polychlorinated biphenyls are atill associated with toxic effects in harbor porpoises (Phocoena phocoena) despite having fallen below proposed toxicity thresholds. Environ. Sci. Technol.
Non-infectious	Anthropogenic stress or disturbance	Noise pollution (e.g. ADDs, pleasurecraft, naval sonar, seismic surveys etc)	4	0	2	3	https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=20856
Infectious	Virus	Canine distemper virus (CDV); dolphin morbillivirus (DMV); porpoise morbillivirus (PMV)	3.5	0	1	3	
Non-infectious	Incidental anthropogenic trauma	Trauma (e.g. boat strike)	3.5	0	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	0.5	3	
Non-infectious	Toxin, pollution or eutrophication	Seabed mining	2	1	1	3	https://doi.org/10.3389/fmars.2023.1095930
Infectious	Virus	Caliciviruses	1.5	0.5	0	2.5	
Other problems	Ecological problems	Prey depletion	4	2	5	4	
Other problems	Climatic conditions	Climate change (e.g. shift in prey distribution, habitat degradation, direct physical impacts etc)	3	2	2	3	https://doi.org/10.1016/j.marpol.2021.104634

2. Order Carnivora

***Families Otariidae and Phocidae (suborder Pinnipedia) ('seals and sea lions')*:** six species; two expert contributors.

Causes of disease considered of medium or greater importance (scoring ≥ 2.5 in any category)			Median score				Key references provided by experts
Infectious agent, non-infectious condition or other problem	Subcategory (as per Tables 4.2 and 11.2)	Agent/ detailed condition (an asterisk indicates a score from one expert only)	Negative impact on biodiversity conservation	Potential for an epidemic and/or serious, widespread impact in people	Negative impact on domestic animal health and human livelihoods	Potential future threat ('one to watch')	
Non-infectious	Incidental anthropogenic trauma	Bycatch, entanglement	5	0	3	5	
Infectious	Virus	Phocine distemper virus (PDV)	4.5	0	1	4	
Infectious	Virus	Influenza A viruses, including Highly Pathogenic avian influenza	4	4	4.5	5	
Non-infectious	Toxin, pollution or eutrophication	Domoic acid	4	3	4.5	5	
Non-infectious	Foreign body ingestion	Foreign body ingestion	3.5	0	1.5	4	
Infectious	Protozoa	*Toxoplasma*	3.5	1.5	1.5		
Infectious	Virus	Canine distemper virus (CDV)	3.5	0	0		
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	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	Urogenital carcinoma*	3	0	0		
Infectious	Bacterium	*Leptospira* *	3	2	2		
Infectious	Virus	Eastern equine encephalitis virus (EEEV)*	1	1	3		

***Family Mustelidae (otters)*: two species; one expert contributor.**

Causes of disease considered of medium or greater importance (scoring ≥ 2.5 in any category)			Median score				Key references provided by experts
Infectious agent, non-infectious condition or other problem	Subcategory (as per Tables 4.2 and 11.2)	Agent/ detailed condition (an asterisk indicates a score from one expert only)	Negative impact on biodiversity conservation	Potential for an epidemic and/or serious, widespread impact in people	Negative impact on domestic animal health and human livelihoods	Potential future threat ('one to watch')	
Infectious	Virus	Canine distemper virus (CDV)	3	0	0	3	https://doi.org/10.1007/s10393-014-0917-z https://www.otterspecialistgroup.org/osg-newsite/wp-content/uploads/2018/03/12.-Lontra-provocax-Red-List-2019.pdf
Infectious	Protozoa	*Toxoplasma gondii*	2	1	0	3	https://doi.org/10.7589/2019-10-269 https://doi.org/10.1371/journal.pone.0199085
Non-infectious	Incidental anthropogenic trauma	Bycatch, entanglement (in gillnets called 'cortina')	3	0	0	3	https://www.iucnosgbull.org/Volume25/Pizarro_2008.pdf
Non-infectious	Incidental anthropogenic trauma	Boat strike/trauma, accidental entrapment in boats	3	0	0	2	https://www.iucnosgbull.org/Volume25/Pizarro_2008.pdf
Other problems	Environmental conditions	High nutrient levels in watersources and wetlands	3	0	0		https://doi.org/10.1017/S0030605322000394
Other problems	Environmental conditions	Habitat loss due to intensive logging for firewood, draining of soil for agricultural use, climate change, introduced species (waterweed Egeria densa) which compete with native species	5	0	0		https://doi.org/10.1017/S0030605322000394
Other problems	Environmental conditions	Forest plantations causing land-use change (e.g for Eucalyptus sp, Pinus sp) around water bodies	4	0	0	5	
Other problems	Environmental conditions	Cutting of temú and pitra trees along with drainage and gradual degradation of the wetlands edge	4	0	0	4	https://doi.org/10.1017/S0030605322000394
Other problems	Ecological problems	Invasive species (American mink Neovison vison; feral and domestic cats)	3	0	0		https://doi.org/10.1371/journal.pone.0199085
Other problems	Genetic problems	Habitat fragmentation leading to reduced genetic diversity	4	0	0		https://www.iucnosgbull.org/Volume25/Pizarro_2008.pdf

3. Order Sirenia (sirenians): four species; four expert contributors.

Causes of disease considered of medium or greater importance (scoring ≥ 2.5 in any category)			Median score				Key references provided by experts
Infectious agent, non-infectious condition or other problem	Subcategory (as per Tables 4.2 and 11.2)	Agent/ detailed condition (an asterisk indicates a score from one expert only)	Negative impact on biodiversity conservation	Potential for an epidemic and/or serious, widespread impact in people	Negative impact on domestic animal health and human livelihoods	Potential future threat ('one to watch')	
Non-infectious	Physiologic response to extreme climate	Cold stunning (including loss of thermal refuges)	5	0	0	4	
Non-infectious	Incidental anthropogenic trauma	Watercraft trauma (boats, commercial platforms, properller wounds, working barges, tugs or cruise ships)	4	0	0	3.5	
Non-infectious	Toxin, pollution or eutrophication	Algal blooms: brevetoxicosis (*Karenia brevis*)	4	1	3	5	
Non-infectious	Foreign body ingestion	Fishing gear ingestion, plastic ingestion (including microplastics)	2.5	0	0	2	
Non-infectious	Incidental anthropogenic trauma	Entanglement	3	0	0	2	https://onlinelibrary.wiley.com/doi/epdf/10.1002/aqc.3590?saml_referrer
Non-infectious	Nutritional disease or deficiency	Starvation (loss of habitat)*	3	0	0	3	
Non-infectious	Nutritional disease or deficiency	Pollution-induced starvation	2	1	1	3	https://www.proquest.com/docview/2505937002?parentSessionId=ZlfssjThYwLHT85kM4dVXw54sbflvdwr3X8zX6yjD%2Fs%3D&pq-origsite=primo&accountid=10673
Infectious	Virus	Morbillivirus (dolphin)	1	0	0	4	
Other problems	Environmental conditions	Loss of seagrass	n/a	n/a	n/a	5	
Other problems	Environmental conditions	Coastal development and habitat loss*	5	0	0		https://www.researchgate.net/publication/349821805_In-Water_Bridge_Construction_Effects_on_Manatees_with_Implications_for_Marine_Megafauna_Species
Other problems	Climatic conditions	Drought and low water levels in the rivers*	n/a	n/a	n/a	3	https://onlinelibrary.wiley.com/doi/epdf/10.1002/aqc.3590?saml_referrer
Other problems	Climatic conditions	Hurricanes*	2	0	4	2	https://www.researchgate.net/publication/239925870_Research_on_the_Impacts_of_Past_and_Future_Hurricanes_on_the_Endangered_Florida_Manatee
Other problems	Ecological problems	Increasing *Sargassum* spp. blooms in the Antilles, Mexico, parts of Florida*	n/a	n/a	n/a	3	https://www.sciencedirect.com/science/article/abs/pii/S0025326X17305374

ii. Class Chondrichthyes

1. Orders Myliobatiformes and Rhinopristiformes (rays): 21 species; two expert contributors.

Causes of disease considered of medium or greater importance (scoring ≥ 2.5 in any category)			Median score				Key references provided by experts
Infectious agent, non-infectious condition or other problem	Subcategory (as per Tables 4.2 and 11.2)	Agent/ detailed condition (an asterisk indicates a score from one expert only)	Negative impact on biodiversity conservation	Potential for an epidemic and/or serious, widespread impact in	Negative impact on domestic animal health and human livelihoods	Potential future threat ('one to watch')	
Non-infectious	Incidental anthropogenic trauma	Bycatch, entanglement	4	0	0	3	https://doi.org/10.1002/aqc.2466
Non-infectious	Incidental anthropogenic trauma	Ship strike	3	0	0	2	https://doi.org/10.1371/journal.pone.0225681
Non-infectious	Other	Developmental defects, relating to chemical pollution*	3	0	0	3	
Non-infectious	Foreign body ingestion	Foreign body ingestion, plastic ingestion	2.5	0	0	1.5	https://doi.org/10.3389/fmars.2019.00679
Non-infectious	Toxin, pollution or eutrophication	Heavy metals*	1	1	0	3	https://doi.org/10.1038/s41598-022-10482-8
Non-infectious	Toxin, pollution or eutrophication	Polychlorinated biphenyls*	1	1	0	3	https://doi.org/10.1038/s41598-022-10482-8
Other problems	Persecution	Guitarfish: fin trade*	5	0	0	4	
Other problems	Persecution	Sawfish: fin trade, medicinal*	5	0	0	4	
Other problems	Persecution	Gill plate trade	4	0	0	4	
Other problems	Persecution	Overfishing	4	0	0	5	

2. Orders Carcharhiniformes, Lamniformes, Orectolobiformes, Squaliformes and Squatiniformes (sharks): 19 species, two expert contributors.

Causes of disease considered of medium or greater importance (scoring ≥ 2.5 in any category)			Median score				Key references provided by experts
Infectious agent, non-infectious condition or other problem	Subcategory (as per Tables 4.2 and 11.2)	Agent/ detailed condition (an asterisk indicates a score from one expert only)	Negative impact on biodiversity conservation	Potential for an epidemic and/or serious, widespread impact in people	Negative impact on domestic animal health and human livelihoods	Potential future threat ('one to watch')	
Non-infectious	Toxin, pollution or eutrophication	Paint fumes - multiple volatile organic chemicals (VOCs)*	4	4	4	5	2022 Biology of Sharks and Their Relatives (CRC Marine Biology Series) 3rd Edition, ISBN 978036786117
Non-infectious	Foreign body ingestion	Foreign body ingestion, plastic ingestion*	4	1	3	5	
Non-infectious	Incidental anthropogenic trauma	Bycatch	4	0	1	5	
Non-infectious	Anthropogenic stress or disturbance	Exertional rhabdomyolysis*	3	0	0	3	
Non-infectious	Incidental anthropogenic trauma	Ship strike*	3	0	1	1	
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	https://doi.org/10.1038/s41598-020-79973-w
Non-infectious	Toxin, pollution or eutrophication	Brevotoxins (*Karenia brevis* - red blooms)*	2	3	3	3	
Infectious	Bacterium	*Tenacibaculum maritimum* *	3	0	3		
Other problems	Persecution	Overfishing	5	0	3	5	https://doi.org/10.1038/s41586-020-03173-9
Other problems	Persecution	Shark fin trade*	5	0	0	5	
Other problems	Climatic conditions	Climate change resulting in changing (increasing) water temperatures (affecting sharks directly as well as reducing available prey species)*	3	n/a	n/a	4	doi: 10.1038/s41598-018-26485-3, https://doi.org/10.1016/j.gecco.2018.e00430
Other problems	Ecological problems	Lionfish/invasive species- competition for prey and destruction of habitat*	1	n/a	n/a	2	https://doi.org/10.1007/s00338-023-02354-y, https://www.nationalgeographic.com/adventure/article/110404-sharks-lionfish-alien-fish-invasive-species-science
Other problems	Ecological problems	Stony coral tissue loss disease - loss of habitat and prey*	2	n/a	n/a	2	doi: 10.7717/peerj.8069

iii. Class Pisces

1. Order Acipenseriformes (‘sturgeons and allies’): 19 species; four expert contributors.

Causes of disease considered of medium or greater importance (scoring ≥ 2.5 in any category)			Median score				Key references provided by experts
Infectious agent, non-infectious condition or other problem	Subcategory (as per Tables 4.2 and 11.2)	Agent/ detailed condition (an asterisk indicates a score from one expert only)	Negative impact on biodiversity conservation	Potential for an epidemic and/or serious, widespread impact in people	Negative impact on domestic animal health and human livelihoods	Potential future threat ('one to watch')	
Non-infectious	Toxin, pollution or eutrophication	*Prymnesium* (haptophyte algae)	5	1	2	5	
Non-infectious	Incidental anthropogenic trauma	Bycatch, entanglement	4	0	3		
Infectious	Helminth	*Nitzschia sturionis*	3	0	4		
Non-infectious	Toxin, pollution or eutrophication	Eutrophication from chemial run offs (pesticides, nitrates, nitrites)	3	3	2	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 ingestion, plasticosis	1	1	3		
Other problems	Environmental conditions	Damming - habitat loss	5	2	2		
Other problems	Persecution	Poaching (bycatch)	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		
Other problems	Climatic conditions	Climate change affecting nutrition, altering food sources	2	3	4	5	
Other problems	Persecution	Overfishing affecting prey stocks	2	0	3		

2. Order Anguilliformes (European eel (*Anguilla anguilla*)): two expert contributors.

Causes of disease considered of medium or greater importance (scoring ≥ 2.5 in any category)			Median score				Key references provided by experts
Infectious agent, non-infectious condition or other problem	Subcategory (as per Tables 4.2 and 11.2)	Agent/ detailed condition (an asterisk indicates a score from one expert only)	Negative impact on biodiversity conservation	Potential for an epidemic and/or serious, widespread impact in people	Negative impact on domestic animal health and human livelihoods	Potential future threat ('one to watch')	
Non-infectious	Incidental anthropogenic trauma	Water power and sluices: grind eels*	4	0	3	4	
Infectious	Helminth	*Anguillicola (Anguillicoloides) crassus*	3.5	0	3	4	https://doi.org/10.1016/j.jembe.2007.08.003□ https://edepot.wur.nl/205952 https://www.wur.nl/en/research-results/research-institutes/bioveterinary-research/animal-diseases/fish-and-shellfish-diseases.htm
Non-infectious	Toxin, pollution or eutrophication	Contaminants*	3	4	3		http://dx.doi.org/10.17895/ices.pub.8143
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	Protozoa	*Trypanosoma* spp.*	3	0	3		
Infectious	Virus	Alloherpesvirus anguillid herpesvirus 1 (AngHV1)	2.5	0	2.5	3	https://doi.org/10.1111/jfd.12885https://www.researchgate.net/publication/232225197_Viral_diseases_of_wild_and_farmed_European_eel_Anguilla_anguilla_with_particular_reference_to_the_Netherlands
Infectious	Virus	Rhabdovirus eel virus European X (EVEX)	2.5	0	2.5	1	https://www.ices.dk/community/groups/Pages/WGEEL.aspx https://doi.org/10.2903/j.efsa.2008.809 https://www.wur.nl/nl/landingspagina-redacteuren/nl/publicatie-details.htm?publicationId=publication-way-343239323938
Other problems	Persecution	Overfishing	5	0	4.5	5	https://www.ices.dk/community/groups/Pages/WGEEL.aspx
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		http://dx.doi.org/10.1007/978-4-431-54529-3_4

3. Order Siluriformes (Mekong giant catfish (*Pangasianodon gigas*)): one expert contributor.

Causes of disease considered of medium or greater importance (scoring ≥ 2.5 in any category)			Median score				Key references provided by experts
Infectious agent, non-infectious condition or other problem	Subcategory (as per Tables 4.2 and 11.2)	Agent/ detailed condition (an asterisk indicates a score from one expert only)	Negative impact on biodiversity conservation	Potential for an epidemic and/or serious, widespread impact in people	Negative impact on domestic animal health and human livelihoods	Potential future threat ('one to watch')	
Non-infectious	Incidental anthropogenic trauma	Electrofishing, small mesh and big mesh fishing, dynamite fishing (illegal fishing)	3	0	1		https://doi.org/10.3390/w12061820
Other problems	Persecution	Overfishing	4	0	1		
Other problems	Persecution	Dry season fishing (in pools)	4	0	2		https://doi.org/10.3390/w12061820
Other problems	Environmental conditions	Dam building affecting movement/migration	4	0	1		
Other problems	Climatic conditions	Climate change - could result in changes in maturation, behaviour and movement	3	0	2		https://doi.org/10.1080/23308249.2021.1906843
Other problems	Climatic conditions	Extreme weather events (e.g. flooding, high nutrient levels in waterbodies, increasing river flows can hamper spawning migrations, erode spawning beds, sweep eggs and juveniles downstream)	3	0	2		https://doi.org/10.1080/23308249.2021.1906843

iv. Class Reptilia

1. Order Testudinata (turtles): eight species; three expert contributors.

Causes of disease considered of medium or greater importance (scoring ≥ 2.5 in any category)			Median score				Key references provided by experts
Infectious agent, non-infectious condition or other problem	Subcategory (as per Tables 4.2 and 11.2)	Agent/ detailed condition (an asterisk indicates a score from one expert only)	Negative impact on biodiversity conservation	Potential for an epidemic and/or serious, widespread impact in people	Negative impact on domestic animal health and human livelihoods	Potential future threat ('one to watch')	
Non-infectious	Incidental anthropogenic trauma	Bycatch	4	0	0	1.5	
Non-infectious	Incidental anthropogenic trauma	Entanglement	4	0	0	1	
Non-infectious	Other environmnental injury	Drowning from entanglement in nets	3	0	0	3.5	
Non-infectious	Foreign body ingestion	Foreign body ingestion, plastic ingestion/ plasticosis	3	0	0	1	
Non-infectious	Toxin, pollution or eutrophication	Poisoning by bioaccumulation of natural marine toxins	3	1	0	4	
Non-infectious	Nutritional disease or deficiency	Malnutrition from habitat degradation, reduction in food sources etc	4	0	0	4	
Other problems	Environmental conditions	Habitat degradation, reduction in food sources etc	4	0	0	4	
Other problems	Climatic conditions	Global (seas and nesting beaches) warming*	2	3	3	4	

2. Order Crocodylia (crocodiles): two species; two expert contributors.

Causes of disease considered of medium or greater importance (scoring ≥ 2.5 in any category)			Median score				Key references provided by experts
Infectious agent, non-infectious condition or other problem	Subcategory (as per Tables 4.2 and 11.2)	Agent/ detailed condition (an asterisk indicates a score from one expert only)	Negative impact on biodiversity conservation	Potential for an epidemic and/or serious, widespread impact in people	Negative impact on domestic animal health and human livelihoods	Potential future threat ('one to watch')	
Non-infectious	Toxin, pollution or eutrophication	Heavy metal bioaccumulation (mercury, lead, zinc)	3.5	2	1	3.5	
Non-infectious	Toxin, pollution or eutrophication	Pesticide bioaccumulation	3.5	2	1	3.5	
Non-infectious	Other environmnental injury	Drowning from entanglement in nets*	3	0	0	5	
Infectious	Virus	West Nile virus (WNV) in farmed crocodiles*	3	4	2	4	
Infectious	Helminth	Lung worms*	3	1	0		
Infectious	Helminth	Skin nematodes*	3	0	0		
Infectious	Virus	Eastern equine encephalitis virus (EEEV)*	2	3	1	2	
Infectious	Bacterium	Salmonellosis*	2	2	2	3	
Other problems	Environmental conditions	Habitat loss, including loss of prey and loss of nesting habitat*	4	0	0	4	
Other problems	Persecution	Local consumption	2	0.5	0	1.5	
Other problems	Persecution	Also often wild caught for farm stocking. NB risk of disease transfer between wild and farmed stock	0.5	0.5	1	3	

c. Terrestrial species

i. Class Mammalia

1. Order Chiroptera

Suborder Yangochiroptera (microbats): 50 species; four expert contributors.

Causes of disease considered of medium or greater importance (scoring ≥ 2.5 in any category)			Median score				Key references provided by experts
Infectious agent, non-infectious condition or other problem	Subcategory (as per Tables 4.2 and 11.2)	Agent/ detailed condition (an asterisk indicates a score from one expert only)	Negative impact on biodiversity conservation	Potential for an epidemic and/or serious, widespread impact in people	Negative impact on domestic animal health and human livelihoods	Potential future threat ('one to watch')	
Infectious	Fungus or Yeast	White Nose Syndrome (WNS) (*Pseudogymnoascus destructans*)	5	0	3	4.5	
Non-infectious	Incidental anthropogenic trauma	Collisions with wind farm blades	5	0	1	3	O'Shea et al. Multiple mortality events in bats: a global review. Mamm Rev. 2016 Jul;46(3):175-190. doi: 10.1111/mam.12064. Epub 2016 Jan 18. PMID: 29755179; PMCID: PMC5942905. Thaxter et al. Bird and bat species' global vulnerability to collision mortality at wind farms revealed through a trait-based assessment. Proc Biol Sci. 2017 Sep 13;284(1862):20170829. doi: 10.1098/rspb.2017.0829.
Infectious	Virus	Coronaviruses	2.5	4.5	3	4.5	
Infectious	Virus	Rabies	2	2	1	3	
Non-infectious	Toxin, pollution or eutrophication	Lead poisoning	2	0	0	3	
Infectious	Bacterium	*Leptospira* spp	1	1	0	3	
Infectious	Virus	Hendravirus	0	1	1	3	
Infectious	Virus	Marburg virus and Ebola virus (Filoviruses)	0	1	1	3	
Infectious	Virus	Nipah virus (Paramyxoviruses) reservoir	0	1	1	3	
Non-infectious	Anthropogenic stress or disturbance	Light pollution	3	0	0	3	
Other problems	Persecution	Retaliatory killings	4	1	0	4.5	
Other problems	Environmental conditions	Loss/fragmentation of habitats	4	0	2	0	
Other problems	Persecution	Poaching for meat	2	3	0	3	
Other problems	Ecological problems	Predation by introduced species	1	3	0		

***Suborder Yinpterochiroptera ('megabats and allied microbats')*:** seven species; three expert contributors.

Causes of disease considered of medium or greater importance (scoring ≥ 2.5 in any category)			Median score				Key references provided by experts
Infectious agent, non-infectious condition or other problem	Subcategory (as per Tables 4.2 and 11.2)	Agent/ detailed condition (an asterisk indicates a score from one expert only)	Negative impact on biodiversity conservation	Potential for an epidemic and/or serious, widespread impact in people	Negative impact on domestic animal health and human livelihoods	Potential future threat ('one to watch')	
Non-infectious	Toxin, pollution or eutrophication	Pesticides, insecticides*	3	3	3	3	
Non-infectious	Physiologic response to extreme climate	Extreme heat mass mortalities*	3	0	3	4	
Infectious	Virus	Coronaviruses	1	5	3	4.5	
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	
Infectious	Virus	Other henipaviruses*	0	4	4	4	
Infectious	Bacterium	*Leptospira* spp	0.5	2.5	1.5	3	
Other problems	Persecution	Retaliatory killings	4	1	1	4.5	
Other problems	Persecution	Poaching for meat	3	3.5	0.5	2.5	

2. Order Artiodactyla

Family Bovidae (bovids): 21 species; two expert contributors.

Causes of disease considered of medium or greater importance (scoring ≥ 2.5 in any category)			Median score				Key references provided by experts
Infectious agent, non-infectious condition or other problem	Subcategory (as per Tables 4.2 and 11.2)	Agent/ detailed condition (an asterisk indicates a score from one expert only)	Negative impact on biodiversity conservation	Potential for an epidemic and/or serious, widespread impact in people	Negative impact on domestic animal health and human livelihoods	Potential future threat ('one to watch')	
Infectious	Bacterium	Anthrax (*B. anthracis*)	5	3.5	5		
Infectious	Virus	Peste des petits 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	Virus	Bluetongue virus	1.5	0.5	2.5		
Infectious	Arthropod ectoparasite	*Sarcoptes scabei*	2.5	1.5	2.5		
Infectious	Arthropod ectoparasite	Ticks	1.5	1.5	2.5		
Infectious	Arthropod ectoparasite	Various mosquitoes, biting midges, sand flies, black flies, tabanid flies, louse flies, and muscoid flies	1.5	1.5	2.5		
Infectious	Virus	Rabies	2.5	2.5	3.5		
Infectious	Bacterium	*Brucella* (*B.abortus*)	2	2.5	4		
Infectious	Bacterium	*Coxiella burnetti* (Q fever)	0	3	2	5	
Infectious	Bacterium	*Ehrlichia ruminantium* (heartwater)	0.5	0	2.5		
Infectious	Bacterium	*Fusobacterium necrophorum*	1.5	0.5	2.5		
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	Helminth	*Taenia* sp.	1	2.5	2		
Infectious	Helminth	Trichostrongyles (*Haemonchus contortus*, *Ostertagia* sp, *Trichostrongylus axei*)	1.5	0	2.5		
Infectious	Protozoa	Theileriosis (*Theileria parva, T. annulta*)	1	0	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	n/a	n/a		
Other problems	Persecution	Poaching*	5	n/a	n/a		

***Family Cervidae (deer)*:** three species; one expert contributor.

Causes of disease considered of medium or greater importance (scoring ≥ 2.5 in any category)			Median score				Key references provided by experts
Infectious agent, non-infectious condition or other problem	Subcategory (as per Tables 4.2 and 11.2)	Agent/ detailed condition (an asterisk indicates a score from one expert only)	Negative impact on biodiversity conservation	Potential for an epidemic and/or serious, widespread impact in people	Negative impact on domestic animal health and human livelihoods	Potential future threat ('one to watch')	
Infectious	Virus	Cervid herpesviruses 1 & 2	5	0	4	5	
Infectious	Virus	Deer alpha herpesviruses	5	0	4	5	
Infectious	Bacterium	Johne's (*M.avium* ssp *paratuberculosis*)	5	3	4	5	
Infectious	Arthropod ectoparasite	Mange mites (*Sarcoptes, Demodex*)	5	0	3	5	
Infectious	Virus	Deer fibromatosis (delta papilloma virus)	4	0	1	2	
Infectious	Bacterium	Tuberculosis (*M. bovis, M. tuberculosis*)	4	4	5	5	
Infectious	Helminth	*Dictyocaulus* spp	4	0	0	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	0	3	4	
Infectious	Helminth	*Haemonchus* spp	2	0	0	3	
Infectious	Helminth	*Nematodirus* spp	2	0	0	3	
Infectious	Helminth	*Trichostrongylus*	2	0	0	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	0	0	3	
Infectious	Protozoa	*Babesia* spp	1	0	5	3	
Non-infectious	Toxin, pollution or eutrophication	Mycotoxicosis from contaminated supplemental feeding: Aspergillosis; *Penicillium*; *Fusarium* sp	1	0	3	1	
Other problems	Climatic conditions	Climate change	5	0	5	5	
Other problems	Ecological problems	Apparent competition with livestock and exotic abundant prey species	5	0	0	5	
Other problems	Ecological problems	Small and declining populations	5	0	0	5	
Other problems	Environmental conditions	Habitat fragmentation	5	0	0	5	
Other problems	Persecution	Dogs attack	5	0	5	5	
Other problems	Persecution	Poaching	2	0	1	4	

***Family Camelidae (camelids)*: two species; three expert contributors.

Causes of disease considered of medium or greater importance (scoring ≥ 2.5 in any category)			Median score				Key references provided by experts
Infectious agent, non-infectious condition or other problem	Subcategory (as per Tables 4.2 and 11.2)	Agent/ detailed condition (an asterisk indicates a score from one expert only)	Negative impact on biodiversity conservation	Potential for an epidemic and/or serious, widespread impact in people	Negative impact on domestic animal health and human livelihoods	Potential future threat ('one to watch')	
Infectious	Arthropod ectoparasite	Mange mites (*Sarcoptes, Chorioptes, Psoroptes*)	5	1	3	5	
Non-infectious	Anthropogenic stress or disturbance	Constant displacement from feeding sites by alpaca farmers*	4	0	0	5	
Non-infectious	Nutritional disease or deficiency	Scarcity of resources during dry season*	3	2	4	4	
infectious	Bacterium	Paratuberculosis*	3	2	5	3	
Infectious	Helminth	Fascioliasis (*F.hepatica*)*	2	0	3	4	
Infectious	Protozoa	Sarcocystis (*S. aucheniae* and *S. lamacanis*)*	2	0	1	4	
Other problems	Environmental conditions	Overgrazing of natural feeding sties by alpaca farmers*	5	0	5	5	
Other problems	Persecution	Poaching because of its fur*	5	0	0	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	
Other problems	Genetic problems	Low density at unprotected areas*	3	0	0	4	

Family Giraffidae (giraffe (*Giraffa camelopardalis*)): two expert contributors.

Causes of disease considered of medium or greater importance (scoring ≥ 2.5 in any category)			Median score				Key references provided by experts
Infectious agent, non-infectious condition or other problem	Subcategory (as per Tables 4.2 and 11.2)	Agent/ detailed condition (an asterisk indicates a score from one expert only)	Negative impact on biodiversity conservation	Potential for an epidemic and/or serious, widespread impact in people	Negative impact on domestic animal health and human livelihoods	Potential future threat ('one to watch')	
Infectious	Virus	Foot and mouth disease (FMD)*	5	1	5		
Infectious	Bacterium	Anthrax (*Bacillus anthracis*)	4	4	4	3	An outbreak of anthrax in endangered Rothschild's giraffes in Mwea National Reserve, Kenya.Veterinary Medicine : Research and Reports; Macclesfield Vol. 4, (2013): 45-48. DOI:10.2147/VMRR.S52238 Lembo et al. (2011). Serologic surveillance of anthrax in the Serengeti ecosystem, Tanzania, 1996–2009. Emerging Infectious Diseases 17(3), 387–394. DOI: 10.3201/eid1703.101290
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	
Infectious	Bacterium	Listeriosis*	2	1	2	4	
Infectious	Bacterium	Q-fever (*Coxiella burnetti*)*	2	1	2	3	
Infectious	Protozoa	*Theileria**	2	0	3		
Infectious	Virus	Lumpy skin disease (Capripoxvirus)*	2	0	3		
Other problems	Environmental conditions	Habitat loss & fragmentation	n/a	n/a	n/a	n/a	
Other problems	Persecution	Civil unrest	n/a	n/a	n/a	n/a	
Other problems	Persecution	Poaching	n/a	n/a	n/a	n/a	

3. Order Carnivora

Family Felidae (felids): five species; three expert contributors.

Causes of disease considered of medium or greater importance (scoring ≥ 2.5 in any category)			Median score				Key references provided by experts
Infectious agent, non-infectious condition or other problem	Subcategory (as per Tables 4.2 and 11.2)	Agent/ detailed condition (an asterisk indicates a score from one expert only)	Negative impact on biodiversity conservation	Potential for an epidemic and/or serious, widespread impact in people	Negative impact on domestic animal health and human livelihoods	Potential future threat ('one to watch')	
Infectious	Virus	Canine distemper virus (CDV)	5	2	0	3	Roelke-Parker et al. (1996) A canine distemper virus epidemic in Serengeti lions (Panthera leo). Nature 379, 441-445, doi 10.1038/379441a0 Kissui & Packer (2004) Top-down population regulation of a top predator: Lions in the Ngorongoro Crater. Proc. Royal Soc B. 271, 1867-1874. doi 10.1098/rspb.2004.2797
Non-infectious	Incidental anthropogenic trauma	Snare entanglement*	5	n/a	n/a	5	Loveridge et al. (2020) Evaluating the spatial intensity and demographic impacts of wire-snare bush-meat poaching on large carnivores. Biological Conservation 244 108504. https://doi.org/10.1016/j.biocon.2020.108504 Becker et al. (2013) Evaluating wire-snare poaching trends and the impacts of by-catch on elephants and large carnivores Biological Conservation 158: 26–36. http://dx.doi.org/10.1016/j.biocon.2012.08.017 Lindsey et al. (2013) The bushmeat trade in African savannas: Impacts, drivers, and possible solutions. Biological Conservation 160 (2013) 80–96. http://dx.doi.org/10.1016/j.biocon.2012.12.020
Non-infectious	Toxin, pollution or eutrophication	Targeted poisoning	5	4	3	4.5	
Infectious	Virus	Rabies virus	4	5	4	2	
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		
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	Bacterium	Tuberculosis (*M. bovis*)	2.5	2.5	2.5		
Infectious	Bacterium	Salmonellosis	1	1	2.5		
Infectious	Protozoa	*Toxoplasma gondii*	2	2	1	4	doi: 10.1111/tbed.14197 doi: 10.1038/s41598-021-89031-8 doi: 10.3390/pathogens11080868 doi: 10.7589/2015-08-212
Infectious	Arthropod ectoparasite	Mites including *Sarcoptes* sp. (sarcoptic mange)	1.5	1.5	2	3	Cheetahs - disease summary: doi: 10.1016/B978-0-12-804088-1.00025-3
Other problems	Environmental conditions	Habitat loss*	5	n/a	n/a		
Other problems	Persecution	Poaching*	5	n/a	n/a		
Other problems	Persecution	Retaliatory killings*	5	n/a	n/a		

Family Ursidae (bears)**:** two species; two expert contributors.

Causes of disease considered of medium or greater importance (scoring ≥ 2.5 in any category)			Median score				Key references provided by experts
Infectious agent, non-infectious condition or other problem	Subcategory (as per Tables 4.2 and 11.2)	Agent/ detailed condition (an asterisk indicates a score from one expert only)	Negative impact on biodiversity conservation	Potential for an epidemic and/or serious, widespread impact in people	Negative impact on domestic animal health and human livelihoods	Potential future threat ('one to watch')	
Non-infectious	Toxin, pollution or eutrophication	Anthropogenic environmental insult e.g. oil spill	3	0	0	5	
Non-infectious	Anthropogenic stress or disturbance	Anthropogenic environmental insult e.g. human conflict	3	0	0	5	
Non-infectious	Nutritional disease or deficiency	Starvation/changes in prey population dynamics and body condition	4	0	0	5	
Non-infectious	Toxin, pollution or eutrophication	Heavy metal (mercury)	3	0	0	3	
Non-infectious	Toxin, pollution or eutrophication	Poisoning: persitent organic pollutants (POPs); PFAs	2	0	0		AMAP papers and reports (Stoten etc.) https://doi.org/10.3389/fevo.2015.00016, AMAP STOTEN Reviews
Other problems	Climatic conditions	Climate change, consequent loss of habitat	5	0	0	5	
Other problems	Ecological problems	Novel inter- and intra- specific competion	4	0	0	4	

***Family Canidae (African wild dog (*Lycaon pictus*))*:** three expert contributors.

Causes of disease considered of medium or greater importance (scoring ≥ 2.5 in any category)			Median score				Key references provided by experts
Infectious agent, non-infectious condition or other problem	Subcategory (as per Tables 4.2 and 11.2)	Agent/ detailed condition (an asterisk indicates a score from one expert only)	Negative impact on biodiversity conservation	Potential for an epidemic and/or serious, widespread impact in people	Negative impact on domestic animal health and human livelihoods	Potential future threat ('one to watch')	
Infectious	Virus	Rabies virus	5	4	4	4.5	
Non-infectious	Incidental anthropogenic trauma	Snare/trap wounds	5	0	5	5	Becker et al. (2013) Evaluating wire-snare poaching trends and the impacts of by-catch on elephants and large carnivores Biological Conservation 158: 26–36. http://dx.doi.org/10.1016/j.biocon.2012.08.017 Lindsey et al. (2013) The bushmeat trade in African savannas: Impacts, drivers, and possible solutions. Biological Conservation 160 (2013) 80–96. http://dx.doi.org/10.1016/j.biocon.2012.12.020
Non-infectious	Toxin, pollution or eutrophication	Poisoning	5	1	4	4	
Infectious	Virus	Canine distemper virus (CDV)	4	0	0	4	
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	0	3		
Infectious	Arthropod ectoparasite	Mites (mange: *Sarcoptes, Demodex*); chiggers/harvest mites (Trombiculidae)	2.5	2	2		
Non-infectious	Incidental anthropogenic trauma	Road traffic accidents*	4	n/a	n/a		
Other problems	Persecution	Other forms of persecution*	5	n/a	n/a		
Other problems	Ecological problems	Feral dogs (interspecies aggresion)*	3	0	3		

4. Order Primates (primates): seven species; three expert contributors.

Causes of disease considered of medium or greater importance (scoring ≥ 2.5 in any category)			Median score				Key references provided by experts
Infectious agent, non-infectious condition or other problem	Subcategory (as per Tables 4.2 and 11.2)	Agent/ detailed condition (an asterisk indicates a score from one expert only)	Negative impact on biodiversity conservation	Potential for an epidemic and/or serious, widespread impact in people	Negative impact on domestic animal health and human livelihoods	Potential future threat ('one to watch')	
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	Bacterium	*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	Bacterium	Anthrax (*Bacillus anthracis*)	5	3	3	5	
Infectious	Undetermined	New unknown emerging pathogen / undetermined virus or bacteria can be from sympatric wildlife, domestic animals or humans	5	5	5	4	
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	Bacterium	*Sarcoptes scabei*	3.5	3	2.5	3	
Infectious	Bacterium	Shigellosis	3.5	2.5	2.5	3	
Infectious	Protozoa	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	Helminth	*Trichuris trichura*	3.5	2.5	2.5	3	
Infectious	Protozoa	*Entamoeba histolytica*	3.5	2	2	4	
Infectious	Protozoa	*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	Helminth	*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	Virus	Rabies	3	2	1	4.5	
Non-infectious	Other	Myocardial fibrosis*	3	3	3		
Other problems	Ecological problems	Snake and spider venoms*	3	3	3		
Non-infectious	Toxin, pollution or eutrophication	Phytotoxins (ingestion of toxic plants)	4	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	
Infectious	Virus	Enterobius vermicularis	2	3	3	2	
Infectious	Virus	Herpesviruses*	2	4	4	3	
Infectious	Virus	Simian foamy virus (Spumavirus)	2	2.5	2.5	3	

5. Order Perissodactyla (equids): five species; three expert contributors.

Causes of disease considered of medium or greater importance (scoring ≥ 2.5 in any category)			Median score				Key references provided by experts
Infectious agent, non-infectious condition or other problem	Subcategory (as per Tables 4.2 and 11.2)	Agent/ detailed condition (an asterisk indicates a score from one expert only)	Negative impact on biodiversity conservation	Potential for an epidemic and/or serious, widespread impact in people	Negative impact on domestic animal health and human livelihoods	Potential future threat ('one to watch')	
Non-infectious	Nutritional disease or deficiency	Starvation*	5	3	5		
Infectious	Bacterium	Anthrax (*Bacillus anthracis*)	4	4.5	3.5	5	Lembo et al. (2011). Serologic surveillance of anthrax in the Serengeti ecosystem, Tanzania, 1996–2009. Emerging Infectious Diseases 17(3), 387–394. DOI: 10.3201/eid1703.101290
Infectious	Helminth	*Anoplocephala* spp*	4	0	1		
Infectious	Helminth	*Anoplocephaloides* spp*	4	0	1		
Infectious	Helminth	*Strongylus* spp.	4	0	2		
Infectious	Arthropod ectoparasite	Ticks	3.5	1	3		
Infectious	Helminth	*Parascaris equorum*	3.5	0	2		
Infectious	Helminth	*Strongyloides* spp.	3.5	0	2		
Non-infectious	Incidental anthropogenic trauma	Snares - non-targeted	3	0	0		
Non-infectious	Nutritional disease or deficiency	Vit E deficiency (equine degenerative myeloencephalopathy)*	3	0	3		
Infectious	Bacterium	Tetanus (*Clostridium tetani*)	3	2	2	2	
Non-infectious	Other	Colic (sand impactions, intestinal accidents, enterocolitis); enteroliths*	3	0	1		
Infectious	Virus	Rabies (lyssavirus)	1.5	3.5	3.5		
Infectious	Virus	West Nile virus (WNV)	1	2	2		
Other problems	Environmental conditions	Habitat loss	4	0	0		

6. Order Proboscidea (elephants): three species; two expert contributors.

Causes of disease considered of medium or greater importance (scoring ≥ 2.5 in any category)			Median score				Key references provided by experts
Infectious agent, non-infectious condition or other problem	Subcategory (as per Tables 4.2 and 11.2)	Agent/ detailed condition (an asterisk indicates a score from one expert only)	Negative impact on biodiversity conservation	Potential for an epidemic and/or serious, widespread impact in people	Negative impact on domestic animal health and human livelihoods	Potential future threat ('one to watch')	
Infectious	Virus	Elephant endotheliotropic herpesvirus (EEHV)*	5	1	5		
Non-infectious	Incidental anthropogenic trauma	Snare entanglement	5	0	5	5	Becker et al. (2013) Evaluating wire-snare poaching trends and the impacts of by-catch on elephants and large carnivores Biological Conservation 158: 26–36. http://dx.doi.org/10.1016/j.biocon.2012.08.017 Lindsey et al. (2013) The bushmeat trade in African savannas: Impacts, drivers, and possible solutions. Biological Conservation 160 (2013) 80–96. http://dx.doi.org/10.1016/j.biocon.2012.12.020
Infectious	Virus	Encephalomyocarditis virus (EMC)*	4	0	5		
Infectious	Virus	Rabies (lyssavirus)*	4	3	4		
Infectious	Bacterium	Anthrax (*Bacillus anthracis*)	4	3	2.5	3	Lembo et al. (2011). Serologic surveillance of anthrax in the Serengeti ecosystem, Tanzania, 1996–2009. Emerging Infectious Diseases 17(3), 387–394. DOI: 10.3201/eid1703.101290
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	
Non-infectious	Toxin, pollution or eutrophication	Algal toxins	n/a	n/a	n/a		Azeem et al. (2020). Mass die-off of African elephants in Botswana: pathogen, poison or a perfect storm? African Journal of Wildlife Research, 50, 149–156. https://doi.org/10.3957/056.050.0149
Infectious	Bacterium	Salmonellosis	3	3	3	2	
Infectious	Bacterium	Acute pasteurellosis (*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	0	3		
Other problems	Persecution	Human elephant conflict	5	0	1.5		
Other problems	Persecution	Poaching for ivory	5	0	2.5		
Other problems	Environmental conditions	Barriers impeding movement (fencing, roads etc)	3	0	3		

ii. Class Insecta

Order Lepidoptera

Monarch butterfly (*Danaus plexippus*): one expert contributor.

Causes of disease considered of medium or greater importance (scoring ≥ 2.5 in any category)			Median score				Key references provided by experts
Infectious agent, non-infectious condition or other problem	Subcategory (as per Tables 4.2 and 11.2)	Agent/ detailed condition (an asterisk indicates a score from one expert only)	Negative impact on biodiversity conservation	Potential for an epidemic and/or serious, widespread impact in people	Negative impact on domestic animal health and human livelihoods	Potential future threat ('one to watch')	
Non-infectious	Toxin, pollution or eutrophication	Pesticides (glyphosphate)	5	5	3	4	https://doi.org/10.1111/j.1461-0248.2005.00722.x https://doi.org/10.1016/B978-0-12-384984-7.00004-x https://academic.oup.com/aesa/article/115/1/10/6409809 https://doi.org/10.1016/S0022-5320(68)80050-4 https://onlinelibrary.wiley.com/doi/epdf/10.1111/eva.12328 https://www.science.org/doi/10.1126/science.aaf8838 https://www.annualreviews.org/doi/pdf/10.1146/annurev-ento-020117-043241 https://www.sciencedirect.com/science/article/pii/S0378112712001284 https://resjournals.onlinelibrary.wiley.com/doi/epdf/10.1111/j.1752-4598.2012.00196.x?saml_referrer https://link.springer.com/article/10.1007/s00114-015-1270-y
Infectious	Virus	Baculoviruses (aka nucleopolyhedrosis viruses) NPVs	4	0	2		
Infectious	Parasitoid	Natural parasitoid flies (Tachinids or other)	4	0	2		
Non-infectious	Toxin, pollution or eutrophication	Neonicotinoids (clothianidin, imidacloprid)	3	4	3	4	
Infectious	Bacterium	*Wolbachia* spp	3	0	2		
Infectious	Parasitoid	Natural parasitoid wasps (including Brachonids, Chalcids, Trichogammids, etc.)	3	0	2		
Infectious	Protozoa	*Ophryocystis elektroscirrha* (OE)	3	0	0	3	
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	0	2	4	
Other problems	Ecological problems	Reduced nectar sources to fuel adult migration	5	0	3		
Other problems	Ecological problems	Milkweed reduction from both agriculture (herbicide use) and climate change	5	0	1		
Other problems	Climatic conditions	Drought	3	0	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	0	1		
Other problems	Climatic conditions	Fires	2	0	4		
Other problems	Ecological problems	Competition due to reduced space	0	0	4		

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