IN-DEPTH ANALYSIS

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The link between biodiversity loss and the increasing spread of zoonotic diseases

Policy Department for Economic, Scientific and Quality of Life Policies
Directorate-General for Internal Policies
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The link between biodiversity loss and the increasing spread of zoonotic diseases

Abstract

Over the last decades, a variety of fatal infectious diseases have had zoonotic origins. The linkages between hosts, vectors, parasites and pathogens can be influenced by a multitude of factors, such as biodiversity, wildlife and land use.

High levels of biodiversity may be a potential source of pathogen transmission, but biodiversity loss can also promote transmission by increasing the number of competent hosts for a pathogen.

Biodiversity conservation reduces the risk of zoonotic diseases when it provides additional habitats for species and reduces the potential contact between wildlife, livestock and humans. Additionally, host and vector management is a viable option.

Other crucial measures include the restriction and sanitary control of wildlife trade, while considering the needs of indigenous peoples and local communities.

Each case requires an assessment of the best way to reduce risk while considering implications for other ecosystem functions or services.

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CONTENTS

LIST OF FIGURES **4**

LIST OF BOXES **4**

LIST OF TABLES **4**

INTRODUCTION **5**

1. RISKS ASSOCIATED WITH ZOONOTIC DISEASES **6**

2. MAIN INTERACTIONS BETWEEN BIODIVERSITY AND ZOONOTIC DISEASES **12**

2.1. Interactions in areas with limited human influence 13

2.1.1. Wildlife in its natural habitats 13

2.1.2. Fragmentation and degradation of natural habitats 14

2.1.3. Natural areas in close proximity or inside human settlements 15

2.2. Interactions in areas under anthropogenic influence 16

2.3. Interactions due to wildlife hunting and wildlife trade 17

3. CONCLUSIONS AND POLICY OPTIONS **19**

3.1. Policy options for areas with limited human influence 19

3.2. Policy options for areas under anthropogenic influence 20

3.3. Policy options connected to wildlife hunting and wildlife trade 21

REFERENCES **23**

LIST OF FIGURES

Figure 1: Illustration of the dilution effect 13

LIST OF BOXES

Box 1: Glossary 6

LIST OF TABLES

Table 1: Examples of zoonotic diseases found outside their native habitats 8

Table 2: Emerging zoonotic diseases and human-animal interface 10

Table 3: Cases of exposure to zoonotic diseases in livestock production 10

INTRODUCTION

Over the last decades, a variety of fatal infectious diseases, including Human immunodeficiency virus infection and acquired immunodeficiency syndrome (HIV/AIDS), avian influenza, Ebola, Severe acute respiratory syndrome (SARS), and most recently Coronavirus disease 2019 (COVID-19)[1], have had zoonotic origins.

In 2020 the COVID-19 pandemic has raised global awareness regarding the risks and dramatic consequences related to the emergence of zoonotic diseases. The potential causes for the pandemic (including direct or indirect roles of biodiversity wildlife and land use) have been gaining importance since decades, however, they were discussed only among experts and have not been at the forefront of general and political discussions.

The response to the current acute pandemic has mainly focused on containment and treatment. Containment measures have shown a dramatic social and economic impact on most societies according to the recent IPBES Workshop Report on Biodiversity and Pandemics. As in so many other cases, prevention is clearly more efficient than treatment and we need to better understand the conditions that favour or contribute to the emergence and spread of zoonotic disease in order to prevent it.

This in-depth analysis aims at supporting the European Parliament to understand which areas of action could result in a lower risk of zoonotic diseases. We therefore provide an overview over existing assessments showing the complex links between biodiversity and zoonotic disease risk and try to address the following questions:

- Which risks are associated with zoonotic diseases?
- Which are the most prominent interactions between biodiversity and zoonotic diseases?
- Which areas of action could help reducing the risk?

Especially the question of potential sets of measures is a complex one, due to the myriad of interactions in play, often combining positive and negative effects on the risk of zoonotic diseases and on biodiversity. This paper thus focusses on providing an overview of the complexity of the topic and potential ways forward in several policy areas, in and outside the territory of the European Union.

[1] Andersen et al. 2020, Wu et al. 2020.

1. RISKS ASSOCIATED WITH ZOONOTIC DISEASES

Between 1940 and 2004, more than 300 events of emerging disease in humans have been identified worldwide[2] either from pathogens that have evolved into a new strain within the same host species or that have switched to new host species.

A variety of deadly infectious diseases emerged, such as HIV-AIDS, avian influenza, Ebola, SARS and COVID-19[3].

Many of the pathogens causing these diseases jumped to humans in natural areas (forests, wetlands) after human encroachment, but soon travelled to other areas of the world.

For example, the West Nile virus is a mosquito-borne flavivirus and human and avian neuropathogen that is native to parts of Africa, Asia, Europe and Australia and maintained in nature in a mosquito–bird–mosquito transmission cycle[4]. It was first detected in the West Nile district of Uganda in 1937.

Box 1: Glossary

Definitive host: The human population, when a pathogen is transmitted from another species to humans.

Dilution effect: describes a situation where higher species diversity leads to a lower disease risk due to reduction of pathogens in certain hosts.

Ecosystem services: the many and varied benefits to humans provided by the natural environment and from healthy ecosystems

Emerging diseases: diseases caused by pathogens that have evolved into a new strain within the same host species or that have switched to new host species

Habitat/Forest fragmentation: The process that leads to discontinuities in the habitat of a species. Habitat fragmentation often results from human activities, such as land conversion (Fahrig 2003).

(Wildlife–livestock–human) interfaces: areas with a higher potential for interaction between wildlife, livestock and humans that can lead to spillover of zoonotic diseases

Reservoir host: Non-humans hosts for a certain zoonotic disease that can be transmitted directly or indirectly through a vector (e.g. a mosquito).

(Reservoir host) competence: The potential of a species to support and transmit pathogens (Huang et al. 2013a).

(Pathogen) spillover: Occurs when a reservoir host population carrying a high number of pathogens comes into contact with a novel host population. The pathogen is transmitted from the reservoir population and may be transmitted within the new host population

Recombination: Refers to the exchange of genetic material between different organisms, which leads to production of offspring with combinations of traits that differ from those found in either parent. The new pathogens may become suddenly very dangerous for people.

Vector: Species that transmits a pathogen between the reservoir and the definitive hosts.

Zoonotic disease: disease in humans caused by a pathogen that has jumped from an animal to a human.

Source: Authors' own elaboration.

[2] Jones et al. 2008.

[3] Wang & Eaton 2007, Allen et al. 2017, Andersen et al. 2020, Wu et al. 2020.

[4] Campbell et al. 2002.

The 1999 New York City outbreak caused an estimated 8200 human infections, resulting in approximately 1700 cases of West Nile fever[5], and was the start of a large epidemic in North America. The virus reached the US west coast in 1999. In the next eleven years, between 1999-2010, 1.8 million people were infected, with 360,000 illnesses, 12,852 reported cases of encephalitis/meningitis, and 1,308 deaths[6].

Zoonotic diseases are generally divided in three groups[7]:

- directly-transmitted diseases, for which the reservoir host (that is not significantly harmed by the pathogen) transmits the pathogen directly to the definitive host (a human who suffers disease);
- vector-borne diseases (the vector transmits the pathogen between the reservoir and the definitive host); and
- diseases caused by parasites.

Definitive hosts are always humans.

Reservoir hosts are often:

- Rodents,
- Bats,
- Carnivores,
- Birds,
- Reptiles, or
- Snails.

Vectors are usually:

- Mosquitos,
- Sandflies,
- Ticks,
- Birds,
- Snails, or
- Small mammals such as rodents.

The pathogens involved include:

- Viruses,
- Bacteria, and
- Fungi.

Parasites include:

- Nematodes, and
- Protozoans (single-cell organisms).

[5] Petersen et al. 2007.

[6] Kilpatrick 2011.

[7] Huang et al. 2017; Rabitsch et al. 2017.

The linkages between hosts, vectors, parasites and pathogens are complex and can be influenced by environmental conditions. Spillover (when a pathogen infects a new host) or spillbacks (when an alien species is introduced into an ecosystem and becomes a host for a native pathogen) can involve several combinations of interactions between native and non-native organisms. Such dynamics are often promoted by drivers of global change, such as climate change, ecosystem degradation or even recovery, among others[8].

Table 1: Examples of zoonotic diseases found outside their native habitats

Disease	Pathogen/ Parasite	Trans-mission	Examples of reservoir host species	Origin	Examples of non-native occurrence
Bovine tuberculosis	*Mycobacterium bovis*	Aerosol transmission	African buffalo, Greater Kudu, Cattle, Bison, Elk, and Deer	African countries	Worldwide
Chikungunya fever	Chikungunya virus	Mosquitos	Humans, Rodents, Birds, other small Mammals	Africa-Asia (India)	Asia, Africa, Europe and the Americas
Dengue Fever	Dengue virus	Mosquitos	Humans, Primates	Tropical	Europe, the Americas
Dirofilariasis	*Dirofilaria repens*	Mosquitos	Dogs (and other Carnivores)	Southern Europe Africa, Asia	Europe
Hantavirus pulmonary syndrome	Andes virus	Aerosol transmission	Sigmodontine rodent, *Abrothrix longipilis, Abrothrix olivaceus, Loxodontomys micropus*	The Americas	Europe, the Americas
Leishmaniasis	*Leishmania* spp.	Sand flies	Dogs, Rodents	(Sub) Tropical, Southern Europe	Europe, North America
Lyme disease	*Borrelia burgdorferi*	Ticks	White-footed mice, Eastern chipmunks, Short-tailed shrews	North America	Northern Hemisphere

[8] Rabitsch et al. 2017.

Disease	Pathogen/ Parasite	Trans-mission	Examples of reservoir host species	Origin	Examples of non-native occurrence
Malaria	*Plasmodium* spp.	Mosquitos	Humans	Africa, (southern Europe)	Tropical and subtropical areas
Plague	*Yersinia pestis*	Fleas	Small mammals	China	Worldwide except Oceania
Usutu fever	Usutu virus	Mosquitos	Birds species, Humans, Horses, and other Mammals	Africa	Europe
West Nile fever	West Nile virus	Mosquitos	Birds (e.g. Blue Jay, Common Grackle, House Finch, American Crow, House Sparrow, American Robin)	Africa, West Asia and the Middle East, Australia, parts of Europe	Americas, parts of Europe
Yellow fever	Yellow fever virus	Mosquitos	Monkeys, Humans	Africa	Africa and Central and South America
Zika fever	Zika virus	Mosquitos	Monkeys	Africa-Asia	Africa, the Americas, Asia and the Pacific

Source: Rabitsch et al (2017); States et al. (2014); Huang et al. (2013a); Piudo et al. (2011); Allan et al. (2009); Allan et al. (2003); https://www.who.int/; https://www.cdc.gov/ (both accessed 17.11.2020).

Several of the most relevant reservoir hosts described in scientific literature are often susceptible to drivers of biodiversity loss, such as land use change. Rodents, for instance, interact closely with humans and livestock. Carnivores are especially important in case of urbanisation, also in Europe, as is the case for *Echinococcus multilocularis*, a tapeworm found in foxes. Non-human primates are relevant in Africa and Asia, while bats are especially important for their ability to travel large distances and predisposition to hold close contact with their peers. Livestock itself can be a reservoir host for several zoonotic diseases mentioned in Table 1[9].

Live animal markets, wildlife hunting, intensive wildlife farming (farming of e.g. deer, rodents, civets, mangooses, fur mammals, ostriches), and domestic animals are the most common animal-human interfaces for the emerging zoonotic diseases; resulting in spillover to humans (Table 2). Pathogens can

[9] White & Razgour 2020.

be transmitted through consumption, medicinal use, handling of the living animal or slaughtering and/or preparation of the meat for sale or consumption.

Table 2: Emerging zoonotic diseases and human-animal interface

Probable animal-human interface	Emerging zoonotic disease
Live animal markets	SARS, COVID-19, Avian influenza
Wildlife hunting	HIV, Ebola
Intensive wildlife farming	COVID-19, Rabies, Avian influenza
Domestic animals	Hendra, Nipah, Avian influenza

Source: Magouras et al. (2020).

Livestock are without doubt the animals with most contact to humans, and therefore play a particular role for transmissions. A systematic review[10] revealed sixteen zoonotic diseases that are transmitted via livestock to humans (Table 3). The occurrences observed more often were Methicillin-resistant *Staphylococcus aureus*, which can cause pneumonia, meningitis, osteomyelitis, endocarditis, toxic shock syndrome, different forms of Avian influenza and *Coxiella brunetii*, which in serious cases could cause pneumonia or hepatitis. The humans mostly exposed were those working in close contact or proximity to the reservoir hosts or those in close contact with farm and livestock workers[11].

Table 3: Cases of exposure to zoonotic diseases in livestock production

Pathogen/zoonotic disease	Animals involved	People infected
Antibiotic Resistant *Escherichia coli*	Pigs	Consumers, Pig workers, Slaughter-plant workers
Avian metapneumovirus	Turkeys	Growers and Processing workers
Blastocystis	Pigs	Pig farm workers
Brucella spp.	Sheep, Goats	Vets, Sheepherders, Lab technicians
Campylobacter spp.	Cattle	Dairy workers, Resident children
Chlamydophila psittaci	Chickens, Turkeys	Slaughterhouse workers

[10] Klous et al. 2016.

[11] Klous et al. 2016 & ww.cdc.org, accessed on 22.11.2020.

Pathogen/zoonotic disease	Animals involved	People infected
Coxiella burnetii	Cattle	Farmers, Vets, Inseminators, Hoof-trimmers
Cryptosporidium parvum	Cattle, Buffalos	Students and Teachers camping on a farm
Cryptosporidium parvum	Cattle	Farm workers, Household members
ESBLI-Enterobacteriaceae	Poultry	Residents in a high and low poultry density area
H5N1, H7N7 Avian influenza	Turkeys, Layers, Broilers, Poultry	Cullers, Cleaners, Biosecurity managers, Poultry workers, Non-exposed controls
Hepatitis E virus	Cats, Chickens, Deer, Goats, Horses, Pigs, Sheep	Pigs slaughterers, Meat inspector
MRSA (Methicillin-resistant *Staphylococcus aureus*)	Pigs	Pig farmers, Processing plant workers, Family, residents
Orf virus	Sheep, Goats	People illegally slaughtering animals
Swine influenza	Pigs	Swine workers
Trichophyton verrucosum	Cattle	Animal workers

Source: Adapted from Klous et al. (2016).

The examples mentioned above show how, through international travel, wildlife hunting and trade, intensified livestock production or intensified contact between wildlife and humans, zoonotic pathogens can easily spill over from reservoir hosts to humans, either through a vector or directly. Chapter 2 aims at showing different kinds of interactions between biodiversity and zoonotic diseases.

2. MAIN INTERACTIONS BETWEEN BIODIVERSITY AND ZOONOTIC DISEASES

The idea that the diversity of an ecosystem has an effect on the transmission of pathogens dates back to more than 60 years ago. In 1958, Charles S. Elton observed that 'outbreaks (of infectious diseases) most often happen on cultivated or planted land... that is, in habitats and communities very much simplified by man'. Understanding how biodiversity influences pathogen transmission has long been a central question in disease ecology.

Intensified transnational trade and international travel can be identified as the most prominent drivers for the occurrence of zoonotic diseases outside their native environments. Among the most prominent examples of a zoonotic disease vector being introduced to Europe is the Asian tiger mosquito, *Aedes albopictus*. This insect is an aggressive daytime biting mosquito that is emerging throughout the world as a public health threat due to its relevance in (among others) West Nile virus, dengue virus and chikungunya virus outbreaks[12]. It was introduced with the used tyre and ornamental plant trade from its native range in East Asia and has established on every continent except Antarctica during the last decades, including Europe (1979), the continental USA (1985) and Central and South America (1980–1990s)[13]. Climate change can act as a promoting factor for the establishment of novel vectors, such as certain mosquito species in temperate European regions[14]. Increased exposure of humans, reservoir hosts such as rodents or livestock to wildlife due to habitat fragmentation or deforestation in tropical areas adds to the risk of spillover of zoonotic diseases.

However, there is still no definite consensus on how biodiversity affects infectious diseases. This depends highly on the type of pathogen and how it is transmitted. For directly transmitted diseases like HIV, measles and human tuberculosis, a change in biodiversity may have no effect at all. For pathogens such as the West Nile virus, on the other hand, changes in biodiversity can have effects because this virus infects not only humans or primates, but also several bird species. This applies also to the hanta virus, which infects not only humans but also several mammals, and to leptospirosis, which is transmitted by excrements from rats. Further complexity gets added, because vectors that interact with several hosts on a regular basis are potentially less affected by changes in biodiversity than vectors with a limited number of hosts. Additionally, genetic impoverishment of wildlife populations in degraded and fragmented habitats can imply low immunity and thus increase competence for pathogens[15]. The size of these wildlife habitats and their closeness and connectivity to neighbouring areas of wildlife has an effect on the diversity of host species and occurrence of competent hosts and pathogens. These also adds to the potential risk of spillover[16].

Natural and anthropogenic ecosystems and processes therein are very much interlinked, particularly in relation to zoonotic diseases and their spillover to humans. To try to exemplify the different interlinkages, in the following, we structure the relevant processes into:

i) processes occurring mainly in natural area with limited human influence (chapter 2.1.),

[12] Bonizzoni et al. 2013.
[13] Medlock et al. 2012; Bonizzoni et al. 2013.
[14] Schindler et al. 2018.
[15] Rohr et al. 2020.
[16] Hassell et al, 2017.

ii) processes occurring mainly in areas under anthropogenic influence such as agricultural land (chapter 2.2.),

iii) processes in particular situations, where humans get in strong contact to wild animals , e.g. in wildlife trade and wet markets (chapter 2.3.).

2.1. Interactions in areas with limited human influence

This chapter presents examples found in scientific literature on interlinkages between biodiversity and the risk of zoonotic diseases for humans.

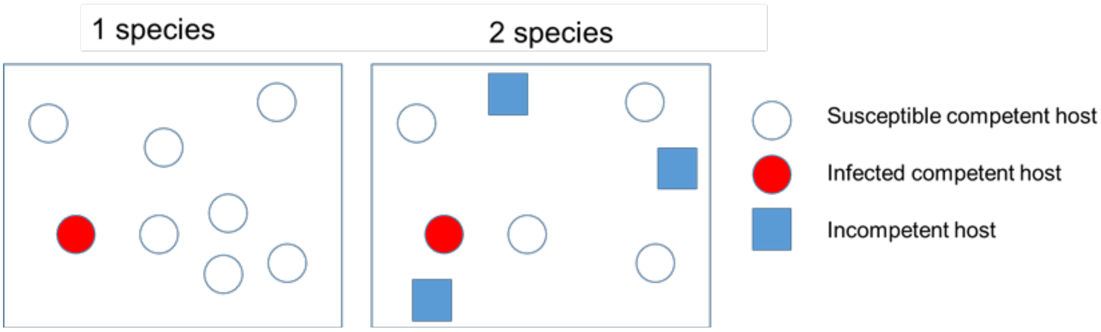
2.1.1. Wildlife in its natural habitats

The effects of wildlife diversity on pathogen transmission can vary, depending on the pathogen and its natural occurrence in wildlife. Wildlife is the main reservoir for emerging zoonotic diseases, and often functions as the agent spreading the pathogen[17].

High levels of biodiversity can imply more pathogen transmission. High levels of biodiversity may provide a large potential source of (novel) pathogens, and can promote pathogen transmission, for example by a high diversity and abundance of vectors (e.g., ticks, mosquitos). This is known as the hypothesis that "diversity begets diversity". Generally, countries with high biodiversity tend to have high disease burdens[18]; but also in temperate regions, the establishment of invasive alien species can lead to increased levels of risk of zoonotic diseases spilling over to livestock and humans[19].

Reduction in biodiversity can mean higher or lower pathogen transmission. However, less biodiversity of certain species can also promote pathogen transmission. For example, if an ecosystem loses species that were incompetent or suboptimal hosts for a certain pathogen, the remaining competent hosts will occur in higher densities. This is related to the so-called "dilution effect" (see Figure 1 for an illustration).

Figure 1: Illustration of the dilution effect



Note: In an area with two species (right-hand side) with competent and incompetent susceptible host (white circles and blue squares), the infected animal (red circle) has lower probability to encounter a competent host than in an area with only competent hosts (left-hand side).

Source : Authors' own elaboration.

[17] Johnson & Thieltges 2010, Keesing et al. 2006, 2010.

[18] Wood et al. 2017.

[19] Rabitsch et al. 2017, Schindler et al. 2018.

With less incompetent hosts, an encounter of an infected animal or an infected vector with a susceptible host happens more often and therefore the pathogen spreads better. This increases the risk of spillover to livestock or humans[20].

In a similar way, when many competent hosts vanish whereas many incompetent hosts remain, the transmission ends because pathogens are more likely to end up in incompetent hosts[21].

2.1.2. Fragmentation and degradation of natural habitats

Undisturbed habitats often have a high diversity of both animals and pathogens[22]. Deforestation and the shift of natural areas to human-dominated areas result in large-scale loss or degradation and fragmentation of habitats and wildlife populations[23]. The resulting remnants of natural areas show increased risk for zoonotic diseases. An example is the spread of Lyme disease as a result of the growing populations of white-tailed deer and white-footed mice in a landscape devoid of large predators[24]. Fragmented habitats can also lead to an increase of host movement from the patches of nature into areas used for livestock and urban settlements[25]. The increasing human encroachment in fragmented natural areas (including livestock grazing) promotes higher contact rates between pathogens and vectors, with domesticated animals and humans.

The edges of the remaining natural areas are thought to be major launch pads for novel viruses that may spill over to humans[26]. Roadless areas, which are highly relevant for the preservation of native biodiversity by ensuring habitat for viable populations, and by functioning as a barrier against invasive alien species and other human influences, are therefore also highly relevant for disease control[27]. For example, the length of the edges of remaining forests increases when humans start developing areas by building roads. In these edges, humans and their livestock are more likely to come into contact with wildlife, especially in areas with a reduction of more than 25% in forest cover[28]. Road building, expansion of human settlements, and livestock and arable land close to remaining forests have led to increasing pathogen spillovers. For example, bats are the probable reservoirs of Ebola, Nipah, SARS, and the virus behind COVID-19. Fruit bats are more likely to feed near human settlements when their forest habitats are disturbed; this has been a key factor in viral emergence in West Africa, Malaysia,

[20] Randolph and Dobson 2012, Huang et al. 2017.

[21] Keesing et al. 2010.

[22] Han et al. 2016, Mollentze & Streicker 2020.

[23] Fahrig 2003; Newbold et al. 2015.

[24] Allan et al. 2003.

[25] e.g. Suzán et al. 2008.

[26] Dobson et al. 2020.

[27] See: The Roadless Area Initiative, launched in 2007 by the Policy Committee of the Europe Section of Society of Conservation Biology (SCB), www.roadless.online/roadless-areas

[28] Faust et al. 2018.

Bangladesh and Australia[29]. Another example related to forest edges is the community of mosquitos that are vectors for many diseases. The creation of grasslands for livestock grazing adjacent to rainforests increases the risk of transmission from mosquitos to livestock[30]. This is also the case for increased risk of Malaria in newly created forest edges in Peru, of the American Cutaneous Leishmaniasis in Costa Rica and of the hantavirus in Panama[31].

Urban systems can be seen as conglomeration of different areas, in which humans, vectors, livestock and wildlife interact with each other at different degrees. These areas of interaction, or so-called interfaces, can be e.g. forest edges, borders between wildlife areas and refuse dumps, sewage plants, parks and green recreational areas, etc. They do not necessarily imply the occurrence of spillover of pathogens to humans. However, paired with knowledge on the existing populations of humans, wildlife, vectors and livestock and their mobility, such interfaces can serve as an indication of risk for zoonotic diseases. Changes in land use can bring a more patchy structure of habitats for wildlife. The border or transition areas between these patches bring a larger potential for interaction between humans, vectors, hosts and pathogens.

2.1.3. Natural areas in close proximity or inside human settlements

An example of vicinity of areas with high densities of wildlife and high densities of humans are lakes and wetlands that host a large variety of waterbirds. Lakes and wetlands often supply ecosystem services, such as water for the humans population or agriculture. The supply of such ecosystem services tends to foster the development of cities, raising the potential for contact between humans and e.g. migratory waterbirds. Migratory waterbirds are known to transport several pathogens including avian influenza that originated in wild birds and was transmitted to humans via poultry[32]. Lakes and wetlands are also crucial for vectors such as mosquitos and thus are considered as areas with high risk for pathogen transmission. For this reason, drying up wetlands was considered an adequate response to the risk of zoonotic diseases during centuries, until the related loss of services provided by these ecosystems, such as water supply, climate mitigation and adaptation, conservation of biodiversity, recreational purposes, etc., got noted in recent decades.

Also other kinds of ecosystems show diverse species communities in vicinity of densely populated areas, such as remnants of natural area and green spaces that form part of cities or are located in their vicinity. In some cases there is poor understanding whether wildlife inhabiting these areas can safely co-exist with people. These areas are also becoming increasingly important for wildlife, because diminishing natural areas no longer provide sufficient habitat for many species, and some pressures to biodiversity such as direct persecution are reduced in the urban context. Some species are attracted to peri-urban and urban areas due to the abundance of food and the presence of structures in which to shelter.

In Europe and other temperate areas, besides rats, mice and cats, coyotes, foxes and wild boars increasingly colonize urban areas and serve as reservoir hosts for zoonotic diseases. For instance, about 8% of the reported red foxes in Estonia exhibited symptoms of sarcoptic mange, a disease that also infects domestic animals, especially dogs[33]. The proportion of mange-infected foxes was higher in the

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[29] Plowright et al. 2011, Pulliam et al. 2012, Olivero et al. 2017.

[30] Steiger et al. 2012.

[31] Gottwalt 2013.

[32] Bi et al. 2016, Li et al. 2017.

[33] Plumer et al. 2014.

largest urban areas. In addition to mange, a substantial fraction of red foxes in Estonia was known to be infected with the life-threatening tapeworm Echinococcus multilocularis, the causative agent of alveolar echinococcosis. Therefore, urban foxes may represent a source of serious infectious diseases for pets and humans.

Wild boar have ventured into northern regions due to climate change and less harsh winters, and have been involved in the transmission of foodborne zoonotic diseases such as brucellosis[34], salmonellosis, tuberculosis, yersiniosis, toxoplasmosis, trichinellosis and hepatitis E.

Excrement samples of coyotes (Canis latrans) in periurban areas in Manitoba (Canada) have been reported to contain the tapeworms E. multilocularis and E. canadensis, which can affect humans. E. multilocularis, for instance may result in a condition in humans with poor recovery prognosis. Even though the tapeworm hadn't infected dogs, the risk was considered high enough to recommend higher surveillance of the tapeworm and if necessary sanitary measures[35]. A similar case refers to a higher occurrence of ticks infected with Lyme disease in green spaces in the urban context, whereas risk seems to be reduced in more rural areas[36].

2.2. Interactions in areas under anthropogenic influence

Around half of the zoonotic diseases that have emerged in humans since 1940 resulted from changes in land use, especially clearing land for crop and livestock production that bring people and livestock close to forests[37]. Animal production and breeding is one of the key drivers of land use change worldwide, as forests are cleared to provide space to cultivate crops and to obtain pastures in order to meet the increasing demand for meat[38]. These human activities have increased the contact rates between humans and wild animals in cultivated land adjacent to patches of high biodiversity and may be a critical factor causing spillover.

Land use change can lead to a local reduction in biodiversity with loss of animal species that are incompetent hosts, so that competent host species remain that facilitate transmission of a certain pathogen to humans (as described above[39]). As a rule, competent host species tend to be more predominant and abundant in landscapes modified by humans than in undisturbed natural areas, as they show more resilience to human modifications of their ecosystems. The magnitude of this effect is strongest for rodent, bat and passerine bird species that are hosts for many pathogens. This underpins the global importance of these species groups as reservoirs for zoonotic diseases.

Livestock plays a particularly relevant role in the spread of zoonotic diseases, because it frequently functions as an interface that promotes spillover of pathogens to humans[40]. This transmission pathway is illustrated by the high number of viruses that domesticated animals share with humans[41]. Diseases such as diphtheria, measles, mumps, rotavirus, smallpox, and influenza A all have their origin in domesticated animals[42]. Species involved in transmissions include according to a recent review[43]

[34] Fredriksson-Ahomaa 2019.
[35] Tse et al. 2019.
[36] Diuk-Waser et al. 2020.
[37] Keesing et al. 2010.
[38] Machovina et al. 2015.
[39] see also Gibb et al. 2020.
[40] Kingsley 2018.
[41] Wells et al. 2020.
[42] Wolfe et al. 2007.
[43] Klous et al. 2016.

mainly cattle, pigs, sheep, goats, horses, poultry, but also cats and dogs. Occupations at particular risk include veterinarians, culling personnel, slaughterhouse workers and farmers, but transmissions can also occur during short visits such as when residents are buying farm products[44].

Highly productive breeds of livestock with relatively low genetic diversity make them less resilient to environmental changes and pathogens[45]. When high densities of livestock occur together under stressful conditions, these animals may be more susceptible to infections[46], creating conditions for the emergence and spread of zoonotic diseases. A good example is the Nipah virus, first spilled over from wild fruit bats to domestic pigs in Malaysia. High densities of pigs in farms, together with the fruit bats moving further into agricultural areas and human settlements, subsequently facilitated the establishment of pig-to-pig transmission, after which the pathogen spilled over from pigs to humans[47].

Evidence of a connection between the expansion of agriculture and zoonotic disease has been found for many zoonotic diseases, including Lyme disease, hantavirus, yellow fever, malaria, among others. Pathogen spillover and adaption of pathogens to new hosts can occur due to the settlement of humans and livestock on former natural ecosystems and to the creation of transition zones between these two types of ecological systems. Sometimes, vectors such as certain species of mosquitos have adapted to irrigation channels for agriculture, therefore propagating deeply into human areas[48].

2.3. Interactions due to wildlife hunting and wildlife trade

Practices related to deforestation and animal husbandry, as well as to wildlife hunting and trade are risky for emerging zoonotic diseases, as humans come into close contact with wildlife that may carry the pathogens causing these diseases. However, this does not necessarily apply to regulated wildlife trade within temperate climate zones in Europe. Regulated trade can act as regulatory element in view of the lack of sufficient natural predators to reduce certain wildlife populations.

Local as well as global demand for wildlife leads to people entering forests to hunt and collect wildlife, which subsequently in many cases is offered for sale in markets in urban and rural areas[49]. Wildlife (or "wet") markets and the legal and illegal wildlife trade bring live and dead wild animals into close contact with hunters, traders and consumers, facilitating pathogen transmission from wild animals to humans. In these markets, animals of many species are kept together in high densities, often under poor sanitary conditions, with a high risk of mixing bodily fluids. These markets also result in high stress for the animals, which weakens their immune systems. Although there is debate about its exact source and infection pathway, COVID-19 appears to have been the result of zoonotic transmission from an original wildlife host, possibly via an intermediate animal host, that came into close contact with humans[50]. Close proximity of different wild and domestic animal species in conditions such as the ones found in wet markets may enable recombination between more distant coronaviruses and the emergence of novel viruses with combinations of traits that differ from those found in either parent[51]. This new pathogens may become suddenly very dangerous for humans. The question remains whether

[44] Klous et al. 2016.
[45] Jones et al. 2013.
[46] Mourkas et al. 2020.
[47] Epstein et al. 2006, see also chapter 3.
[48] Jones et al. 2013.
[49] Dobson et al. 2020.
[50] Andersen et al. 2020, Wu et al. 2020.
[51] Li et al. 2020, Petrovan et al. 2020.

novel pathogens emerge because wild and domestic animals are kept close together in wet markets, or because of the overall poor hygienic conditions found in these markets.

Wildlife trade could have been one of the key factors in making the COVID-19 pandemic occur. However, this does not necessarily mean that consumers' awareness for the risk of zoonotic disease will in all cases lead to a reduced consumption. One example of raised consumption are wildlife oil products, such as seal oil that are traditionally associated with health benefits and have seen a rise in consumption in areas such as the Dagestan (Russia), situated at the Caspian Sea [52].

A similar effect of the COVID-19 pandemic has been observed in Africa, where areas under natural conservation, which are a source of livelihood for local communities extracting plant and animal resources, are being used more heavily due to economic pressures. At the same time, funding for conservation has been significantly reduced due to less public expenditure and international aid and reduced tourism. On the other hand, countries like Gabon have banned the consumption of bats and pangolins as a reaction of the COVID-19 pandemic and less demand from Asian markets could reduce the export of certain wildlife species [53].

A generalised ban on wildlife trade has been advocated by many stakeholders during the COVID-19 crisis. However, a generalised ban on the hunting and trade with wildlife would have a negative impact on the livelihoods of millions of people in Asia, Africa and Latin America, especially indigenous peoples and local communities. A more sustainable option, taking into account health, biodiversity and socioeconomic benefits could be to enhance the monitoring and enforcement of a ban on unsustainable wildlife trade outside local communities and of transnational trade with wildlife [54]. Not all these forms of unsustainable trade are illegal. Large numbers of wildlife is imported yearly globally in accordance with existing legislation.

An additional factor to be counted in is the practice of legal intensive wildlife farming. Mammals being bred include deer, rodents, civets and fur mammals, sometimes under conditions that foster compromised immune systems and the transition of zoonotic diseases. Examples include avian influenza in ostrich farms in South Africa, rabies in kudu farms in Namibia and most recently the emergence of (potentially mutated) SARS-CoV-2 in mink farms in the Denmark, Netherlands and Belgium [55].

[52] Svolkinas 2020.

[53] Lindsey at al. 2020.

[54] Borzée et al. 2020.

[55] Magouras et al. 2020.

3. CONCLUSIONS AND POLICY OPTIONS

There is no standard approach on how to assess implications for the risk of zoonotic diseases caused by changes in the state of biodiversity. There seems to be consensus that the relationships between biodiversity and zoonotic diseases are quite diverse, depending on the way of transmission, probability of interaction between hosts, pathogens and/or vectors, among other factors. Each case would require special attention to assess the best way to reduce the risk and care must be taken on the consideration of a multitude of other factors, including implications for indigenous peoples and local communities in biodiversity hotspots, for green-house gas emissions, for green and recreational areas in the urban context, or for any other ecosystem functions or services.

One way to assess the risk of pandemics from zoonotic spillover is by assessing viral diversity in animal hosts. This is based on the observation that COVID-19, SARS-CoV, MERS-CoV[56] and Ebola, among other zoonotic diseases, have included a spillover from animals to humans. However, viruses are constantly circulating between different animal hosts and humans, without causing transition to further humans. Therefore, virus monitoring alone may not be enough and should be complemented by the assessment of interactions between humans and animals. This can involve a monitoring of vectors of disease, such as mosquitos and ticks, or an assessment of fragmentation of animal habitats and closeness to agricultural lands and human dwellings in biodiversity hotspots[57].

Wilkinson et al. (2020) developed a model that uses the relationship between species and the areas they inhabit and predicts the risk of humans suffering certain novel zoonotic diseases depending on the level of human population. Their findings support other studies suggesting that the risk of novel zoonotic diseases rises with the loss of biodiversity until an intermediate level of biodiversity loss is reached.

However, there is empirical evidence on the benefits of promoting a larger share of non-competent hosts in a certain area, rather than managing competent hosts. This applies especially to zoonotic diseases with multiple hosts transmitted by multiple vector[58]. In particular cases, such as wildlife close to urban areas in Europe, reservoir host management (reducing the risks of interaction with carnivores or wildlife, for instance) or vaccination of reservoir hosts could be the option of choice[59].

The following chapters aim at providing some examples of policy options currently being proposed, following the differentiation of interlinkages proposed in chapter 2. Several of these options were also identified in the recently published Workshop Report on Biodiversity and Pandemics, prepared by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services[60].

3.1. Policy options for areas with limited human influence

Biodiversity conservation may be a particularly good choice for risk reduction in cases where host diversity reduces the risk of spillover and it is difficult to manage competent hosts, such as rodents[61]. Especially in megadiverse areas, conservation efforts could focus around potential emergence

[56] Middle East respiratory syndrome (MERS)

[57] Bloomfield 2020.

[58] Bayliss et al. 2017; Rabitsch et al. 2017.

[59] Rohr et al. 2020.

[60] IPBES Workshop on Biodiversity and Pandemics - Workshop Report, 2020, https://ipbes.net/sites/default/files/2020-12/IPBES%20Workshop%20on%20Biodiversity%20and%20Pandemics%20Report_0.pdf

[61] Rohr et al. 2020.

'hotspots' of wildlife pathogens. Typical examples include tropical forests and wetlands. Mapping and surveying not only pathogens, but also vectors and reservoir hosts, may facilitate the identification of these areas. However, the high number of potential zoonotic pathogens in megadiverse areas may be a limiting factor for this approach.

Buffer zones around natural areas with high diversity of pathogens, hosts and vectors would mitigate wildlife-livestock-human contact and help reducing the likelihood of new pathogens' emergence. The link between deforestation and emergence of (novel) pathogens suggests that a major effort should be done to retain intact forest cover in tropical countries[62].

A policy option currently in discussion relates to a sustainable EU trade policy and the initiative of the European Parliament to enable legally binding tools to ensure deforestation-free trade as a way forward to tackle the impact of the EU as consumer of goods and materials affecting forests worldwide.

Development cooperation can be re-oriented towards not only providing funding for ambitious action that can reduce the risk of zoonotic diseases, but also provide developing countries with the technical capacity to enable transformative change of their economies and meet international and EU environmental and social standards, especially those related to deforestation-free and land-neutral trade chains.

When biodiversity loss should be reduced by establishing and enlarging protected areas networks, it should be considered that protected areas more distant to human population hubs are better for zoonotic disease prevention. Similarly, large and well-connected protected areas cause less risk of disease emergence than smaller ones scattered throughout anthropogenic landscapes. Risk of spillover could be reduced if biodiversity is promoted in areas remote to human settlements or if measures are taken to ensure that wildlife lives in areas of enough size that are appropriately interconnected and as far away as possible from human settlements and livestock. This applies for instance to wildlife in temperate regions which begin to thrive due to the improvement of peri-urban ecosystems.

Both of these options could benefit from an ambitious Post-2020 Global Biodiversity Framework, which should be agreed on during the 15th meeting of the Conference of the Parties of the Convention on Biological Diversity in Kunming, China, in 2021. Relevant targets for the framework being negotiated include the expansion of protected areas, further efforts for ecosystem restoration, working towards sufficient resource mobilisation by enabling tools for business to foster biodiversity-positive investments, and mainstreaming of biodiversity conservation into other sectors, including the health sector.

3.2. Policy options for areas under anthropogenic influence

On a general level, the most important option is to aim at reducing the probability that pathogens become established and transmit to a new host population or species by reducing the contact probability between wildlife and livestock, as well as wildlife and humans.

Of equal importance are sanitary conditions of livestock production and processing. Poor health conditions of livestock and gaps in sanitary controls can elevate the risk of zoonotic diseases, especially when domesticated animals are in close proximity to wildlife. Improving animal health is a way to

[62] Dobson et al 2020.

improve human health, i.e. support technology and know-how transfer to improve livestock production and veterinary standards in areas close to potential disease emerging hotspots.

When monitoring biodiversity and pathogens, the importance of Invasive Alien Species (IAS) as potential vectors and reservoir hosts should be taken into consideration. There is a clear need for better recording/reporting of impacts to determine whether particular alien species and related zoonotic disease cases present a human health issue, to identify any trends (such as changes in health impacts) and to appropriately inform policy and management. A precautionary approach should be adopted towards species likely to pose a threat to human health, and measures of prevention, detection and rapid response should be prioritised for such species[63].

Public awareness and transition towards green finance with clear metrics to assess investment's impact on biodiversity can also serve to channel investments within and outside the EU to boost the sustainable use of biodiversity and to establish nature-friendly value chains.

The EU Biodiversity Strategy stresses the need for greening of urban areas. Even though this might imply a short-term increase of the risk for spillover of zoonotic diseases, balanced and functional ecosystems should provide resilience of pest and diseases on the long run. As urban wildlife can serve as reservoir and vector for a variety of zoonotic pathogens, some of which are responsible for severe disease in humans, host management could include mitigating measures including sanitation, rodent control and animal vaccination. Baits with vaccines can be used to interrupt the transmission of viral pathogens between reservoirs, as for the vaccination of foxes against rabies[64].

3.3. Policy options connected to wildlife hunting and wildlife trade

As preventing measure for future pandemics, a trade ban on live wild animals at wet markets has been proposed by the UN[65]. Such a trade ban on wild animals for food could be accompanied by restrictions on the trade for animals as pets, fur and medicine[66].

Wildlife trade without health checks still continues due to the lack of legislation and limited international regulations. To reduce the spread to zoonotic diseases, border controls should include testing on known zoonotic pathogens. International conventions such as the Convention on International Trade in Endangered Species of Fauna and Flora (CITES) deal with only a part of the problem. Although CITES regulates international wildlife trade on the basis of species conservation status, only a few countries use strict veterinary import controls, and there are no global regulations on pathogen screening associated with the international trade in wildlife[67].

Adequate regulatory and enforcement mechanisms could be put into place both at the national and international level. These regulations could especially target primates, bats, pangolins, civets, and rodents to prevent their hunting and commercial trade.

Another viable option would be to revise the illegal wildlife trade action in the EU and at EU borders. Transnational wildlife traffic crime could be addressed within multilateral efforts against organised transnational crime.

[63] Bayliss et al. 2017.

[64] Henning et al. 2017, Van der Poel et al. 2020.

[65] Carrington 2020.

[66] Leibler et al. 2009.

[67] Watsa 2020.

However, a complete restriction of access to wildlife for food is not a viable option, as many indigenous peoples and local communities depend on protein provided by wildlife for their livelihood. Within the right to have (traditional) diets based on wildlife, people can nonetheless be at risk from harvesting wildlife[68]. The promotion of traditional knowledge and provision of other sources of income for indigenous peoples and local communities can ensure that wildlife extraction and consumption remains local. This could be achieved, for instance, through payments for the contribution of indigenous peoples and local communities to the conservation of local biodiversity.

Regulations need also to be established for monitoring food and veterinary safety at wet markets for high-risk zoonotic pathogens. People working in wet markets should be monitored carefully and receive medical aid. Where needed, governments must include education and awareness on animal handling, sanitation, and disease transmission as well as sustainable wildlife management. They could also support the development of general awareness for the risks of wildlife as food and acceptance of alternative food sources[69].

[68] Dobson et al. 2020.
[69] Dobson et al. 2020.

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Webinar/event

- Webinar on "Global Biodiversity Conservation and COVID-19: Building Back Better with Nature". Hosted by the EU Delegation to Canada and the Government of Canada. 15 July 2020, at 15h30 CEST.
- High-level event “Nature is sending us a message”. Hosted by the German Environment Ministry. 29 June 2020 from 3.30 pm to 5.30 pm (CET).
- Intergovernmental Platform on Biodiversity and Ecosystem Services – IPBES (2020), IPBES Workshop on Biodiversity and Pandemics - WORKSHOP REPORT. https://ipbes.net/sites/default/files/2020-12/IPBES%20Workshop%20on%20Biodiversity%20and%20Pandemics%20Report_0.pdf, accessed 22.11.2020.

Qualitative interviews

- Qualitative interviews with European development cooperation experts.

Over the last decades, a variety of fatal infectious diseases have had zoonotic origins. The linkages between hosts, vectors, parasites and pathogens can be influenced by a multitude of factors, such as biodiversity, wildlife and land use.

High levels of biodiversity may be a potential source of pathogen transmission, but biodiversity loss can also promote transmission by increasing the number of competent hosts for a pathogen.

Biodiversity conservation reduces the risk of zoonotic diseases when it provides additional habitats for species and reduces the potential contact between wildlife, livestock and humans. Additionally, host and vector management is a viable option.

Other crucial measures include the restriction and sanitary control of wildlife trade, while considering the needs of indigenous peoples and local communities.

Each case requires an assessment of the best way to reduce risk while considering implications for other ecosystem functions or services.

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