

The spread of pathogens through trade in wildlife

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Summary

Discussions on diseases of wildlife have generally focused on two basic models: the effect of disease on wildlife, and the role that wildlife plays in diseases affecting people or domestic animal health, welfare, economics and trade. Traditionally, wildlife professionals and conservationists have focused on the former, while most human/animal health specialists have been concerned largely with the latter. Lately, the (re-)emergence of many high-profile infectious diseases in a world with ever-increasing globalisation has led to a more holistic approach in the assessment and mitigation of health risks involving wildlife (with a concurrent expansion of literature). In this paper, the authors review the role of wildlife in the ecology of infectious disease, the staggering magnitude of the movement of wild animals and products across international borders in trade, the pathways by which they move, and the growing body of risk assessments from a multitude of disciplines. Finally, they highlight existing recommendations and offer solutions for a collaborative way forward.

Keywords

Globalisation – Infectious disease – Risk assessment – Trade – Wildlife – Wildlife disease – Wildlife trafficking – Zoonoses.

Wildlife, globalisation and disease

The disruption of intact biodiverse ecosystems severely affects the ability of those environments to provide clean water, energy, food, recreation and other services that contribute to human health and well-being (64, 91, 114, 148, 189). Biodiversity is currently threatened across the globe as wildlife extinctions are estimated to be 100 to 1,000 times greater than the historical norm, and up to 50% of the higher taxonomic groups are endangered (184). While rarely the cause of extinction, diseases play a role in shaping biodiversity, causing unpredictable but often drastic declines or local extirpation of keystone species (115, 136, 184). Over harvesting and unsustainable trade are often among the top factors contributing to species decline (178, 199). When diseases co-mingle with anthropogenic factors, such as habitat destruction and international trade, the impact can increase substantially, affecting biodiversity and ecosystem services crucial to people, especially in underdeveloped countries (69, 84, 184).

Not surprisingly, changes in biodiversity can also affect the risk of transmitting diseases to humans (157). As biodiversity within an ecosystem increases, so do the number of potential pathogens available in the ecosystem, but this does not necessarily translate to the risk of transmission and spread within the same environment (141). For instance, the 'dilution effect' model predicts that high species diversity often results in the protection of humans against transmission of zoonotic diseases (158, 188, 189). However, there is still uncertainty surrounding this effect in different complex ecological contexts and thus zoonotic transmission in nature remains difficult to predict (43, 49, 165).

Wildlife plays a complex and important role in the maintenance of endemic diseases, as well as the emergence of new diseases (43, 49, 92, 141, 158, 165, 188, 189). In the last 20 years, the term 'emerging disease' has gained prominence in the popular press, due to well-publicised outbreaks of pathogens such as Ebola haemorrhagic fever virus, severe acute respiratory syndrome (SARS), monkeypox, Nipah and Hendra viruses, and West Nile virus (44, 79). These events have increased global attention

on the relationship between wildlife and diseases of regulatory importance (i.e. rabies, tuberculosis, brucellosis, tularemia, avian influenza and plague). The unique role that wildlife plays in the ecology of these diseases highlights the fact that valid methods need to be available to properly assess and mitigate risks to human and animal health, as well as the potential impacts on the global economy.

The recent emergence and re-emergence of many infectious diseases appear to be driven largely by globalisation and ecological disruption, while the loss of habitat and biodiversity has also resulted in a homogenisation of biota, which, in turn, has allowed the increased distribution of diseases (158). Large shifts in human behaviour and cultural practices contribute to the emergence and spread of infectious diseases by influencing the rate and quality of contact between domestic animals, people, wildlife and their products (92, 126, 220). For instance, the historic shift in human lifestyle from pastoralism to agro-pastoralism, with accompanying animal domestication, resulted in a change in contacts between humans and animals, which led to a wave of zoonotic disease emergence (126, 220). Recently, as agro-pastoralists have settled into more permanent and high-density communities, there has been a shift from infectious to chronic diseases, partly due to decreased everyday contact with animals (59). However, in less developed places, where relatively little industrialisation has occurred, infectious diseases remain of primary importance (41). In temperate latitudes, such as Europe and North America, disease emergence has mostly been associated with intensification of agricultural practices (i.e. antibiotic resistance leading to the re-emergence of diseases such as tuberculosis), while in tropical areas with greater biodiversity wildlife has played a larger role (92).

Emerging diseases are important because they represent an unknown risk in a risk-averse world. Thus, the need to assess and mitigate the risks posed by these diseases is often of paramount importance. In 2001, it was shown that approximately 61% of human pathogens, 77% of livestock pathogens, 90% of carnivore pathogens and 75% of emerging pathogens are zoonotic or have multiple hosts (32, 194). In 2008, it was established that the majority (71.8%) of emerging zoonotic infectious diseases originate in wildlife, and that the role that wildlife plays in disease emergence is increasing significantly over time (92). Lately, globalisation has resulted in an unprecedented volume of trade in meat and animal products (31, 41, 195, 229). In turn, this has supported the creation of new pathways, both legal and illegal, to supply wildlife and wildlife products, in the form of exotic companion animals, trophies, crafts, bushmeat (food) and both modern and traditional medicines. It has been shown that the trade in wildlife and wildlife products represents a significant pathway of risk for the release of pathogens of importance

to humans, domestic animals and other wildlife (30, 96, 128, 185, 191, 213, 219).

For example, amphibian populations, crucial in wetland ecosystems and sentinels of environmental and human health, are currently in decline around the world, due to the global spread of chytridiomycosis, a recently emerged disease (45, 103, 153). Some estimates state that one-third or more of the 6,300 species of amphibians worldwide are threatened with extinction, as a result (209). One of the major pathways of disease spread is thought to be the farming and transport of infected amphibians (130, 173, 180). Understanding the volume of these movements and the risks associated with them is fundamental in elucidating the epidemiology, and thus the risks (63).

Examining the source: scope and scale of the global trade in wild animals and wildlife commodities

Trade

There are many definitions of 'wildlife' and 'commodity'. For this discussion, the authors use the United States Fish and Wildlife Service definition of wildlife:

'... any wild animal, whether alive or dead, including any wild mammal, bird, reptile, amphibian, fish, mollusk (i.e., clam, snail, squid, octopus), crustacean (i.e., crab, lobster, crayfish), insect, sponges, corals, or other invertebrate, whether or not bred, hatched, or born in captivity, and including any part, product (including manufactured products and processed food products), egg, or offspring' (202).

For 'commodity', the World Organisation for Animal Health (OIE) definition is used:

'... live animals, products of animal origin, animal genetic material, biological products and pathological material (means samples obtained from live or dead animals, containing or suspected of containing infectious or parasitic agents, to be sent to a laboratory).'

The global trade in wildlife, encompassing the sourcing, selling and consumption of live specimens, as well as wildlife commodities, occurs across a wide range of trade routes, at various geographic and economic scales. The wildlife trade occurs across all regions inhabited by humans and is supported by complicated networks that are increasing as human populations expand. Wildlife harvest and trade range in magnitude from local

communities hunting or gathering species for subsistence living to large commercial enterprises, involving millions of specimens travelling long distances across international borders.

Global wildlife trade is challenging to quantify. Many trade sectors need to be considered, including the multitude of different species involved, large-scale legal trade (which often has inconsistent regulatory requirements internationally), illicit trade and internet commerce (both legal and illegal). Estimates from TRAFFIC, the Wildlife Trade Monitoring Network, in 2005 estimated the legal international wildlife trade to be worth over US\$21 billion (€16 billion), calculated from declared international import statistics (55). (This number excludes the fisheries industries, the inclusion of which would increase that figure exponentially.) Breaking down the US\$21 billion includes such figures as US\$338 million (€257 million) in reptile skins and US\$319 million (€242 million) in ornamental fish (55, 168).

There is a massive illegal trade in wild animals and wildlife products at local, regional and global levels. Quantitative estimates for smuggling and the illegal wildlife trade are usually extrapolated and inferred from international seizure data, with numbers that are sometimes enormous. The worldwide illicit trade in wildlife is considered to be a multi-billion-dollar industry, with profits on a par with those of illicit drugs. The fact that penalties for wildlife trafficking are much less severe than those handed out for drug trafficking helps to maintain lucrative profits for wildlife trafficking, with relatively low risk from law enforcement. Occasionally, some drugs and arms traffickers also smuggle wildlife. The worldwide illegal trade in wildlife is a complex web, which capitalises on the variability of laws, cultures and wildlife markets among countries and regions. For instance, illegal trade is often intertwined with legal trade; species banned in international trade may literally be hidden beneath legal species, such as illegal bushmeat being claimed on importation documents to be fish (81). Another example is illegally wild-harvested specimens being fraudulently identified as captive bred. Once in the marketplace, the sources are usually not distinguishable or not tested to verify their status.

A more complicated situation arises when animals are illegally harvested from the wild, but are imported into countries with less stringent or non-existent restrictions, as has been observed for abalone from South Africa and shark fins from South America, which end up in Asian markets (198). Another variation on this theme includes the circumventing of import bans from particular regions by re-exporting from another country. An example of this occurred with African grey parrots (*Psittacus erithacus*). In the 1990s, the European Union (EU) imposed trade restrictions on the importation of these birds because

of concerns about declining populations. The parrots were still harvested and exported from Côte d'Ivoire to Europe, but were simply re-exported through South Africa (55).

Drawing a global picture of the wildlife trade process is a daunting task. A basic evaluation of risk factors along the supply chain, such as collection, preservation, packing and shipment methods, travel routes, and the impact of highly variable regulation of these commodities, results in countless opportunities for the generation and transfer of pathogens. Although there are some major trends and trade flows which can be identified, these 'industries' are fraught with complex circumstances, specific to both species and geographic areas, whether the trade is legal or illegal. However, in general, wildlife trade flows from developing to developed countries (169). The largest consumers of wildlife are the People's Republic of China (China) and the United States, though for very different markets, products and uses. For instance, in China, exotic foods and traditional medicine products derived from wildlife (such as shark fin soup) are considered status symbols, while in the United States wildlife commerce is dominated by imports for the trade in exotic companion animals.

Wildlife commodities

Broadly speaking, there are four categories of wildlife commodities:

- food
- medicine
- clothing/fashion
- ornamental.

Many species have multiple uses, which affects trade routes and market networks, as well as the potential for regulation. For instance, Asian pangolins (*Manis* spp.) are traded for their meat, skin and scales (used in traditional medicines in Southeast Asia for their purported properties to treat inflammation and toxicosis). Despite the fact that all international trade in Asian pangolins is illegal, they are being smuggled in staggering volumes with multiple international seizures in recent years. For example, in June 2010, a vessel travelling from Southeast Asia to China was inspected and found to have 7.8 tonnes of frozen pangolins (for meat) and 1,800 kg of pangolin scales (destined for traditional medicine markets) (199).

Food

A vast proportion of the wildlife trade is for food. Food can be subdivided into several categories, such as food for subsistence, luxury foods (providing status, for instance), foods as part of a cultural tradition and medicinal food. Three well-documented examples are turtles, bushmeat and live reef fish.

Turtles are predominantly harvested or raised for food, but they are also sold as medicine and companion animals, while decorative products are made from their shells. In 2000, 25 tonnes of turtles were exported every week from Sumatra to China while 24,000 turtles were observed for sale in the major wildlife markets in southern China (216). As turtle populations declined in China and neighbouring regions, such as Bangladesh and Vietnam, the market supply shifted to large-scale harvesting in other areas like Brazil and the United States, where new populations are still available and regulations are not yet in place (88, 205). This shifting of supply after depletion to meet a focused demand from Asia makes the trade in turtles a good example of the heavy effects of globalisation on wildlife trade. Currently, in the southern United States, hundreds of thousands of freshwater softshell and snapping turtles, considered almost a nuisance species by farmers, are being shipped every year to Asia; China in particular (144).

Although largely synonymous with Africa, 'bushmeat' refers to the unsustainable harvesting and consumption of wildlife 'meat', consumed as a protein source for humans, anywhere in the world. For centuries, communities have harvested wildlife for local consumption, but traditional hunting practices and trade mechanisms have changed with development. For instance, guns and wire snares are now used to kill and trap species, and forest access has dramatically increased, due to new roads opened by logging concessions. Thus, the consumers of wildlife are no longer simply indigenous communities locally harvesting and trading wildlife for subsistence use, and bushmeat is available throughout the world's cities, where it is sold in restaurants and markets for higher prices. Internationally, there is a demand for bushmeat from the African diaspora, notably in the United States and Europe, where it is smuggled to be sold in covert markets and restaurants (75). A variety of fauna are hunted, including endangered and threatened species. In 2001, Fa and Peres (60) calculated a conservative annual estimate of 28 million forest antelopes (*Tragelaphus eurycerus*), 7.5 million red colobus monkeys (*Procolobus kirkii*), 1.8 million river hogs (*Potamochoerus porcus*) and 15,000 chimpanzees (*Pan troglodytes troglodytes*) being harvested out of the forests of Central Africa. These are the conditions under which diseases such as Ebola virus, simian immunodeficiency virus/human immunodeficiency virus (SIV/HIV), and SARS have emerged.

The live reef fish trade involves the capture and sale of a variety of coral reef species, principally sold as luxury food, with some specimens being sold into the ornamental aquarium industry. Some fish are 'grown out' in an aquaculture setting before being sold. The most prominent species in the food fish trade are groupers, and some of the most popular fish are now threatened or endangered, such as the giant grouper (*Epinephelus lanceolatus*) and the humphead wrasse

(*Cheilinus undulatus*). The live reef fish trade, centred around Southeast Asia, has mushroomed in recent decades, with the expansion of the Asian economy and effects of globalisation. Nearly all of the food fish and 85% of the ornamental aquarium fish are supplied from this region. Over 60% of the trade serves the demand in Hong Kong and China for live reef food fish. Fish supplies have dwindled around Hong Kong and, at present, the fish are sourced broadly in the Indo-Pacific region. Major exporting countries involved are Indonesia, the Philippines, Australia, Malaysia, Thailand and Vietnam. The total value of the trade exceeds US\$1 billion (€0.76 billion) per year (24). As evidenced by the substantial economic and widespread nature of this commerce, there are many communities dependent on the live reef fish trade for their livelihoods. This trade is complex, from source (fisher) to market (retailer) and is not, at present, well regulated (174).

Clothing/fashion

There is a wide range of species, products and markets catering to the clothing and fashion industry, in the form of skins, wool, fur, feathers and jewellery (e.g. pearls, coral, teeth). A report from TRAFFIC, using figures generated from 2005, lists global market values for animal products for clothing and ornamental use at €4 billion (US\$5.3 billion) for animal furs and fur products, €255 million (US\$296 million) in reptile skins, €85 million (US\$112 million) in ornamental corals and shells, and €57 million (US\$75 million) for natural pearls (55). Reticulated pythons are the most desired reptile skin for the fashion industry, along with skins from the water monitor (*Varanus spp.*), American alligator (*Alligator mississippiensis*), brown spectacled caiman (*Caiman crocodilus fuscus*), and black and white tegu (*Tupinambis merianae*). Most of these are harvested from the wild, with the top five exporters for the 2000 to 2004 period being Columbia, Argentina, Malaysia, the United States and, most of all, Indonesia (208). Import statistics for exotic leather skins of species listed by the United Nations Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) into Europe for the five-year period between 2000 and 2005 tabulated 3.4 million lizard skins, 2.9 million crocodile skins and 3.4 million snake skins (55). Trade data for the EU in 2005 for reptile skins alone totalled €100 million (US\$132 million), ranking the EU first in this category, with skins going principally to Italy, France and Germany (55). Some of the trade in skins is secondary to the trade in meat, for example, peccaries in Latin America and sharks, and thus these markets are linked but follow different trade pathways from source to consumer.

Ornamentals

Ornamental wildlife includes aquarium species, the companion animal trade, decorative products and hunting trophies. The examples are seemingly endless, and include a multi-billion-dollar global market for a variety of live animals and their parts and products, such as tropical fish and reptiles. The United States and Europe support an enormous trade in exotic companion animals. These species come from all over the world. Official importation records for the United States provided these numbers for 2006:

- 136,216 mammals
- 243,000 birds
- 1.3 million reptiles
- 4.6 million amphibians
- 222 million fish (228).

With such variation in specimens and source countries, regulation is a challenge.

Release pathways and hazard identification for wildlife diseases

Most microbe–wildlife interactions are harmless and present relatively few risks to humans or domestic animals. However, wildlife presents a risk to humans and domestic animals when it acts as a disease reservoir, intermediate host or biological amplifier (12, 16, 22, 25, 26, 41, 43, 49, 56, 78, 92, 96, 116, 160, 167, 177, 183, 190, 214, 220, 226). From an ecological standpoint, the release of diseases from wildlife often involves a number of co-factors, including ecosystem alteration (anthropogenic or natural) (44, 64, 105, 148) and climate change (17, 57), changes in the microbes themselves (22, 31, 41, 43, 44, 227) and movement of hosts, pathogens or disease vectors (anthropogenic or natural) (12, 63, 95, 98, 109). In addition, there has been a recent increase in the recognition of new pathogens from wildlife due to improved surveillance in some areas, and/or advances in diagnostic capabilities (22, 215).

Wildlife–human–domestic animal interactions broadly follow three major pathways:

- the increased direct exposure of people to wildlife, caused by the movement of one population into an area formerly dominated by the other (human encroachment into natural habitat or the expansion of wildlife or biological vectors into human habitation)
- persistent or increased contact between wildlife and domestic animals, highlighting transboundary disease issues of concern to regulatory medicine

- the risks inherent in the trade of wildlife and wildlife-associated products.

It is conceivable that the wildlife trade is the biggest risk factor in the global spread of zoonotic and emerging infectious diseases, and it is unarguably among the top-ranking modes of transmission (96). The United States alone imports hundreds of millions of live animals every year, mostly for the companion animal and aquarium trade, but also for specialty markets and research laboratories (89, 179). Invasive alien species pose a disease threat from multiple angles. Many species imported for food or the exotic companion animal trade are intentionally or inadvertently released and may harbour pathogens. In addition, these species may disrupt ecosystems, allowing for increased vulnerability to pathogens or creating favourable conditions for the emergence of a new pathogen (53, 228).

When the authors conducted a search for pathogens that were documented as having spread among animals (wild and domestic) or by zoonotic transmission as a result of the movement of wildlife, a variety of avenues for transmission were revealed. The intentional or accidental introduction of invasive species and housing animals from disparate parts of the world together (such as in zoological institutions, laboratory animal facilities or live animal markets) are two of the most common ways in which diseases move from one part of the world to another. Moreover, human encroachment or habitat alteration was associated with most of the emerging infectious diseases in Table I.

Types of movement were divided into seven pathways:

- the live animal trade
- trade in wild animal parts
- the research animal trade
- the accidental or intentional introduction of invasive species
- migration and expansion of habitat
- the bushmeat trade (both local and international)
- human encroachment into previously undisturbed habitats.

To refine this search, a preliminary list of ‘pathogens of concern’ was drawn up, including OIE-listed diseases, pathogens generally listed as ‘emerging’, or ‘select pathogens’, as defined by the Centers for Disease Control and Prevention (www.cdc.gov) or the World Health Organization (WHO) (www.who.int). Searches included the Google Scholar Engine (scholar.google.com/), as well as PubMed (www.ncbi.nlm.nih.gov/pubmed), BIOSIS Previews and CAB databases. Grey literature covering the wildlife ‘pet’ trade and emerging and zoonotic diseases of wildlife, people and domestic animals was also reviewed.

Table I
Documented transmission of wildlife diseases through the movement of wildlife

Disease (disease agent)	Political importance	Type of animal	Movement route	Reference
African tick bite fever (<i>Rickettsia africae</i>)	Zoonotic, EID	Ticks	HE	(90)
Aleutian disease (Aleutian mink disease virus)	Invasive	American mink	IS, LAT	(119, 120)
Alveolar echinococcosis (<i>Echinococcus multilocularis</i>)	OIE-listed, zoonotic	Foxes, other small carnivores	IS	(106)
Argentine haemorrhagic fever (Junin virus)	EID, zoonotic	Rodents	HE	(46, 74, 156)
Australian bat lyssavirus (Australian bat lyssavirus)	EID, zoonotic	Bats	HE	(44, 124, 125)
Avian malaria (<i>Plasmodium relictum</i>)	Invasive	Birds	IS	(206)
Avian poxvirus (<i>Poxvirus avium</i>)	OIE-listed	Birds	IS	(206)
Bohle iridovirus (<i>Bohle iridovirus</i>)	Invasive	Anurans, fish	LAT	(39)
Bolivian haemorrhagic fever (Machupo virus)	EID, zoonotic	Rodents	HE	(29, 138)
Bovine tuberculosis (<i>Mycobacterium bovis</i>)	OIE-listed OIE-listed OIE-listed	Ungulates Brush-tailed possums Rhinoceroses, monkeys	HE IS LAT	(151) (207) (186)
Brucellosis (<i>Brucella abortus</i>)	OIE-listed	Elk, bison	HE	(50)
Brucellosis (<i>Brucella suis</i>)	OIE-listed	Wild boar	LAT, HE, WAP	(70)
Cholera (<i>Vibrio cholerae</i>)	Zoonotic, invasive	Marine invertebrates, oyster-eating fish	IS	(47, 118)
Chytridiomycosis (<i>Batrachochytrium dendrobatidis</i>)	Invasive	Amphibians	LAT, RT, IS	(45)
Crayfish plague (<i>Aphanomyces astaci</i>)	Invasive	North American crayfish	IS	(4)
Ebola virus	Zoonotic, EID	Primates	BM	(111)
Ehrlichiosis (<i>Ehrlichia canis</i>)	EID, zoonotic	Wild canids, domestic dogs	HE	(2)
Ehrlichiosis (<i>Ehrlichia chaffeensis</i>)	EID, zoonotic	Deer, rodents, ticks	HE	(27)
Giant liver fluke (<i>Fascioloides magna</i>)	Invasive	North American wapiti	IS	(140)
Foot and mouth disease (<i>Aphthae epizooticae</i>)	OIE-listed	African buffalo	HE, LAT	(176)
Korean haemorrhagic fever (Hantaan virus)	Zoonotic, EID	Norway rat	IS	(107)
Hantavirus (Sin Nombre hantavirus)	Zoonotic, EID	Rodents	HE	(58)
Hendra virus	Zoonotic, EID	Fruit bats	HE	(44)
Hepatitis E virus	Zoonotic, invasive	Deer, wild boar	LAT, BM	(193)
Herpes B virus	Zoonotic	Macaques	RT, HE	(54, 86)
Elephant endotheliotropic herpesvirus	Invasive	African elephant	LAT	(166)
Human immunodeficiency virus	EID	Primates	BM	(67)
Infectious keratoconjunctivitis (<i>Mycoplasma conjunctivae</i>)	Invasive	Alpine chamois	IS	(68)
Influenza H5N1	OIE-listed, zoonotic OIE-listed, zoonotic	Crested hawk eagle Birds	LAT LAT	(203) (211)
Lagos bat lyssavirus	Zoonotic, EID	Bat	LAT	(30)
Leishmaniasis (<i>Leishmania</i> sp.)	OIE-listed, zoonotic	Wild canids	HE, LAT	(172)

Table I
Documented transmission of wildlife diseases through the movement of wildlife (cont.)

Disease (disease agent)	Political importance	Type of animal	Movement route	Reference
Leprosy (<i>Mycobacterium leprae</i>)	Zoonotic, invasive	Monkeys, rodents, armadillo	HE, LAT	(170)
Leptospirosis (<i>Leptospira</i> sp.)	OIE-listed, zoonotic	Wild/domestic mammals, rodents	HE, LAT	(192)
Malignant catarrhal fever (Alcelaphine herpesvirus 1, ovine herpesvirus 2)	OIE-listed	Wild ruminants	LAT, HE	(2)
Marburg virus	Zoonotic, EID	African green monkeys	RT, HE	(83)
Menangle virus	Zoonotic, EID	Grey-headed and little red fruit bats	HE	(152)
Monkeypox virus	Zoonotic	Rodents	LAT	(77)
Mycobacterial tuberculosis (<i>Mycobacterium</i> sp.)	Zoonotic, EID	Elephants	LAT	(133)
<i>Mycoplasma conjunctivitis</i> (<i>Mycoplasma gallisepticum</i>)	OIE-listed, invasive	Birds	ME	(112)
<i>Neospora caninum</i>	Zoonotic, invasive	Wild canids, ruminants, felines	ME, HE	(72, 73)
Nipah virus	Zoonotic, EID	Fruit bats	HE, ME	(56)
Paramyxovirus (Avian paramyxovirus types)	Invasive	Parrots, lovebirds, finches	LAT	(96)
Paratuberculosis (<i>Mycobacterium avium paratuberculosis</i>)	OIE-listed	Wild rabbits, red deer		(42, 65)
Phocine distemper virus	Zoonotic, invasive	Harp seals	ME, HE	(43)
Pilchard herpesvirus	Invasive	American pilchard	LAT, WAP	(212)
<i>Pseudamphistomum truncatum</i>	Invasive	Sunbleak and topmouth gudgeon fishes	IS	(154)
Psittacosis (<i>Chlamydia psittaci</i>)	OIE-listed, zoonotic	Parakeets, parrots, cockatiels	LAT	(137)
Rabbit haemorrhagic disease virus	OIE-listed, invasive	Wild European rabbits, domestic rabbits	IS	(110)
Rabbit myxomatosis virus	OIE-listed, invasive	Wild rabbits, domestic rabbits	IS, ME	(171)
Rabies virus	OIE-listed, Zoonotic	Kudu Raccoons Raccoon dog Marmosets	HE IS, ME, HE LAT, WAP LAT	(85) (225) (30) (61)
Ranavirus	Invasive	Amphibians	IS, LAT, WAP	(40, 187)
Rinderpest virus	OIE-listed	Ungulates	LAT, HE, ME	(48)
Salmonella (<i>Salmonella</i> sp.)	Zoonotic	Terrapins	LAT	(117)
Severe acute respiratory syndrome (SARS coronavirus)	EID, zoonotic	Bats, civets	LAT	(12)
Simian foamy virus	Zoonotic	Primates	LAT, BM	(222)
Squirrel parapoxvirus	Invasive	Grey squirrel	IS	(122, 197)
Steinhausiosis (<i>Steinhausia</i> sp.)	Invasive	Partula snails	IS, LAT	(43)
T-cell lymphotropic virus-1	Zoonotic	Primates	BM	(221)
Toxoplasmosis (<i>Toxoplasma gondii</i>)	Zoonotic, EID	Marine mammals, rodents, felids, ruminants	LAT, HE, ME	(51, 108)
Trichinella (<i>Trichinella native</i>)	OIE-listed, zoonotic	Bears	BM	(5)
Tularemia (<i>Francisella tularensis</i>)	OIE-listed, zoonotic	Hares, rabbits, rodents Prairie dog	IS HE	(218) (3, 9)
<i>Varroa jacobsoni</i>	OIE-listed	European honey bee	IS	(143)
West Nile virus	Zoonotic, EID	Birds, mosquitoes, mammals	ME, HE,	(100, 161)
<i>Yersinia pestis</i>	Zoonotic	Rodents, fleas, domestic cats	HE, IS	(230)

BM: bushmeat trade

EID: emerging infectious disease

HE: human encroachment or habitat alteration

IS: invasive species/introduced species

LAT: live animal trade

ME: migration or expansion of habitat

OIE: World Organisation for Animal Health

RT: research animal trade

WAP: wild animal parts

Wildlife disease risk assessment

In 1998, Samet *et al.* (175) introduced readers of the *American Journal of Epidemiology* to the 'new' methods of disease risk assessment. They stated that: 'while epidemiologists and epidemiological data may have prominent roles in [health risk assessments], the epidemiologic literature contains surprisingly few discussions of risk assessment'. Today, there has been progress in some areas. A search of keywords that combine the terms 'infectious disease' and 'risk assessment' on the PubMed database (October, 2010), returned 911 citations; while the terms 'risk assessment' and 'OIE' returned 36. 'Risk assessment' and 'OIE' and 'wildlife' returned only four citations. These four citations highlighted the risks associated with foot and mouth disease surrounding Kruger National Park in South Africa (93), suggested methods for wildlife hazard identification/prioritisation methodology in New Zealand (123) and the United Kingdom (80), and examined the role of bats in rabies ecology (33). On the other hand, wildlife is often included in risk assessments of zoonotic or regulatory diseases of domestic animals, particularly those of ungulates, suids and avian species. In these cases, wildlife experts are called on to assist and summaries often appear in the peer-reviewed literature (37, 76, 84, 98, 102).

Although formal disease risk assessments of the trade in wildlife, based on the methodology of the OIE (including release, exposure and consequence assessments), appear infrequently in the peer-reviewed literature, expanded search methods provide a great deal more information. Entering the search terms 'wildlife disease risk assessment and OIE and trade' into PubMed resulted in 'no items found', while the same terms entered into the Google internet search engine returned 18,800 results, many of which are downloadable reports and assessments completed by national governmental and non-governmental organisations. In fact, there are many well-constructed reports of this kind by various groups, such as agricultural and wildlife regulatory authorities, conservation organisations and even bioterrorism defence bodies, although locating and interpreting such reports often requires time and background knowledge of risk assessment methodology and terminology. These reports are of varying degrees of quality and transparency, requiring a great deal of time to assess their value.

Regulatory issues

Although the important role of wildlife in emerging disease ecology is well established, regulatory responsibility for wildlife is often unclear. As a result, wildlife issues often fall

'between the regulatory cracks', which often translates into a lack of organisation and funding for wildlife health policy in many countries. In addition, when policies are enacted, they are often reactionary rather than precautionary, leading to increased risk and costs of mitigation and control. A common exception is that of island nations, which often have particularly well-developed quarantine and pest protection procedures in place against invasive species. Even then, the existence of protocols does not ensure compliance. In general, wildlife is regulated by agencies dedicated to the management of natural resources, and is not under the purview of human or agricultural health officials. This means that health officials are commonly disengaged from those managing wildlife and exotic animals, making it difficult to organise proper wildlife health surveillance and risk assessment protocols. Exceptions occur in response to individual cases, such as regulation of the importation of rodents in the United States by the Centers for Disease Control in response to an outbreak of monkeypox, traced to the shipment of exotic animals destined for the companion animal trade. Regardless, despite a great deal of evidence that wildlife-associated diseases present significant potential risk to humans, domestic animals and other wildlife, they are still assigned a relatively low priority by many regulatory departments and officials.

Challenges and uncertainty

The high degree of uncertainty inherent in conducting wildlife risk assessments may limit their practical application. First, an overall lack of wildlife disease surveillance infrastructure (funding, people, expertise and equipment) limits the amount of data available for hazard identification. Insufficient wildlife population data (and even insufficient population estimation methodology, in many cases) often create uncertainty in the 'denominators' needed to calculate the important epidemiological rates used to assess baseline risk. Secondly, there are great logistical challenges involved in the collection of wildlife health data. Important wildlife reservoir species (e.g. rodents, bats, non-human primates) often live in remote places with little infrastructure, making sample collection, preservation and shipment a challenge. A lack of adequate diagnostic methodology for many wildlife species and emerging diseases can make it difficult to establish baselines and case definitions for outbreak investigations. Finally, incomplete wildlife trade pathway data limit the ability to conduct release and exposure assessments, even when important disease hazards have been identified (e.g. SARS). Although pathways of legally traded wildlife may be relatively easy to follow, there is usually limited information on the point of origin and health history. Individuals are rarely uniquely identified, making trace-back almost impossible, and are often shipped in groups, with little thought to stress reduction or

disease exposure during transit. Thus, risk at export does not always equal risk at import.

There may be health protocols (e.g. quarantine and testing) in existence, but compliance is uncertain since wildlife units are often underfunded and understaffed. In addition, even when risk mitigation programmes exist for legal trade, the unknowable magnitude of illegal trade makes it hard to ascertain what percentage of the real risk is accounted for. Since pathway assessments often help to prioritise potential mitigation strategies, uncertainty in this area limits the effectiveness of both risk assessment and risk mitigation techniques in these cases.

Collaborative opportunities

Although few wildlife disease risk assessments have been conducted in accordance with OIE risk analysis standards, information on wildlife disease risk may be found in the substantial literature available from other disciplines. These include epidemiological risk factor studies, wildlife disease investigations conducted by field biologists, and disease ecology modelling conducted by conservation biologists and ecologists. Much of the literature focuses on the risk of disease emergence and the interaction of wildlife within a specific pathway of concern. Other publications focus on the biology, ecology or epidemiology of specific diseases, all of which could be considered assessments of risk, although not specifically 'risk assessments', *per se*. A few examples include public health studies examining the risk of cross-species transmission as a result of contact with wildlife during international travel (121, 139), through bushmeat hunting and exotic animal consumption (1, 95, 127, 134, 219, 221, 222) or via exotic companion animal ownership (3, 9, 28, 30, 38, 52, 162) or xenotransplantation (145). Some of these mechanisms are now also being examined at the molecular level (147, 182). There is a vast body of literature on the risk of domestic animal-wildlife interactions, resulting in the spread of animal regulatory diseases (15, 19, 21, 34, 36, 93, 98), and growing concern about risks associated with commonly found wildlife products (13, 14, 23, 132). Aquatic animal health risk assessment is a growing field, with assessments published on wildlife interaction in fisheries (7), aquaculture facilities (20), fish translocation (62) and international trade (82), as well as shrimp farming (113) and basic aquatic animal health management and hygiene (150).

Ecologists are increasingly applying models of climate change (66, 155), vector distribution and abundance (10, 11, 165), invasive species (6, 87, 163) and avian migration (94, 99), as well as land use and ecosystem services (18, 142, 164, 181), to find solutions to the risk of disease emergence and spread. Conservation biologists, zoologists and veterinarians are now more concerned about disease

when discussing the preservation, recovery, translocation or reintroduction of endangered species (50, 109, 223, 224), and often specifically aim to integrate their methods with those of epidemiologists (104). Finally, there is a growing body of literature discussing the issue of wildlife trade and disease emergence and spread; much of this being a reaction to concerns surrounding Ebola virus and avian influenza (63, 71, 96, 97, 149, 185, 191, 206).

The way forward

It is now well established in the global community that wildlife disease matters and that severe consequences have occurred, and are still occurring, as a result of human and domestic animal exposure to wildlife. It has also been established that these diseases are very difficult to control, even in developed countries (8, 217). Of the three basic pathways of exposure to wildlife (direct exposure of humans to wildlife due to human encroachment into previously wild areas; increased co-mingling of domestic animals and wildlife due to changes in land use; and through the increasing volume of international movement of wildlife), trade is probably the pathway with the highest potential for exposure and with the least inherent control. Thus, collaborations must be strengthened to harness the great resources needed to improve the science of wildlife disease risk analysis. This, in turn, will help facilitate the development of effective policy in the face of rapidly changing risk. This can be accomplished by focusing on four areas:

- network development
- methodology development
- data acquisition
- policy formulation.

There have been many calls for such collaboration in recent years. Success on this front will require reconciling the ethics and values of multiple disparate disciplines (economists, regulatory officials, conservationists, public health practitioners, ecologists, veterinarians and wildlife biologists, to name a few). Solutions will only come through a transdisciplinary approach to this problem (146), and thus it should be the mandate of the OIE Working Group on Wildlife Diseases to foster these discussions and connections. Once proper partnerships and working relationships are established, wildlife disease risk assessment methodology must be enhanced and standardised, to some degree, as this will allow for greater transparency and repeatability, enhancing the reliability of the process and its potential for publication (135, 196, 200, 210).

Elegant models are only partially useful without quality data. Fortunately, a great deal of funding is currently being dedicated to increasing the amount of wildlife disease data

and diagnostics available on a global scale (201). There are also efforts to improve wildlife disease hazard identification and surveillance methods (123, 129, 131, 224). However, there are still questions about the usefulness of regarding wildlife as sentinels for human disease (159). For this reason, depending on human health needs to drive the funding for wildlife disease surveillance (as in the cases of Nipah virus, Ebola virus, SARS and West Nile virus, for instance) is not sustainable.

Wildlife questions are big and complex. Thus, unique approaches, requiring significant investment and sustained political support, are required immediately to address the issues presented in this paper. Novel relationships, such as public-private partnerships and international coalitions, must continue to be explored to aid in aligning objectives among differing interests while continuing to foster the 'One Health' philosophy currently in vogue. New partnerships among those with previously disparate or competing interests, such as international-trade-regulating bodies (e.g. CITES, the World Bank and the World Trade Organization), and continuation of fledgeling partnerships between international health agencies (WHO, the Food and Agriculture Organization of the United Nations and the OIE), created under the strain of recently emerging

zoonotic diseases, must take a proactive lead and be supported, both politically and financially. Finally, models aimed at addressing complex wildlife questions must include input from numerous disciplines not usually included in the OIE-based risk assessment process, including expertise in land use planning (148), wildlife use and natural resource management (101), international conservation ethics, international regulation of wildlife trade and macro- and micro-economics, amongst many others (35). Regionally and locally, this means that wildlife must have a clear place in the regulatory framework of nation states. Ideally, this would allow for the fostering of respect for the preservation of natural resources while simultaneously addressing real-world disease risks and concerns at a global level.

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La dissémination d'agents pathogènes lors des échanges internationaux d'animaux sauvages

D.A. Travis, R.P. Watson & A. Tauer

Résumé

Les discussions sur les maladies de la faune sauvage font généralement référence à deux modèles fondamentaux : le premier privilégie les effets des maladies sur la faune sauvage, tandis que le deuxième prend en compte le rôle de faune sauvage dans les maladies qui affectent la santé publique, la santé et le bien-être des animaux domestiques, l'économie et le commerce. En règle générale, les spécialistes de la faune sauvage et les défenseurs de la nature s'inspirent du premier modèle, tandis que la plupart des spécialistes de la santé humaine et animale s'intéressent surtout au second. Depuis quelque temps, l'émergence et la réémergence de plusieurs maladies infectieuses complexes dans un environnement de plus en plus mondialisé ont conduit à rechercher une méthode plus holistique pour évaluer et atténuer les risques sanitaires associés à la faune sauvage (avec une expansion concomitante des articles scientifiques consacrés à cette question). Les auteurs examinent le rôle de la faune sauvage dans l'écologie des maladies infectieuses, l'ampleur extraordinaire des mouvements d'animaux sauvages et de leurs produits suite aux échanges

internationaux, les voies des déplacements d'animaux sauvages et le volume croissant des évaluations du risque faisant appel à diverses disciplines scientifiques. Pour conclure, ils font le point sur les recommandations actuelles et proposent quelques solutions pour aller de l'avant dans une perspective de collaboration.

Mots-clés

Commerce international – Évaluation du risque – Faune sauvage – Maladie animale – Maladie des animaux sauvages – Mondialisation – Trafic de faune sauvage – Zoonose.



Propagación de agentes patógenos por el comercio de animales salvajes

D.A. Travis, R.P. Watson & A. Tauer

Resumen

Las reflexiones sobre las enfermedades de los animales salvajes se han venido centrando en general en dos modelos básicos: los efectos de determinada enfermedad en la fauna salvaje; y la función que ésta desempeña en las patologías que inciden en la salud o el bienestar de personas y animales domésticos, en la economía o en el comercio. Históricamente, los profesionales que trabajan con animales salvajes y los ecologistas se han preocupado sobre todo del primer aspecto, mientras que la mayoría de los especialistas en salud humana o animal se han centrado sobre todo en el segundo. En los últimos tiempos, el (re)surgimiento de muchas enfermedades infecciosas de gran relevancia, en un mundo cada vez más globalizado, ha traído consigo un planteamiento más holístico a la hora de determinar y atenuar los riesgos sanitarios ligados a la fauna salvaje (junto con abundantes artículos científicos al respecto). Los autores examinan el papel de los animales salvajes en la ecología de las enfermedades infecciosas, la sorprendente magnitud de los desplazamientos transfronterizos de animales salvajes y sus derivados a resultas de transacciones comerciales, las rutas que siguen esos desplazamientos y el creciente acervo de determinaciones del riesgo acometidas desde una multitud de disciplinas. Por último, destacan las recomendaciones existentes en la materia y proponen soluciones para avanzar de forma colegiada.

Palabras clave

Comercio – Determinación del riesgo – Enfermedad de la fauna salvaje – Enfermedad infecciosa – Fauna salvaje – Mundialización – Tráfico de animales salvajes – Zoonosis.



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