Ecosystem restoration and zoonotic disease risk in humans: an integrative literature review

Paul Leeson

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Abstract

The objective of this thesis was to conduct a review of the literature to investigate the links between ecosystem restoration and zoonotic disease risk in humans. This topic is relevant, as zoonotic disease is an increasing problem, and the UN's Decade of Ecosystem Restoration was launched in 2021.

The main results found that ecosystem restoration especially in the tropics and forested wildness areas can prevent emerging infectious zoonotic diseases. The mechanism through which this is hypothesized to work is through strengthening ecosystem regulation of disease though high biodiversity mediated dilution effect and through the prevention of zoonotic disease spillover. Large scale ecosystem restoration is seen as a protective measure against a future zoonotic pandemic disease. High priority target areas are fragmented tropical forest habitats and the periphery of remaining primary forests and intact wilderness areas.

However, ecosystem restoration can also lead to the increase and spread of already known and endemic zoonotic diseases through increased wildlife resulting in higher animals to human transmission risk. The most researched example being the spread of Lymes Disease in Europe and North America. The mechanisms through which these are hypothesized to work is through an increase of available habitat resulting in increased abundance of wildlife and subsequent increased risk of transmission of zoonotic disease in humans. This problem is compounded by human induced trophic changes such as reduction or extermination of large apex predators such as wolves and bears which would otherwise keep deer and other wildlife populations in check, free of such top-down restraint's deer, and other animal numbers are higher than they would be otherwise, resulting in high incidence of zoonotic disease. High at-risk areas identified for an increase of zoonotic disease because of ecosystem restoration are peri-urban and urban areas where high wildlife population densities would increase the risk of transmission of zoonotic disease through increased human-animal interactions.

The results of this thesis could be beneficial in designing ecosystem restoration projects which acknowledge the complex interactions between ecosystems and zoonotic disease and human health.

Keywords: ecosystem restoration, zoonotic disease, vector-borne disease

Contents

1 Introduction

We live in unprecedented times, with the global human population and resource use at levels never before reached in the history of our species, the beginning of an era where the impact of humans on the natural world is altering natural systems globally, resulting in planetwide degradation of soil, air, fresh, and marine water, altering planetary climate, ecosystem functions and processes, and reducing biodiversity. This new geologic age is known as the Anthropocene. (Gillings & Hagan-Lawson 2014).

Human civilization emerged during the Holocene, an era of relative environmental stability. The natural world has been a source of health for humans as a species, providing many services on which we have relied, such as clean air and water, food sources, a stable climate, fertile land, building and industrial materials, medicine, mental health, and recreational benefits. As we enter the Anthropocene, we are faced with the plantwide loss of these services and a resulting deterioration of human health. (Gillings & Hagan-Lawson 2014). This is already being highlighted by air pollution being the main cause of global premature deaths. (Landrigan 2016).

However, human technical and scientific knowledge and wealth have also reached unprecedented levels. This gives us hope that, collectively as a species, we will be able to halt and even reverse this degradation.

Acknowledgment of the seriousness of the current situation has resulted in concerted efforts worldwide to halt this ecosystem destruction and degradation, and there has been much interest in ecosystem and environmental restoration. In 2021 the United Nations launched the decade of ecosystem restoration, 2021–2030. There is optimism and hope that with political will, financial resources, and scientific and cultural knowledge, such ecosystem restoration projects can restore degraded environments and, with it, reclaim some of the health benefits provided by ecosystems and environmental services. (UN, W.F.O 2023).

Robinson et al. (2022) argue convincingly that ecosystem restoration should be a core public health intervention. I agree and think that this also applies to the field of global health. Ecosystem restoration, supported by a One Health approach, should also be a core global health intervention that, if executed effectively, can tackle a range of global health issues, enhance human, animal, plant, and ecosystem health, and meet sustainable development goals.

Proponents of ecosystem restoration often cite zoonotic disease regulation and prevention as one of the services provided by ecosystems. (UN, W.F.O 2023; Robinson et al. 2022; Breed et

al.2021; European Commission 2022). However, a quick search of the literature provides little scientific or practical knowledge on incorporating zoonotic infection prevention and control measures into ecosystem restoration projects. As there are to be many upcoming ecosystem restoration projects worldwide, (UN, W.F.O 2023), this is an opportunity to reduce the risk of zoonotic disease and could be a cost-effective way to combat these diseases by integrating measures that will reduce incidents of zoonotic disease.

The main goal of this thesis is to conduct a review of the literature to investigate the link (both positive and negative consequences) between ecosystem restoration and zoonotic disease. This review hopes to uncover the links between ecosystem restoration and zoonotic disease risk and to find evidence for incorporating infection prevention and control methods when designing and implementing ecosystem and environmental restoration projects. Such evidence would be useful for producing guidelines or models based on the results of this literature review which could be beneficial in designing ecosystem restoration projects.

This thesis is taken from a global health perspective, and the focus is on reducing disease risk in humans through ecosystem restoration as a means of infection and prevention control to promote human health. Disease risk in wildlife, plants, and domesticated animals is beyond the scope of this investigation, although they will be mentioned when relevant to human disease risk.

2 Background

To better understand the relationship between ecosystem restoration and zoonotic disease, some background is needed. The background section of this thesis will begin with the health benefits and health services provided by healthy ecosystems, followed by a look at zoonotic disease in humans and how degraded and damaged ecosystems are thought to increase the risk of zoonotic disease. Restoring damaged ecosystems is a method that can be used to return and strengthen the health benefits to humans of the natural environment, hence the background will include a chapter on ecosystem restoration and the theoretical framework of One Health which can be used to support ecosystem restoration and zoonotic disease risk reduction.

2.1 Zoonotic disease in humans

Zoonotic diseases are those that can be transmitted from animals to humans, accounting for over two-thirds of all infectious diseases (Leal Filho et al. 2022). There are more than 200 known zoonotic diseases that can infect humans (Conrady 2021). Prior to the COVID-19 pandemic, it was estimated that zoonotic diseases caused 2.4 billion infections and 2.7 million deaths annually (Rahman et al. 2020).

Zoonotic diseases, which can be transmitted from animals to humans, are not a new phenomenon, they are an age-old problem that have been causing illness and death throughout human history. The earliest records of zoonotic diseases can be traced back to ancient Babylonian and Israelite texts, which mention “mad dogs,” thought to be referring to Rabies (Hubalek & Rudolf 2010). Zoonotic diseases have a long history of causing local outbreaks, regional epidemics, and even global pandemics. For instance, the 1346-1352 plague pandemic, known as “The Black Death,” resulted in the deaths of at least 25 million people in Europe and an estimated 25 million throughout Asia. The 1918-1920 “Spanish flu,” believed to be an avian influenza virus, claimed the lives of at least 21 million people (Hubalek & Rudolf 2010), and most recently, possibly the COVID-19 pandemic. This novel coronavirus, whose origins are still being investigated, is hypothesized to be zoonotic in nature, possibly originating in bats or pangolins (Zapatero Gaviria & Barba Martin 2023).

Zoonotic disease can be transmitted to humans by direct contact, through animal secretions such as feces, the fecal-oral route (Leal Filho et al. 2022), through microorganism-contaminated food and water, and insect vectors (Skowron et al. 2023). Risk factors for zoonotic disease include either direct or indirect interaction with animals, both domesticated and wild. Direct interaction is close contact with animals, and indirect is from infection by zoonotic microorganisms from the environment such as from soil, plants, and water. (Elsohaby & Villa 2023).

Driving forces and factors affecting the extent of a zoonotic outbreak include the geographical context such as climate (weather, temperature, and rainfall patterns), environment and land-use, economic and social elements such as population density, socioeconomic situation, water quality and sanitation, the health of the population, governmental response, crisis such as war or famine and changes in vector and host abundance (Skowron et al. 2023; Stephens et al. 2021).

Filho et al. (2022) describe four useful categories of zoonotic diseases which are helpful for formulating human health priorities, these categories are not mutually exclusive and there is overlap:

- Endemic zoonoses are zoonotic diseases which are well established and widespread particularly among poor populations with poor health care facilities, poor sanitation, and poor diets. This category is also described as neglected tropical zoonotic diseases. Endemic diseases are often associated with livestock and food production, where the population is in close daily contact with animals and food contaminated foodborne zoonosis such as Salmonella. This category of zoonotic diseases has the largest toll on human health killing millions and making billions of people sick annually. Other examples include brucellosis, Q-fever, leptospirosis, plague, Rift

Valley fever, Chikungunya and bartonellosis. These diseases are often neglected and due to overlap in geographical distribution, presentation of similar symptoms and poor health services are often difficult to diagnose and treat (Leal Filho et al. 2022; Halliday et al. 2015).

- Outbreaks of epidemics of zoonotic disease, these occur irregularly and are often linked to a cause of the outbreak such as following natural disasters, or changes in climate or land-use, or reduced population immunity due to malnutrition or illness. These include anthrax, rabies, Rift Valley fever, and leishmaniasis (Leal Filho et al. 2022).
- Zoonotic diseases which were originally caused by contact with host animal species but have become established in human populations and are now mainly spread through human-to-human contact (a classic example of this is HIV/AIDS which was originally from apes and is now spread only between humans) Another human-to-human contact through an intermediate vector usually mosquitos (such as Dengue, malaria), and measles (Leal Filho et al. 2022).
- Emerging zoonotic disease. This category includes re-emergence of zoonotic disease and newly emerging zoonotic disease which are new to science (Leal Filho et al. 2002). Emerging infectious diseases are diseases which have infected humans for the first time such as MERS, Covid-19, or have been previously known but have spread to new geographical areas, hosts or vectors (Skowron et al. 2023).

The number of different zoonotic diseases and the number of overall zoonotic disease outbreaks appear to be significantly increasing over time, with a trend of new emerging zoonotic diseases also increasing (Smith et al. 2014).

A number of global trends have been proposed as factors driving the re-emergence of zoonotic disease and the emergence of novel zoonotic diseases, these include worldwide large-scale changes, such as climate change, population growth, environmental degradation, forest clearing, land use shifts, farming intensification, and more international travel and commerce, all of which displace animal populations or put humans in closer contact with potentially infected animals (Elsohaby & Villa 2023). Climate change is of particular concern as changes in temperatures and rainfall patterns and their associated vegetation changes are creating new habitable zones for hosts and vectors of zoonotic disease, (especially for mosquito-borne diseases such as Malaria, Zika, Dengue, Yellow Fever, Chikungunya and Japanese Encephalitis and tick-borne diseases and the hantavirus through rodent host species (Leal Filho et al. 2022).

A UNEP IPC (Infection Prevention and Control) report in 2020, titled Preventing the Next Pandemic: Zoonotic diseases and how to break the chain of transmission, identified traditional food markets (including wet markets) as one of the key areas to prevent the

spread of zoonotic diseases. The report recommended regulating, monitoring, and improving IPC of wet markets. However, some people want to ban the sale of live animals (especially wild animals) in wet markets, which could be hard to implement and could lead to illegal or hidden wet markets. This is because wet markets have many advantages, such as low cost, easy access, fresh products, local and traditional cuisines, support for the informal economy, strengthening social and community interactions, maintaining cultural heritage, and providing employment (UNEP 2020; WHO 2021). Shutting down or banning wet markets could raise food prices and food insecurity locally. Therefore, wet markets are likely to remain for the foreseeable future and IPC in the wet market is a useful area of focus.

2.2 Ecosystems and human health

Human beings have evolved against a background of healthy natural ecosystems. These ecosystems have been a source of health for humans providing the basic resources needed for human health, including clean air, clean freshwater for drinking, sanitation and farming, medicines, food, stable climate, materials for shelter, clothing and utensils, and timber, fiber, and fuel. Healthy ecosystems also contribute to psychological health through providing cultural, spiritual, aesthetic, and recreational value (Corvalan et al. 2005).

The World Health Organization's Millenium Ecosystem Assessment Board published the Ecosystems and Human Well-being Health synthesis report in 2005 (Corvalan et al. 2005). The report highlighted the importance of ecosystems in providing ecosystem services, which are essential for or enhance human health and well-being. These ecosystem services and their health benefits are described as follows:

Table 1: Human health benefits of ecosystem services (adapted from Corvalan et al. 2005).

Ecosystem service	Health benefits
Fresh water	In their natural state ecosystems through hydrological processes which include catchment collection and natural filtration processes provide clean, freshwater, which is accessible to humans from springs, streams, rivers, lakes, wetlands, and rainfall. Fresh water is essential for human health, needed for drinking water and used in food production, i.e., watering crops, aquaculture, and wild food. Fresh water is also used for diluting and removal of waste, dilution of pollutants and personal hygiene.
Food security	Natural ecosystems are a source of food, available to humans from fruits, berries, seeds, plants, and animals, these provide protein, calories, and nutrients essential for human health.

Medicine and health supplements	The natural world is a source of the chemical compounds that have led to many medicines such as aspirin.
Timber, fibres and fuels	Ecosystems are a source of fuel and energy production such as wind, water and biomass Source of natural materials. Ecosystems provide natural materials such as wood, fibres and other natural material which provide tools and shelter and economic Housing and sources of livelihood support and enhance human health.
Recreation, spiritual and cultural	The natural world is a setting for people to enjoy the beauty, inspiration and cultural bonds created by nature. Such services support social and psychological well-being, enhancing human mental health.

Further benefits of healthy ecosystems of importance on a planetary scale are soil formation and nutrient cycling, climate regulation and stabilization and the regulation of infectious disease.

- Climate regulation and stabilization: Healthy ecosystems especially forests are vital for evapotranspiration, cloud formation and rainfall. The carbon locked in ecosystems especially, forests, peatlands and sea grass reduce atmospheric carbon stabilizing the carbon cycle and greenhouse gasses. The darker albedo of vegetation also plays an important role in absorbing the heat from the sun warming the Earth's atmosphere (Smith et al. 2012).
- Soil Formation and Nutrient Cycling: Globally and locally, healthy ecosystems and their vegetation cover contribute to the creation of nutrient-rich soils. This is achieved through the formation of soil organic biomass, prevention of erosion, and soil coverage with vegetation that provides shade and retains water (Smith et al. 2012).
- Regulation of infectious disease: Healthy ecosystems are thought to regulate infectious disease by keeping wildlife assemblages potentially harbouring zoonotic disease isolated from other ecosystem wildlife assemblages (Wilkinson et al. 2018). Another possible mechanism that may explain how healthy ecosystems regulate zoonotic diseases is the "dilution effect". Many zoonotic diseases are caused by pathogens that can infect different host species, but some hosts are more susceptible or suitable for the pathogen than others. In a healthy ecosystem with high biodiversity, the pathogen is diluted among many different species, some of which may be unsuitable hosts or poor transmitters of the disease, keeping the pathogen in check (Ostfeld 2017).

2.3 Ecological degradation and zoonotic disease

Disturbed and degraded ecosystems have been linked with increases of zoonotic disease outbreak risks to humans (Prüss-Üstün et al. 2006). One of the major impacts of human induced damage to ecosystems is decline in biodiversity. Species extinctions and decline in wild animal populations leads to reduced biodiversity. Low biodiversity has been linked to the emergence and increase of zoonotic disease. There are several mechanisms which are thought to be behind this, but the main one is disruption of the "dilution effect". Many zoonotic diseases are caused by pathogens that can infect different host species, but some hosts are more susceptible or suitable for the pathogen than others. In a healthy ecosystem with high biodiversity, the pathogen is diluted among many different species, some of which may be unsuitable hosts or poor transmitters of the disease, keeping the pathogen in check. However, ecosystem degradation tends to reduce biodiversity and favour the dominance of species that can thrive in disturbed and fragmented ecosystems, such as rodents and mosquitoes. These species may provide a large population of suitable hosts for the pathogen to spread from (Ostfeld 2017). It is thought that increasing biodiversity will act as a control mechanism to reduce zoonotic disease. These mechanisms will be explained in detail in the results section of this thesis.

As mentioned earlier, healthy ecosystems are thought to regulate infectious disease by keeping wildlife assemblages potentially harbouring zoonotic disease isolated from other ecosystem wildlife assemblages (Wilkinson et al. 2018). Habitat fragmentation and the subsequent encroachment of humans and domestic animals to once wild areas along with the spread of invasive species. This is one possible explanation for the increase in zoonotic disease as it has resulted in novel species assemblages where disease is more likely to emerge. This is also supported by evidence that zoonotic disease risk is higher in ecosystem peripheries when compared to the core untouched ecosystem. This is known as "zoonotic spillover" (Wilkinson et al. 2018).

The deforestation of the world's largest rainforest, the Amazon rainforest, is one of the most urgent environmental issues, which is a useful case study to explore the links between environmental degradation and zoonotic disease. Bonilla-Aldana et al. (2019) explored how deforestation and wildfires in the Amazon could affect vector-borne and emerging zoonotic diseases. This article is interesting for several reasons: It highlights a pressing environmental problem that is common in many tropical areas (such as Africa and Southeast Asia) and that may have similar effects on disease dynamics there. It shows the links between human-induced land use change and changes in zoonotic disease patterns through a chain of events and it highlights how these processes expose indigenous peoples to the risk of contact with outsiders and their livestock. Bonilla-Aldana et al. (2019) explain´´ that deforestation and wildfires, often caused by slash and burn practices, transform humid and complex tropical

ecosystems with high biodiversity into simple grassland ecosystems, introduce livestock, mainly cattle, into these areas, and increase human presence. These changes in the ecosystem are summarised in table 2 below.

Table 2: Effects of tropical forest deforestation on zoonotic disease (adapted from Bonilla-Aldana et al. 2019).

Effects of tropical forest deforestation on zoonotic disease
Increases the interaction between humans and domesticated animals with wildlife, creating opportunities for spillover and transmission of pathogens.
Alter the microclimate and hydrology, affecting the abundance and distribution of vectors and hosts of diseases.
Reduce the availability of natural resources and services, affecting the health and well-being of local communities.
Loss of biodiversity can also indirectly affect zoonotic disease by eliminating potential medicinal properties that could be used to treat such diseases

Stephen (2014) raises a valid point when discussing definition of wildlife or ecosystem health, arguing that the presence of infections and parasitic disease are natural and part of a healthy ecosystem. Viruses, microorganisms and parasites are part of the natural assemblage of life. Whereas the eradication of infectious disease in human is a desirable task, this would be undesirable on an ecosystem level and would disrupt the natural environmental functioning. This has to be recognized when incorporating a One Health approach into a ecosystem restoration project, for example are disease outbreaks in wildlife a regulating function in response to overabundance, therefore it would be more focused specific human or domesticated animal disease should be focused on. The definition of health in humans “the absence of disease” would not be suitable for definition of ecosystem health. The differing meanings of health need to be considered when collaborating between disciplines. Stephen (2014) also has a good point in showing that the threats to health from humans will be focused on infectious disease but the main threats to ecosystem health is not infectious disease, but damage caused by human activities.

2.4 Ecosystem restoration

Restoration ecology is the scientific discipline that aims to restore ecological systems that have been disturbed by human activities to a more natural state. The ideal outcome of restoration would be to bring back the environment to its original or pristine condition. However, this is hard to achieve because of irreversible changes such as species extinction, changes in ecosystem function and structure, or changes in surrounding land use. Moreover, factors such as invasive species, pollution, changes in zoonotic disease ranges, and climate change make it even more difficult to reach a natural state that resembles the pre-

disturbance situation. However, even though it may be challenging to restore an ecosystem to its pre-disruption state, it is possible for an ecosystem can be restored by reestablishing ecosystem services, function, and biodiversity (Vaughn et al. 2010).

Acknowledgment of the importance of restored ecosystems for combating biodiversity loss, climate change, food security, clean air, water and healthy soils as well as human health has resulted in recent important ecosystem restoration goals by the United Nations and the European Union. The seriousness of the current situation has resulted in concerted efforts worldwide to halt this ecosystem destruction and degradation, and there has been much interest in ecosystem and environmental restoration. The UN has launched the decade of ecosystem restoration, 2021–2030. With political will, financial resources, and scientific and cultural know-how, there is optimism and hope that such restoration projects can restore degraded environments and, with it, some of the health benefits provided by ecosystems and environmental services (UN, W.F.O 2023).

The UN action plan states that the main goals of the restoration are to halt biodiversity decline and mitigate climate change. Ecosystem restoration is vital for meeting the Sustainable Development Goals and the Global Biodiversity Framework, both of which are seen as necessary for improving human health at local, national, and global levels. The UN action plan document does not specifically mention zoonotic disease in relation to ecosystem restoration (UN, W.F.O 2023). However, the UN strategy document does mention zoonotic disease on page 22, where it says that restoring ecosystems can reduce the risk of vector-borne diseases. On page 27, it also says that people may not be aware of the benefits of intact ecosystems and that they may perceive the damaged ecosystem as a source of vector-borne diseases, without realizing that this is a result of the degraded state. The action plan sets out that global efforts are needed to restore the ecosystem functions that support human well-being and nature conservation (UNEP, FAO, 2020).

UN Decade on Ecosystem Restoration 2021-2030 Strategy

The EU Nature Restoration Law is a legislation that was passed by the European Union in June 2023. It requires EU member states to legally commit to restoring 20% of damaged ecosystems by 2030 and the remaining by 2050. These are very ambitious targets. The main purposes of the EU Nature Restoration Law are to halt and reverse biodiversity loss, mitigate climate change, and ensure food security (European Commission 2022). The law also states that:

“The restoration of ecosystems, coupled with efforts to reduce wildlife trade and consumption, will also help prevent and build up resilience to possible future communicable diseases with zoonotic potential, therefore decreasing the risks of outbreaks and pandemics, and contribute to support EU and global efforts to apply the One Health approach, which

recognises the intrinsic connection between human health, animal health and healthy resilient nature" (European Commission 2022, 1 & 20).

The EU Nature Restoration Law calls for the restoration of wetlands and river systems, reforestation and the creation of more natural agricultural landscapes, as well as increasing urban tree canopy cover. Such large-scale restoration will surely have an impact on zoonotic disease in relation to human health. However, because of the complexity of zoonotic disease dynamics and human interaction with nature, these issues need to be explored in more detail (European Commission 2022).

Based on the recommendations of the U.N. and the EUs recently passed nature restoration laws there is going to be large scale ecosystem restoration worldwide. The political will seems to be there, and financial resources have been allocated. I am interested in the topic from the question: what does this mean in regard to zoonotic disease? What are the benefits, what are the risks, and how to incorporate or enhance the benefits?

Conceptual and theoretical background important to ecosystem restoration are: one health, planetary health, ecosystem health and restoration ecology. Highlighting the zoonotic disease prevention or mitigation may be a way to help governments, organisations companies and populations support restoration projects.

2.5 Theoretical frameworks and conceptual models: One Health

The One Health concept recognises the link between human health, animal health and environmental/ecosystem health. Everything is connected, humans and their health do not exist in a vacuum, we are not isolated from the natural environment and other organisms on this planet. Consequently, many human health problems arise from a damaged environment and poor animal health and welfare standards, which are a breeding ground for zoonoses, such as Avian and Swine influenzas and antibiotic resistant microbes (Garg & Banerjee, 2021).

The goals and objectives of One Health is to improve public health through improvements in animal and environmental health. Whereas medical health seeks to improve personal or individual health, public health is focused on improving the health of entire populations of people, this can be on a local, national or global level (OHHLEP, 2022).

The main methods at the heart of One Health is collaboration between many different sectors and professions. In other words, cross disciplinary teamwork. Especially between the WHO, The UN Food and Agriculture Organization (FAO) and the World Organisation for Animal Health (OIE), (OHHLEP, 2022).

Some of the key results of the One Health program are improvements in food safety and nutrition, combating zoonoses and drug resistant microbes. This has been achieved through

collaboration and focusing on win-win solutions in which all sectors profit. Vast improvements in public health have been achieved by embracing the philosophy of One Health which could be summed up as, what is good for the environment and animal health is good for human health (Garg & Banerjee, 2021; OHHLEP, 2022).

The One Health Approach was developed because of the increasing clearer evidence that environmental damage caused by human actions, especially land use change, was the major factor driving changes in infectious disease between humans, domestic animals, and wild animals (Garg & Banerjee, 2021). The re-emergence and exacerbation of known zoonotic infectious disease and more troubling the emergence of new zoonotic infectious disease is a pressing global and public health issue. Simply using traditional infection prevention control methods whenever an outbreak occurs is a reactive approach, which although necessary does not address the underlying causes behind such outbreaks. One Health aims to prevent zoonotic outbreaks and reduce zoonotic disease risk by acknowledging the complex interactions between ecosystem, animal and human health (Garga & Banerjee, 2021).

Formal definition of One Health by the UN One Health High Level Expert Panel OHHLEP dec 1 2021

“One Health is an integrated, unifying approach that aims to sustainably balance and optimize the health of people, animals and ecosystems. It recognizes the health of humans, domestic and wild animals, plants, and the wider environment (including ecosystems) are closely linked and independent. The approach mobilizes multiple sectors, disciplines, and communities, at varying levels of society to work together to foster well-being and tackle threats to health and ecosystems, while addressing the collective need for clean water, energy and air, safe and nutritious food, taking action on climate change, and contributing to sustainable development.” (OHHLEP 2022).

Machalaba et al. (2021) recognise the need for incorporating the One Health approach to the field of Global Health, to tackle many global health issues, as there are many which can be addressed using One Health, and the similar Planetary Health and EcoHealth approaches. As many of the global and public health problems are directly or indirectly linked to ecosystems and the environment.

3 Thesis goal, objectives and research questions

Goal:

The goal of my thesis is to support ecosystem and environmental restoration projects by exploring how restoration is related to zoonotic disease risk in humans.

Objectives:

The objectives of my thesis are to reveal the current knowledge regarding ecosystem restoration and zoonotic disease risk to humans; by investigating the effect (positive or negative ecosystem restoration has on zoonotic disease risk to humans, and how ecosystem restoration can address these risks or strengthen zoonotic disease risk reduction measures.

Research Questions:

In what ways can restoration reduce the zoonotic disease risk in humans? In what ways can restoration increase the zoonotic disease risk in humans?

3.1 Relevance of this thesis

The topic I have chosen to explore is relevant, as zoonotic disease is an increasing global health problem as well as ecological restoration becoming more imperative nationally and globally, as highlighted by the UN's Decade of Ecosystem Restoration launched in 2021. Disease control is a much-cited benefit of ecosystem restoration but the mechanisms of how this works and how this can be strengthened is often left unexplained. By focusing on zoonotic disease and human health I have chosen a topic broad enough to get a holistic approach that is relevant to global health, which includes many scientific fields and disciplines such as epidemiology, conservation biology, one health and planetary health. By focusing on one aspect of restoration (zoonotic disease and human health) narrows the topic down so that the search results will be manageable for one person. There seems to be a need for this literature review as there does not appear to be a large collection of work on the subject to date.

3.2 Working life connection

This thesis will help support the development and expansion of Laurea University's Global Window online workspace. Using co-creation of Learning by Developing (LbD) the aim is to also create material for a One Health area on Global Windows, focusing on ecosystem restoration and zoonotic disease in humans, based on the results of the literature review. This will provide free accessible information on ecosystem restoration, zoonotic disease, one health and global health issues to anyone with internet access. This topic is a good way to

introduce One Health and planetary health approach to students of global health by using a topic familiar to global health which is zoonotic disease, which will complement the curriculum of the Global Health and Crisis Management Master's degree at Laurea.

One of the specific objectives of the Global Windows project are: "to serve a platform for implementing global goals, policies and models, E.G. "Sustainable development agenda: 2030" of United Nations (UN 2015; Valtioneuvoston kanslia 2020); "The One Health" of World Health Organisation (WHO 2017)" (Aholaakko 2021) This thesis will help fulfil that objective by providing information on the One Health model in the context of global health.

Serve as an open platform area where Laurea's students and teachers and guest lecturers can share their materials, addressing One Health approach solutions to global health challenges and problems, this will build up over time as material is added, could also provide a platform for other higher education institutions and organizations collaborating and partnering with the Global Windows project.

4 Methodology

4.1 Integrative literature review

An integrative literature review is a qualitative scientific research method which collects scientific articles, which is then used to synthesize and analysis the collective knowledge of a topic in the hopes of answering original predefined research questions (Torraco 2016). An integrative literature review is not simply an overview of a topic but should be analyzed thematically for trends and patterns and evaluated critically to allow conclusions and insights to be made which add new knowledge to the topic (Torraco 2016). The final result of an integrative literature review is original research, even though it is based on the work of others (Paré & Kitsiou 2017). Identifying gaps in the research is an important outcome of an integrated literature review as well as providing best evidence available, which can be useful for creating guidelines or recommendations which can be of practical use to those developing policy and those working in the field (Oermann & Knafl 2021). Having a holistic overview of a topic from many different fields and methodologies can allow for theoretical or conceptual frameworks to appear (Torraco 2005).

The strengths of an integrative literature review are that they allow for the synthesis of research articles from many different scientific fields and includes both quantitative and qualitative research. This allows for a clear picture of accumulated knowledge of a particular subject related to the research question to emerge (Kutcher & LeBaron 2022), in the case of this thesis, knowledge on ecosystem restoration and zoonotic disease risk in humans, providing an overall picture of what is known on the topic. Integrative literature reviews are

holistic in nature, allowing for a large amount of accumulated collective scientific knowledge form many diverse scientific fields to be easily accessible in one place to interested parties (Paré & Kitsiou 2017), this is very important for the topic I am investigating as restoration and zoonotic disease risk in humans is a subject which is of interest to many different fields such as epidemiology, restoration ecology, ecology, biology, environmental sciences, health sciences, global and public health. Interest in this topic is set to grow especially since the launch of the UN's Decade of Ecosystem Restoration which calls for large scale restoration worldwide. (UN Environment Program 2023).

Tarraco (2016) argues that integrative literature reviews can be divided into what he calls mature topics and emerging topics, mature topics are those that have a long history of research and are well-developed (for example the health risks of obesity), whereas emerging topics are relatively new topics which would benefit from a holistic view of the current available knowledge to date. I feel that ecosystem restoration and zoonotic disease in humans is an example of such an emerging topic.

Tarraco (2016) reasons that the researcher conducting the review needs to have an understanding and clear purpose for doing so. Tarraco proposed five purposes for conducting an integrative literature review, these are: Review, update and critique the literature; Meta-analysis; Review, critique and synthesize the literature; Reconceptualization of the topic; and answering specific research questions. Reflecting on Tarraco's work, the purpose of my thesis literature review will be to synthesize and critique the literature and to answer my specific research questions.

Tarraco (2016) also argues that for clarity, readability and to present findings logically, there are three useful ways to structure and organize the results of integrative literature reviews. These are: by methodology (grouping findings and critiquing the literature by the research methods used); by temporal structure (presenting findings and critiquing the literature by chronological or historical order); and finally, by conceptual or thematic structure (analyzing the results by conceptual models or themes which emerge from the literature). I will use the conceptual/thematic structure as I am hoping to find themes and patterns in the literature which will help answer my research questions and provide practical evidence-based advice.

Kutcher and LeBaron (2022) set out a step-by-step guide to conducting a high-quality integrative literature review, I will follow these steps and use them as a guideline when conducting this integrative literature review, shown in table 3. below.

Table 3: Steps of this integrative literature review, adapted from Kutcher and LeBaron (2022).

Step 1	Choose a concept to investigate. The subject should be of relevance and interest and ideally should be a subject that has not been explored many times before so as not to duplicate findings. The topic should be broad enough to include a wide range of articles for the synthesis of the results but narrow enough that the search is possible to complete. The topic I have chosen to explore is relevant as zoonotic disease is an increasing problem as well as ecological restoration becoming more important as highlighted by the UN's Decade of Ecosystem Restoration. Disease control is a much-cited benefit of ecosystem restoration but how this can be strengthened is often left unexplained. By focusing on zoonotic disease and human health I have chosen a topic broad enough to get a holistic approach including many scientific fields and disciplines while focusing on one aspect of restoration so that the search results will be manageable for one person. There seems to be a need for this literature review as there does not appear to be a large collection of work on the subject to date.
Step 2	Decide the aims of the analysis. These should be clear and if appropriate a theoretical framework should be included. The theoretical framework of my topic is the One Health and Planetary Health approach, both of which were described in the background section of this thesis.
Step 3	Conduct the literature search. The search terms must be clearly stated. The search words should be broad enough to include a wide range of articles for the synthesis of the results but narrow enough that the search is possible to complete. Choose words that will help reach the objectives of the literature review. Keep a record of all search results, including articles not included. Use more than one database for the search. Include grey material. How the search was conducted is discussed in more detail below in the search methodology subsection.
Step 4	Evaluate the data. After selecting the results to be included in the literature review, evaluate them for both quality and relevance of the content.
Step 5	Analysis the finding and synthesise the results, to identify themes. For each source of information investigate whether it helps answer the research questions. Keep a record of each article and a summary of the findings related to the research questions. Identify themes and patterns and synthesise the results to create original findings.
Step 6	Summarise the results and make conclusions. Decide how to show the results in a logical and clear manner, making use of tables, diagrams, and figures.
Step 7	Present and disseminate the results: the results of my work will be kept in the Theseus database as well as a press release from Laurea University, as well as being presented in Laurea University's Global Window. My thesis results will be defended and presented online to other students and faculty on the Global Health and Crisis Management Master's Degree Programme.

4.2 PICO model

To help choose my topic and formulate relevant and appropriate research aims, objectives and research questions I utilized the PICO Framework. The PICO model was developed by Richardson et al. (1995), originally as a way to answer clinical questions in a medical setting, particularly in regard to treatment methods. The PICO framework can help researchers formulate research questions in such a way as to allow for the results to provide the best evidence available when conducting a database search to answer research questions (Richardson et al. 1995).

Since its development the PICO Framework has been broadened beyond the clinical/medical setting it was originally developed for, as the usefulness to plan and frame research questions in a wide area of scientific fields was recognized, especially when the best available or current evidence is required. The PICO Framework is helpful for creating research questions, as the framework guides the question through a series of steps which results in useful as it requires the identification of the Problem, Intervention, Control and Outcome, this is where the acronym PICO comes from (Richardson et al. 1995; Nishikawa-Pacher 2022).

As already mentioned, the PICO Framework was developed for use in medical and clinical questions (Nishikawa-Pacher 2022). Therefore, it is not always suitable for all types of enquiries and can potentially miss important information in the results, therefore there are limitations to using PICO as a database search method (Tucker et al. 2023). However, I have used the PICO Framework to develop my research questions and have adapted the PICO as seen below to suit the nature of my research questions more closely.

P: Population and Problem

- The population can be scaled up from local population i.e., people living in or near the ecosystem or environmental restoration project (these will be directly impacted) to larger national populations (those effected by larger epidemic) to global populations (those effected by pandemics).
- The problem is zoonotic disease infecting humans and if ecological restoration can reduce the risk of zoonotic disease transmission to humans or will it increase the risk.

I: Intervention

- Provide advice and guidelines for those planning and conducting restoration projects on the risks of zoonotic disease, and how to take measures to reduce these risks, and to assess for any potential increases in zoonotic disease risk because of the restoration.

C: Context/Comparison

- Context: Zoonotic disease and ecological/environmental restoration.
- Comparison: Zoonotic disease risk in conservation/natural areas and degraded lands compared to restored ecosystems

O: Outcomes

- A synthesis analysis and critique of current knowledge from diverse scientific disciplines on ecosystem restoration and zoonotic disease in humans.
- Awareness of how ecosystem restoration can reduce zoonotic disease risk in humans.
- Awareness of how ecosystem restoration could potentially increase zoonotic disease risk in humans.
- Practical advice or guidelines for addressing zoonotic disease in restoration projects.
- Identify gaps in the current research on restoration and zoonotic disease risk to human populations.

The PICO Framework helped create the thesis goals, objectives, and research questions as stated earlier above.

4.3 Database search methodology

To access a wide range of results I will conduct a database search on the following platforms: PUBMED, SCIENCE DIRECT. Inclusion criteria: last 10 years, in English, full text, accessible from Laurea online library services and relevant to articles discussing both ecosystem restoration and zoonotic disease.

For others to assess the quality of my literature review and allow others to replicate my literature search, I need to provide a clear record of all search terms and which databases were used. The criteria for including an article or excluding an article need to be clearly stated. A record of all articles which appeared in the search results will be kept, clearly showing included articles, excluded articles and duplicate articles. Included articles are articles which meet the inclusion criteria that will help answer the research questions i.e., that the article contains relevant information about some form of ecological restoration and zoonotic disease capable of infecting humans. Disease risk in wildlife, plants and domesticated animals is beyond the scope of this investigation, although they will be mentioned when relevant to human disease risk. Duplicate articles are articles which appear in the results of more than one database search and will be counted as one result in the combined database searches. Excluded articles are which appear in the search results but when evaluated for inclusion did not meet the criteria (that the article contains relevant information about some form of ecological restoration and zoonotic disease capable of

infecting humans) the article was deemed as not useful in answering the research questions and was rejected for inclusion.

How the search result was excluded will be recorded as well, these are based on the title, abstract or full text. Abstract exclusion: some results are obvious from the title that they will not be relevant, here is an example from my results: “Sorption thermodynamics and kinetics properties of tylosin and sulfamethazine on goethite”. Simply from looking at the title I can tell that the article is not relevant to answering the study objectives. This can be rejected without looking at the abstract or full article. This saves me time and makes the process of sifting through search results more efficient.

Some results look relevant from the title, but after reading the abstract, it is clear that the article is not relevant for answering the research questions. For example, the article: Assessing the validity of crowdsourced wildlife observations for conservation using public participatory mapping methods. When reading the abstract, it can be seen that the article does not address ecological restoration or zoonotic disease, hence the article is excluded by the abstract.

The majority of the excluded texts were excluded by skimming through the full text or using word search for zoonosis/disease/reforestation/restoration and other key words were deemed not suitable as they only mention restoration out of context for the study aims or in passing. For example, the result: A holistic framework for facilitating environmental and human health, seems useful by the title but when reading the full text there is no focus on zoonotic disease or restoration.

This process should be as transparent as possible. To enhance transparency all search hits were uploaded to Zotero reference manager, and the information whether the articles were excluded by title, abstract or full text and why they were excluded is recorded. All included articles were stored on Zotero with a brief description of the relevance to the subject of ecosystem restoration and zoonotic disease as well as themes of the article.

A scoping search was conducted on ScienceDirect. (("ecosystem restoration" OR "environmental restoration") AND ("zoonotic disease" OR "infectious disease")) 2023-2013 research article or review articles open access 106 hits

The scoping search produced many results that were not relevant to ecosystem restoration, so the search terms were expanded on.

The expanded search term was ((restoration OR reforestation) AND (ecosystem OR environment OR wetland OR ecological) AND (zoonotic OR zoonosis OR zoonoses) Inclusion

criteria: last 10 years, in English, full text, accessible from Laurea online library services, and relevant to articles discussing both ecosystem restoration and zoonotic disease.

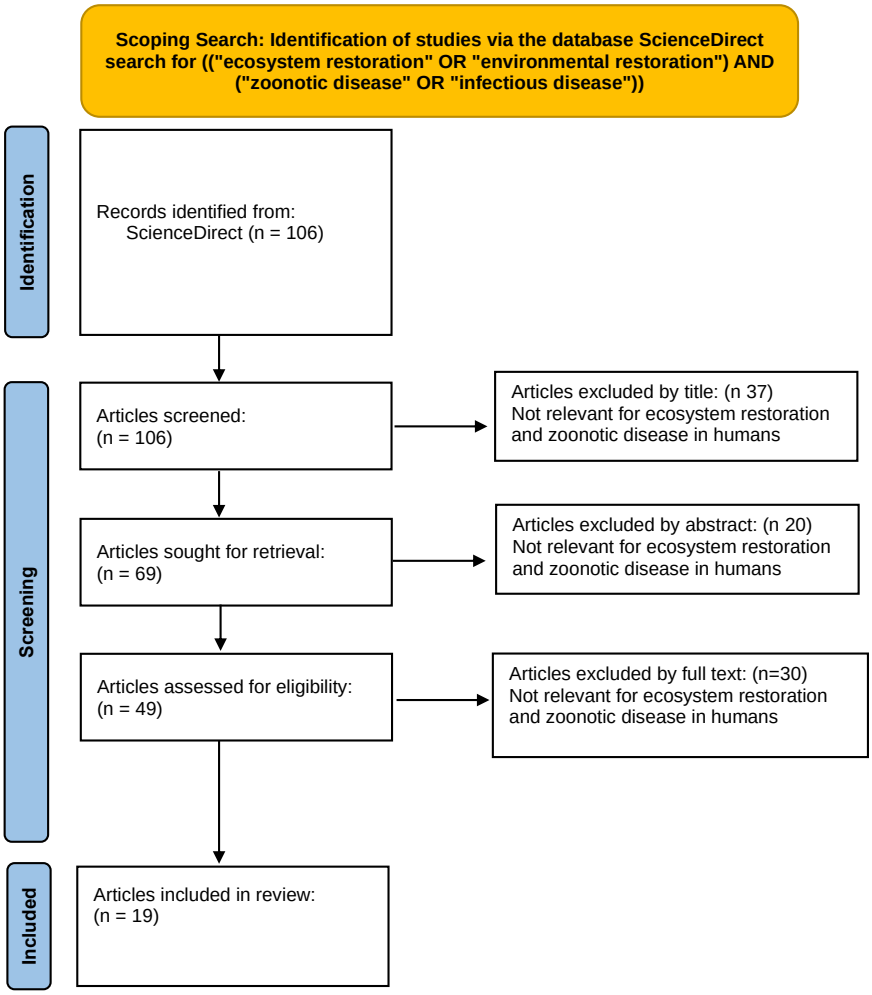

Figure 1: PRISMA flow chart showing the scoping search conducted on ScienceDirect database. Adapted from Page et al. (2021)

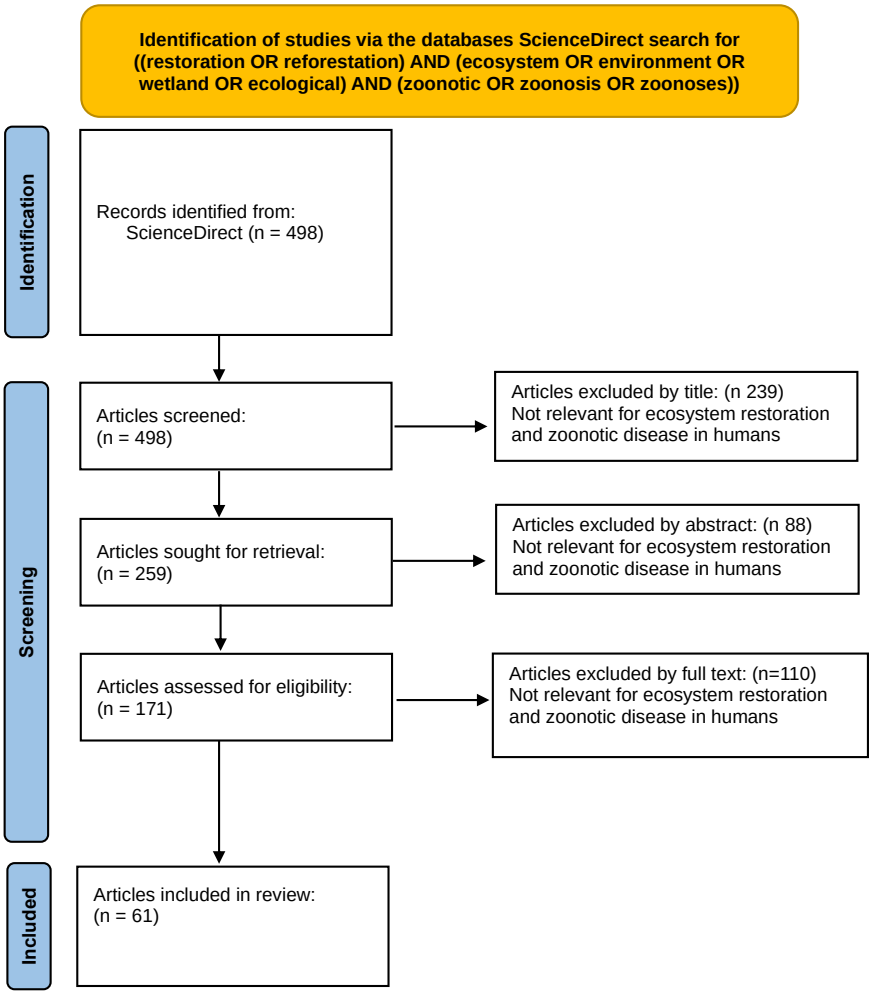

Figure 2: PRISMA flow chart showing the database search conducted on ScienceDirect. Adapted from Page, et al. (2021)

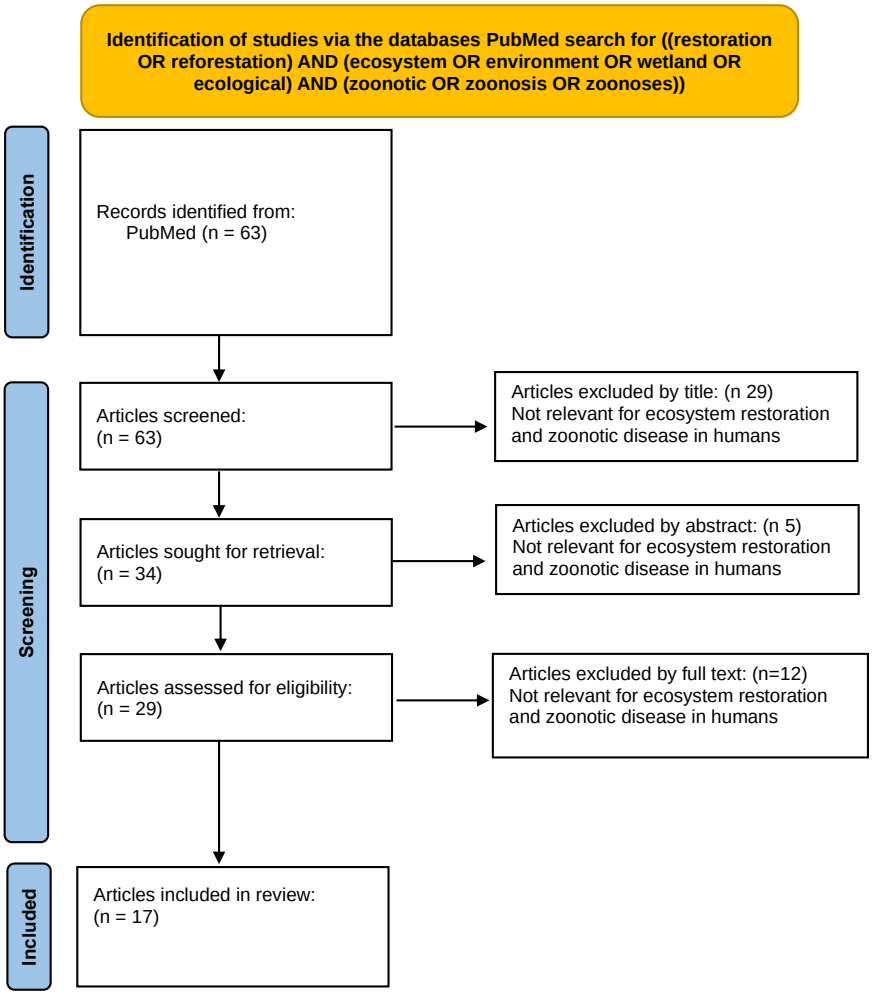

Figure 3: PRISMA flow chart showing the database search conducted on PubMed. Adapted from Page et al. (2021)

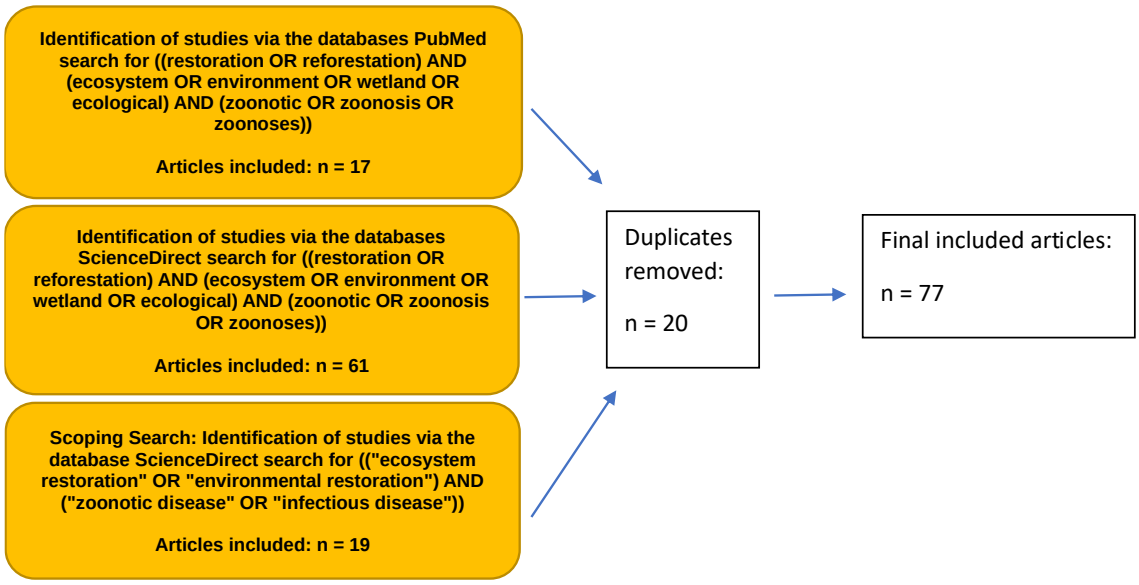

Figure 4: PRISMA flow chart showing the combined database searches conducted on PubMed and ScienceDirect. Adapted from Page et al. (2021)

4.4 Analysis and synthesis

Analysis of the included articles was conducted by reading the articles and recording the themes present in the article in relation to ecosystem restoration and zoonotic disease in humans, for example tick-borne disease, or rainforest restoration etc. Many of the articles only contained a paragraph or small section relevant to ecosystem restoration and zoonotic disease in humans, whereas others the whole article was relevant to the subject. Once the themes were identified, information from the articles by theme topic was combined and synthesized to get a picture of the knowledge contained in the included search result articles. The themes of each article were recorded in Zotero reference manager. Synthesis of the results by theme should allow for new perspectives on the topic to emerge and lead to identification of gaps in the knowledge and ideas for future research (Kutcher & LeBaron, 2022).

5 Results and findings

A look at the date of publication may show trends. There was a rise in articles relevant to ecosystem restoration and zoonotic disease in humans, in the year 2021 and subsequent years. This may be because of the Covid-19 pandemic which drew attention to the seriousness of pandemic infectious disease.

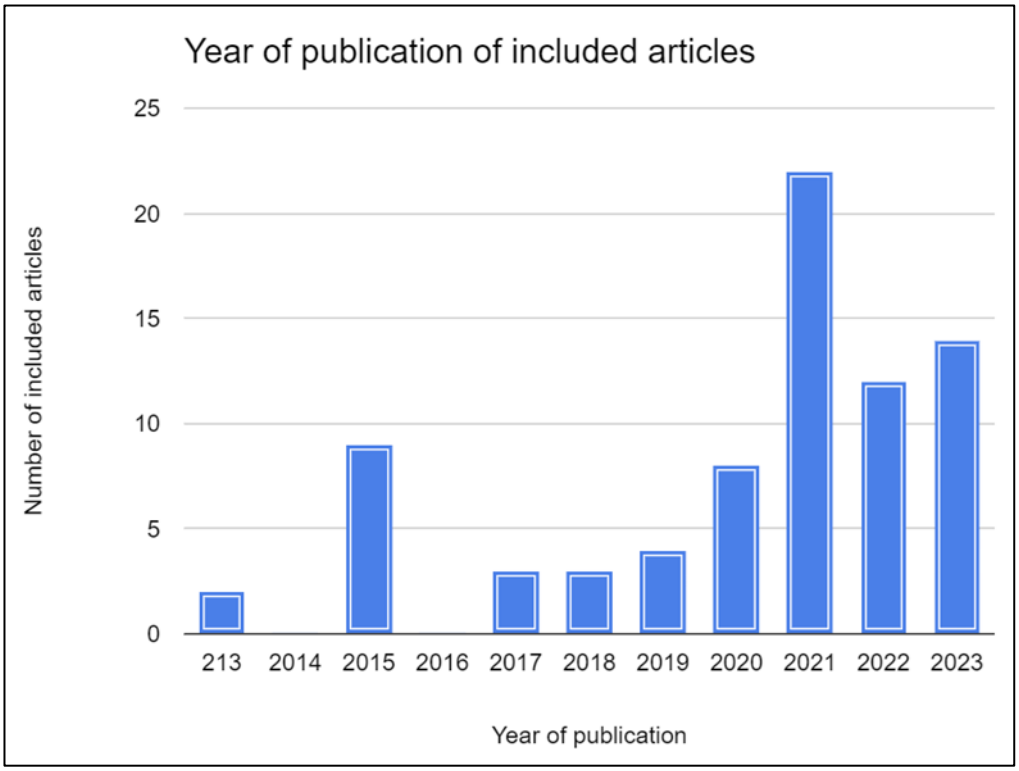

Figure 5: Year of publication of articles included in the integrative literature review

The articles in the literature search appeared to have more case studies involved in the spread of zoonotic disease risk increased because of restoration projects, whereas the studies promoting ecosystem restoration as a protective and preventive measure against zoonotic disease lacked case studies and were more hypothetical and theoretical this was especially the case when discussing emerging global pandemics.

The main overall themes emerging from the integrative literature review through analysis and synthesis of the literature are shown in table 4 below:

Table 4: Main findings themes emerging from the integrative literature review on ecosystem restoration and zoonotic disease risk in humans.

Main themes Identified in the Integrative Literature Review	Further explanation
Conceptual and theoretical models and frameworks which can help manage zoonotic disease and ecosystem restoration.	One Health, Planetary Health, Landscape approaches and Landscape Immunity, and Ecosystem Services and Disservices.
That ecosystem restoration especially in the tropics and forested wildness areas can prevent emerging infectious zoonotic diseases.	The mechanism through which this is hypothesized to work is through strengthening ecosystem regulation of disease though high biodiversity mediated dilution effect and through the prevention of zoonotic disease spillover. Large scale

	ecosystem restoration is seen as a protective measure against a future zoonotic pandemic disease. High priority target areas are fragmented tropical forest habitats and the periphery of remaining primary forests and intact wilderness areas.
Ecosystem restoration can lead to the increase and spread of already known and endemic zoonotic diseases through increased wildlife resulting in higher animals to human transmission risk.	The most researched example being the spread of Lymes Disease in Europe and North America. The mechanisms through which these are hypothesized to work is through an increase of available habitat resulting in increased abundance of wildlife and subsequent increased risk of transmission of zoonotic disease in humans. This problem is compounded by human induced trophic changes such as reduction or extermination of large apex predators such as wolves and bears which would otherwise keep deer and other wildlife populations in check, free of such top-down restraint's deer, and other animal numbers are higher than they would be otherwise, resulting in high incidence of zoonotic disease. High at-risk areas identified for an increase of zoonotic disease as a result of ecosystem restoration are peri-urban and urban areas where high wildlife population densities would increase the risk of transmission of zoonotic disease through increased human-animal interactions.
Tools and strategies for management of ecosystem restoration to reduce zoonotic disease risk.	Ecosystem restoration should be conducted with an awareness for the potential increase in zoonotic disease risks. The literature suggested numerous ways to mitigate or reduce the risk of zoonotic disease. These include removal of invasive species, reinstating top-down predator controls, managing microhabitats conducive to disease, disease and wildlife surveillance, monitoring and awareness, prevention, and risk reduction behaviors in local populations. GIS and modeling software can help predict and map risk areas and create modeling scenarios for potential disease outbreaks.

5.1 Conceptual and theoretical models and frameworks applicable to zoonotic disease and ecosystem restoration.

Conceptual and theoretical models and frameworks that can help manage zoonotic disease and ecosystem restoration identified from the literature were: One Health, Planetary Health, Landscape Immunity, and Ecosystem Services and Disservices. These are shown in table 5.

with references mentioning these frameworks. Each will be described and examined as how they relate to ecosystem restoration. One of these conceptual models (One Health) was also discussed in the background section of this thesis.

Table 5: Theoretical and conceptual frameworks, applicable to zoonotic disease and ecosystem restoration, identified in the integrative literature review.

Theoretical and conceptual frameworks identified in the integrative literature review.	
One Health	Bawa et al. 2021; Bouchard et al. 2023; Felappi et al. 2020; Harrison et al. 2020; Hopkins et al. 2020; Lawler et al. 2021; Machtinger et al.2024; McNeely 2021; Nishi & Hashimoto 2022; Reaser et al. 2021; Rocklov et al. 2023; Shanks et al. 2022; Wang et al. 2022;
´´Planetary Health	Hopkins et al. 2020; Lawler et al. 2021; Nishi & Hashimoto 2022; Reaser et al. 2021; Rosenstock et al. 2019;
Landscape Approaches and Landscape Immunity:	Nishi & Hashimoto. 2022; Prist et al. 2021; Reaser et al. 2021; Sandifer et al. 2015
Ecosystem Services and Disservices	Lliso et al. 2022; Thorn et al. 2021; Vaz et al. 2017; Yin et al. 2021

5.1.1 One Health

A description of One Health was given in the background section of this thesis; therefore, this section investigates the results of articles in the integrative literature search that promote ecosystem restoration as part of a One Health approach to zoonotic disease risk reduction and control.

The fundamental concept at the core of the One Health approach is that human, animal and ecosystem health are all interlinked and that health or ill-health in one group can lead to health or ill-health. Shanks et al. (2022) discuss how the One Health approach to date has mostly focused on the health of domestic animals and humans, and the ecosystem component including health of wildlife is often overlooked. Increasing evidence linking ecosystem degradation and biodiversity loss to zoonotic disease demands that the environmental health component of One Health needs to be emphasized (Shanks et al. 2022). However, the Covid-19 pandemic does seem to have created a shift in priorities as several articles (Harrison et al.

2020; Lawler et al. 2021; McNeely 2021; Reaser et al. 2021; Shanks et al. 2022; Wegner et al. 2022) discussed conserving healthy ecosystems and restoring ecosystem health through environmental restoration, as a potential way to prevent novel emerging zoonotic diseases capable of creating another pandemic. These articles promote using a One Health approach, which recognizes the anthropogenic causes of ecosystem degradation are driving changes in ecological functions of disease regulation and increased interaction between zoonotic disease wildlife hosts and vectors and domesticated animals and humans.

Harrison et al. (2020) identify tropical peatlands as ecosystems with a high potential for emerging zoonotic infectious diseases, because of a combination of; high wildlife biodiversity; high levels of ecosystem degradation and fragmentation caused by conversion of land to farming, burning and drainage of peatlands, and deforestation; wildlife harvesting; and high density of domesticated animals. They recommend prioritization of conservation, protection, sustainable use and restoration of tropical peatlands worldwide to reduce this risk. They also recommend that countries with tropical peatland ecosystems adopt national One Health approaches which recognize the importance of peatland ecosystem health to human health. Tropical peatland restoration can be promoted by taking a One Health approach, especially highlighting the link between ecosystem degradation and the emergence of zoonotic disease. Peatland restoration goals should include fire prevention, restoring functional hydrological features, and reducing peatland habitat fragmentation.

The One Health approach can be used on different scales to approach zoonotic disease issues, for example on a national scale Bawa et al. (2021) outline how protecting biodiversity can improve health in India, particularly in relation to zoonotic diseases. They recommend environmental restoration as the most cost-effective measure to achieve a reduction in zoonotic disease and increase human health and well-being and recommend that a One Health approach be incorporated into national policy. Bawa et al. (2021) support large-scale ecosystem restoration at a national level to provide ecosystem services for climate change mitigation and safeguard against emerging infectious diseases, especially if a One Health approach towards human, animal and ecosystem health is taken. Ecosystem restoration is recommended as a way to secure biodiversity which can protect against emerging zoonotic diseases. Their article is relevant as it highlights a national policy that takes into account the relationship between biodiversity and human health, including protection against zoonotic diseases. India is particularly relevant as it is the most populous country on Earth, a biodiversity hotspot, and sub-continental in size. Many zoonotic diseases are present in the country. On the other end of the scale an example is provided by Bouchard et al. (2023) who describe successfully using a One Health approach to combat Lyme disease on a much smaller regional level in the Estrie region, southern Quebec, Canada, which will be discussed in more detail in the results section on ecosystem restoration and tick-borne zoonotic diseases.

Felappi et al. (2020) took a One Health approach to urban greening in cities, they found that green areas provide psychological restorative effects thus reducing stress and improving the mental health of urban populations. This in turn reduces the risk of disease including zoonotic disease by reducing chronic stress which reduces immunity therefore making individuals more suspectable to infectious diseases. They argue that improving the health of the urban environment can improve the health of the urban population. However, they do acknowledge that urban greening could theoretically increase zoonotic and vector-borne diseases but imply that urban greening (a form of environmental restoration) can reduce urban populations stress levels therefore adding some degree of protection against infectious zoonotic and vector-borne disease.

5.1.2 Planetary Health

Planetary health stresses the importance of the link between global ecological processes and human health and well-being. The emphasis is on ecosystems on a planetary scale, and that to safeguard human health we need to look at the causes of human ill health much of which is now caused by environmental/ecological changes on a planetary and continental level, such as climate change, pollution, deforestation and biodiversity loss. Planetary health is a global public health response to planet wide environmental degradation and deterioration of the Anthropocene and is similar to One Health but with less focus on zoonotic disease in domesticated animals and humans but with a greater emphasis on ecosystem health at a global level (Nishi & Hashimoto 2022). The field of Planetary Health also encompasses the links between ecosystems and zoonotic disease in human populations. A Planetary Health perspective views human activities and human-induced land-use changes as drivers for the emergence of zoonotic disease. A Planetary Health approach using ecosystem conservation and restoration to reduce zoonotic disease risk is proposed as a win-win solution to improving both ecosystem and human health. Planetary Health endorses large-scale global ecosystem restoration as a means to prevent a new emerging zoonotic pandemic (Lawler et al. 2021).

However, Hopkins et al. (2022) identified in their literature search only one intervention with high-level evidence, which was vaccinating dogs against rabies to protect human and wildlife health, studies looking at other various ecosystem conservation and restorations interventions had low-level of evidence of effectiveness to improve human health outcomes by reducing disease threats. Hopkins et al. (2022) stress that the field of Planetary Health needs to have stronger evidence-based solutions in order to be able to promote the discipline and recommend high quality research to reduces evidence-gaps, this will then allow stakeholders to strengthen the case for Planetary Health approaches to reducing zoonotic disease risk.

5.1.3 Ecosystem Services and Disservices

Zoonotic disease can be seen as an ecosystem dis-service (EDS) and the role ecosystems have in regulating zoonotic disease as an ecosystem service (ES) (Vaz et al. 2017). Vaz et al. (2017) identify different types of ecosystem disservices one of which they termed Health Ecosystem Disservices, which are elements of an ecosystem which could possibly harm humans, for example bites, stings or zoonotic infection from interactions with wildlife, conversely a regulating and maintenance ecosystem service was control of pests and diseases. The goals of ecosystem restoration should be to restore ecosystem functions and restore and strengthen ecosystem services. Increase in zoonotic disease risk may be unavoidable in certain circumstances. However, if there is to be ecosystem disservice such as zoonotic disease ecosystem restoration should be adapted to minimize the ecosystem disservices resulting in zoonotic disease or maximize the ecosystem service minimizing zoonotic disease.

Yin et al. 2021. Ecosystem services are critical for achieving the UN's Sustainable Development Goals. Ecosystem restoration can enhance ecosystem services which are necessary for sustainable development, including Sustainable Development Goal 3 (SDG3) Good Health and Well-being. One of the ecosystem services which safeguards human health, is the ecosystem service of disease regulation. The breakdown and deterioration of this ecosystem service is expected to result in increased zoonotic disease outbreaks, underpinned by increased interaction between humans, their domesticated animals and wildlife which is characteristic of human-modified degraded ecosystems. This increased interaction is thought to lead to increased risk of zoonotic viral spillover and the emergence of novel zoonotic diseases, some of which will have the potential to cause pandemics. Covid-19 has demonstrated the huge cost a pandemic can inflict on economies, societies and human health worldwide. Therefore, acknowledging and accounting for the value ecosystem services provide, including disease regulation, should be integrated into socio-economic development though sustainable development and ecosystem restoration. Because of financial restraints, ecosystem restoration should be prioritized to high quality restoration which restores biodiversity and strengthens ecosystem services such as ecosystem resilience against disease spillover.

Lliso et al. (2022) discuss how ecosystems do not only provide services which enhance human health and well-being but can also have disservices which can be detrimental to human health and well-being. They describe these as instrumental disservices which are "something that leads to an undesirable end or has a negative impact on wellbeing" (Lliso et al. 2022). This is a useful framework for recognizing the services and disservices of an ecosystem, in a way that can be understood socio-economically and in health indicators, thus allowing for the measurement of costs (instrumental disservices) and benefits (instrumental services). This can be applied to ecosystem restoration and allow for policymakers to promote ecosystem

restoration while acknowledging and mitigating against possible negative impacts the restoration may have on human health. Lliso et al. (2022) identify zoonotic disease from wildlife as an instrumental disservice. This framework allows socio-economic and ecological trade-offs to be identified and better managed, an example of this is given for wetland restoration, one possible instrumental service gained from the restoration is flood protection and one possible disservice is an increase in mosquito-borne zoonotic disease.

The importance of identifying trade-offs was also discussed by Thorn et al. (2021) who found that ecosystem disservices of zoonotic disease can be a barrier to peri-urban greening (urban ecosystem restoration) to promote climate resilience in sub-Saharan African. Peri-urban can be defined as populated areas transitioning between urban and rural areas, in a sub-Saharan context these are characterized by high levels of poverty, urban-sprawl, poor urban planning and vulnerability to extreme climatic conditions, such as flooding, heatwaves and drought, both of which are predicted to get worse because of climate change. Urban greening, a form of ecosystem restoration, aims to use green spaces and vegetation cover as nature-based solutions to flooding, by acting as a permeable sponge, and heatwaves, by creating shade and cooling the surrounding air. One of the barriers to adopting nature-based solutions was perception by policymakers and local populations that increased vegetation will result in increased zoonotic disease risk, especially if the green areas are poorly maintained and neglected. Educating and engaging local government, policymakers, local businesses and the local population on the benefits of ecosystem services from urban greening, as well as involving local traditional knowledge, can help overcome the perceived barrier of ecosystem disservices.

5.1.4 Landscape approaches and landscape immunity

On a spatial scale landscape approaches are the most locally focused of the theoretical frameworks discussed so far. The main idea of the landscape approach to health and well-being is that landscapes and health are closely interrelated because of the interactions that take place on this level. This approach is useful as it is more practical and inclusive as central to this approach is taking into consideration the specific context of the natural environment as well as the social, economic and political contexts (Nishi & Hashimoto 2022). Nishi and Hashimoto (2022) also argue that landscape approaches are well-suited to health and zoonotic disease topics as they have much in common with health focused approaches; in that both use systems thinking to find solutions to complex issues, both are holistic, and both use interdisciplinary collaboration and cooperation to solve health problems. Taking a landscape approach to zoonotic disease and ecosystem restoration could be a very practical and fruitful method as the focus is interactions happening within the specific landscape that results in human health or illness. Ecosystem restoration would consequently change the landscape and with it the interactions within the landscape. This raises questions such as should human

interaction be minimized or restricted following ecosystem restoration to protect biodiversity (which can act as disease regulation through the dilution effect) or will ecosystem restoration increase zoonotic disease by creating more habitat for wildlife, therefore increasing zoonotic disease risk though increased human-animal interaction and the spill-over effect (Nishi & Hashimoto 2022). Looking at the specific landscape context can help answer such relevant questions.

Because of its holistic, multidisciplinary nature, landscape approaches to ecosystem restoration are compatible with One Health, Planetary Health and sustainable development, as ultimately all three play out on a landscape level.

Reaser et al. (2021) argue that ecosystem restoration is a public health service. They recognize that the driving force for the increase in zoonotic spillover is land-use change and termed this process land-use induced spillover. Because the problems are caused by land-use change, Reaser et al. (2021) see modifying the landscape in such a way that ecosystem restoration can result in what they termed landscape immunity. Employing ecological countermeasures can act as landscape-based solutions to reduce or prevent zoonotic disease.

5.2 Ecosystem restoration as protection against zoonotic disease risk

One of the overall themes that emerged, which also answered one of my research questions (does ecosystem restoration decrease zoonotic disease risk?) was the potential for ecosystem restoration to decrease zoonotic disease risk, especially on a global scale. The subthemes which supported this were:

- Ecosystem restoration to enhance biodiversity as protection against zoonotic disease.
- Ecosystem restoration as a tool to reduce zoonotic spillover, and deforestation and forest fragmentation induced zoonotic disease.
- Restoring ecosystem function and trophic levels to reduce zoonotic disease risk.
- Removal and control of invasive alien species as ecosystem restoration to reduce zoonotic disease risk.
- Restoring amphibian and bat populations as insect-borne disease vector control.

Speldewinde et al. (2015) discussed whether restoring an ecosystem good for your health? They concluded that natural ecosystems provide many benefits to human health through ecosystems services, one of which is disease regulation. And that restoring an ecosystem can partially restore these ecosystem services, but never fully. However, they remind us that ecosystem restoration outcomes are unpredictable and that it is unlikely that the ecosystem will be restored to a pre-degraded pristine environment, as often biodiversity and ecosystem functions are not fully restored. Speldewinde et al. (2015) conclude that ecosystem restoration is needed to help reverse environmental degradation worldwide, and the adverse

effects this has on human health, but that the precautionary principle should be applied to ecosystem restoration. Because environmental degradation is likely to have created changes to species composition and assemblages, biodiversity, ecosystem functions, and biogeochemical processes the probable result of an ecosystem restoration is a novel ecosystem where the outcomes on specific zoonotic infectious disease risks in humans will be unknown.

5.2.1 Ecosystem restoration to enhance biodiversity as protection against zoonotic disease.

The link between high biodiversity and protection against zoonotic disease is not fully understood but is thought to work through the dilution effect. Some diseases that can pass from animals to humans are caused by microorganisms and viruses that can infect many different species of animals, but some animals are more likely to be infected or better hosts and vectors for pathogens than others. When there are many species of animals in a healthy ecosystem, the pathogens are spread among them, and some of these animals may not be good hosts or carriers of the disease, keeping the diseases under control. This is called the "dilution effect". (Everard et al. 2020; Glidden et al. 2021). The strength of the dilution effect depends on the characteristics of the pathogen, the host, and the environment. There is an opposing school of thought which suggests high biodiversity increases zoonotic disease risk through "amplification" basically the more species the more potential zoonotic disease hosts and vectors (Glidden et al. 2021).

However, there is strong evidence to suggest that human induced reduction in biodiversity affects zoonotic disease dynamics, increasing zoonotic disease risk. Glidden et al. (2021) propose the following ways in which human induced reduction in biodiversity leads to increase in zoonotic disease risk in humans:

- Ecosystem habitat loss and habitat fragmentation increase the overlap and create mixes of new zoonotic disease hosts, reservoirs, vectors, and humans.
- Biodiversity loss of apex predators and large herbivores can lead to an increase in rodents which are a major reservoir of infectious disease.
- In disturbed ecosystems with low biodiversity, there are fewer species and those that can thrive in disturbed ecosystems, such as rats and mosquitoes, become more common. These animals provide many suitable hosts for the zoonotic pathogens to spread from to humans.
- Human modified landscapes with low biodiversity are also characterized by humans, and their domestic animals, invasive species, and wildlife harvesting, creating opportunities for cross-species transmission of zoonotic disease with remaining wildlife, which has the potential for the emergence of novel infectious disease.

Being aware of the above mechanisms and incorporating spillover risk reduction into ecosystem restoration can reduce these zoonotic disease risks, by increasing intact habitats, restoring predators and large herbivores (Glidden et al. 2021). Biodiversity has been linked to lower rates of disease transmission in terrestrial landscapes, this is thought to occur because of the dilution effect although other factors could be involved such as behavioral changes effecting transmission because of the absence or presence of other species, or how other species modify the environment (Sandifer et al. 2015).

Keesing and Ostfeld (2021) support the restoration of biodiversity as management of zoonotic disease risk. They explored the dilution effect and found that the idea of all wildlife to be reservoirs of potential zoonotic disease to be outdated and that some groups of mammals are much more likely to transmit zoonotic pathogens than others. These are bats, rodents, primates, meso-carnivores (such as racoons, dogs, cats, weasels), and ungulates (such as deer, pigs and goats). They argue that the idea that high biodiversity increases zoonotic disease risk to be unfounded as that all wildlife assemblages in an ecosystem are not equal in risk of transmission to humans. Animals with high potential for zoonotic disease tend to increase in disturbed environments with low biodiversity, whereas a high biodiverse ecosystem provides disease regulation service through the “dilution effect”.

Bawa et al. (2021) outlines how protecting biodiversity can improve health on a national scale, in India, one aspect of which is zoonotic diseases prevention and control. Bawa et al. (2021) recommend large-scale ecosystem restoration at a national level as the most cost-effective measure for tackling many environmental health problems as it will strengthen ecosystem services including climate change mitigation and safeguarding against emerging infectious diseases, among others. Bawa et al. (2021) recommend using a One Health approach to achieve this by creating a national policy that takes into account the full relationship between biodiversity and human health, in which healthy ecosystems with high biodiversity can protect against zoonotic diseases. India is particularly relevant as it is the most populous country on Earth, a biodiversity hotspot, and sub-continental in size. Many zoonotic diseases are present in the country.

5.2.2 Ecosystem restoration as a tool to reduce zoonotic spillover, and deforestation and forest fragmentation induced zoonotic disease

Large-scale afforestation and reforestation are promoted as methods to combat climate change by reducing atmospheric carbon, through forests acting as carbon sinks. However, the benefits of forests are much more than simply carbon storage. They also contribute to human health, particularly in the regulation of zoonotic disease spillover (Buřivalová et al. 2023).

Human activities often lead to forest fragmentation, which in turn increases the likelihood of zoonotic spillover. This happens when forest wildlife, many species of which are potential

disease vectors, come into increased contact with humans and domestic animals as these groups move into spaces once occupied by intact forests and their wildlife. Intact pristine forested ecosystems once acted as buffer zones separating humans and domesticated wildlife from wildlife zoonotic reservoir hosts (Mohan et al. 2021). Robinson et al. (2022) argue that ecosystem restoration can be used to restore fragmented ecosystem habitats to recreate this buffer but only if humans are prevented or limited from encroaching on the restored land. The Ebola, Zika and Nipah viruses are examples of emerging zoonotic diseases which are thought to be related to deforestation and forest fragmentation. Reforestation and ecosystem restoration reduces forest fragmentation and therefore reduces zoonotic spillover as wildlife disease vectors are once again able to live in forests separated from human and domestic animals. Reforestation and restoration efforts around remaining intact primary forests, which are potential habitats for novel emerging zoonotic diseases, can serve as a buffer, further distancing humans and domestic animals from potential zoonotic spillover. This approach is supported by the One Health and planetary health approaches which acknowledges the interconnectedness between ecosystem, animals, and human health. Highlighting these additional benefits can further promote and support the conservation, restoration, and protection of forests (Buřivalová et al., 2023; Mohan et al. 2021; Okeke et al. 2022).

Guégan et al. (2023) also discuss how deforestation and forest fragmentation are a driving mechanism for emerging zoonotic disease, and can increase zoonotic disease spillover, but also mentions it is more complex as large-scale complete deforestation can reduce certain zoonotic diseases, for example malaria, through decimation of wildlife hosts and vectors. However largescale reforestation is a good way to stop emerging diseases on a global scale, through prevention of zoonotic spillover. These findings have implications for reforestation and restoration activities, if these mechanisms are taken into consideration in planning and management, inferring that reforestation efforts should be large-scale with the aim of creating intact closed forests instead of small-scale localized habitat restoration which could potentially increase zoonotic disease risk by creating fragmented forest habitats.

In their 2022 study, Cao et al. conducted an analysis of the projected loss of wilderness areas by 2100 under various scenarios of land use and human activities. Their results predict a potential loss of 4.6 million km^2 of the planet's remaining wilderness areas, an area larger than India, by 2100. Interestingly, they found that approximately 50% of the projected wilderness loss is concentrated in just 10 countries. Four of these countries - Indonesia, Myanmar, Papua New Guinea, and the Democratic Republic of Congo - are predominantly tropical forest wilderness. Indonesia tops the list with the largest area of projected wilderness loss. Cao et al. (2022) also highlighted the potential consequences of such loss to biodiversity. They suggested that the loss of remaining wilderness areas could possibly increase the risk of emerging zoonotic disease outbreaks due to zoonotic spillover. Therefore, they emphasized that these remaining wilderness areas should be targeted and prioritized for

ecosystem restoration efforts. As this would not only protect and conserve intact wilderness therefore reducing habitat fragmentation, but also maintain biodiversity. Such efforts can reduce the risk of zoonotic diseases by minimizing zoonotic spillover and promoting the "dilution effect". Wang et al. (2022) also recommend the protection of forests, ecosystem restoration, reforestation and the conversion of agricultural land to more natural states as protection against the emergence of zoonotic disease. They also recommend the surveillance of viruses in wildlife which could act as an early warning system for outbreaks for zoonotic disease in humans, using a One Health approach recognizing the importance of wildlife health on human health. Therefore, ecosystem restoration projects should incorporate some form of zoonotic surveillance, especially in tropical forested areas.

Forest fragmentation in the tropics has been linked to several zoonotic viral disease outbreaks such as Nipah, Ebola, Hendra, Marburg, and SARS, all of which have been linked to bats. Bats are a vector for many diseases which are immune to carriers of the viruses, Direct human contact with bats is rare, but the viruses are thought to be transmitted by saliva, urine, and feces. Disturbance of intact forest forces bats into closer contact with humans, bats are highly mobile and will roost in buildings and farms, further increasing risk of zoonotic disease transmission. Ranjan (2021) used scenario modelling and found that if farmers on fragmented forest landscapes adopted agroforestry this could connect patches of fragmented forest, providing a habitat for bats so that they would no longer have to roost in human structures where transmission risk is highest. This agroforestry-based forest restoration could be an effective way to prevent transmission of bat-borne diseases such as Nipah virus.

Shyamsundar et al. (2021) also recognize the links between deforestation, forest habitat fragmentation and zoonotic disease, arguing that reforestation and restoring fragmented forest habitats will have beneficial health benefits to rural poor communities reliant on forests for their livelihoods. These communities, especially in tropical areas, are very vulnerable to emerging zoonotic disease and would be the first communities to be impacted by an outbreak, therefore ecosystem restoration could be an effective public health measures to improve poor forest-reliant communities characterized by inadequate health services.

Wegner et al. (2022) acknowledge that there is still debate between links between wildlife zoonosis and newly emerging infectious diseases in humans caused by spillover effect, they argue that this is because it would be very difficult to detect the origin and emergence of such a disease in real time, as there are so many complicated factors involved but recommend adopting the precautionary principle. The precautionary principle needs to be adopted and that we should assume that the following socio-economic drivers of increased wildlife origin infectious disease are livestock driven tropical deforestation, livestock production in and wildlife hunting and trade.

5.2.3 Restoring ecosystem function and trophic levels to reduce zoonotic disease risk

Several articles suggest that simply planting trees and protecting the restoration area is insufficient to restore ecosystem service functionality. Instead, specific measures must be taken to restore the ecosystem's functioning. In other words, successful, high-quality ecosystem restoration needs to restore the proper functioning of ecological systems. A low-quality ecosystem restoration project is unlikely to restore the functions of the original ecosystem.

Everard et al. (2020) discuss the importance of ecosystem functions and services in the context of infectious disease. Ecosystem and biodiversity services and functions exist on a spectrum of unimpacted or pristine ecosystems to degraded. One ecosystem service of a functioning ecosystem that affects zoonotic disease dynamics is the dilution effect, where high biodiversity means not all species will be suitable pathogen hosts or vectors thus "diluting" any zoonotic pathogens transmission ability within that environment. This function starts to get weaker the more degraded an ecosystem is, with species more adapted to disturbed environments proliferating, creating a more homogonous biodiverse poor dominated ecosystem, such conditions facilitate the transmission of zoonotic diseases. Everard et al. 2020 promote ecosystem restoration to try to return the degraded ecosystem to its more unimpacted state in an attempt to strengthen the ecosystem service of disease regulation, through increased biodiversity and unfragmented habitat.

Several articles (Wallach et al. 2015; Glidden et al 2021) highlight the importance of trophic interactions in restoring ecosystem services, such as disease prevention. Disturbed ecosystems often have very different trophic interactions from the original ecosystem. One of the most prominent features of degraded ecosystems is low biodiversity particularly in apex predators in the food chain, such as large carnivores like wolves, big cats, and bears. The removal of these predators, release population control of herbivores, such as deer and pigs, both of which act as vectors for many zoonotic diseases, especially ticks and rodents which are vectors and hosts of zoonotic diseases (She et al. 2023). Many invasive species are vectors for zoonotic disease, one reason they proliferate is lack of natural predators (Wallach et al. 2015). Native species composition and densities can also change in the absence of apex predators (Wallach et al. 2015). Ecosystem restoration can incorporate top-down regulation of infectious zoonotic disease though protection, rewilding and introduction of apex predators. Reintroducing apex predators, such as wolves and tigers, can help restore and reestablish top-down trophic cascades can have many benefits for disease control, by reducing disease reservoirs such as deer and rodents.

This is one explanation for the spread of tick-borne diseases in North America and Europe, as many of the top predators in the trophic chain are no longer present in these ecosystems, or

if they are, they are in reduced numbers. This is especially true in Europe, where wolves and bears are either locally extinct or found in very low numbers. This leaves deer and wild pigs without predators to control their numbers, resulting in large populations of deer and pigs, and consequently, ticks.

In tropical regions, disturbed and degraded ecosystems are characterized by a shift from old growth pristine forest to human dominated landscapes, Filgueiras et al. (2021) argue that this results in winners and losers in species composition. Losers will be disturbance sensitive species adapted to old growth unfragmented forests; these will decline whereas species able to adapt to degraded habitats will increase. Filgueiras et al. (2021) reason that the ecosystem disservice of zoonotic disease will increase in disturbed environments, examples given are predator- free habitats which will result in an increase of zoonotic reservoir species, such as capybara, increase of meso-predators such as civets and other ferret like creatures which have an increased risk of zoonotic disease transmission and increased proximity of wildlife to livestock which act as a source of blood for vampire bats. Tropical forest restoration has the potential to reduce the ecosystem disservice of zoonotic disease by reducing disturbed and fragmented forest which would otherwise be ideal habitat for species with higher risk of zoonotic disease transmission to humans.

Pires and Galetti (2023) examined neotropical forests and how various degrees of human disturbances have led to three distinct scenarios: Predator-dominated forests ecosystems, these are found in the most naturally intact areas. Large herbivore-dominated forest ecosystems, these occur where predators are scarce or locally extinct. And mesopredator or small seed-eating herbivore-dominated forest ecosystems, these are found in the most disturbed landscapes. These ecosystems are linked to zoonotic diseases due to the dynamics of their specific trophic interactions. In the predator-dominated ecosystems, which are closest to natural systems, the ecosystem services of disease prevention and control are intact, and no single species dominates. In contrast, rodent-dominated ecosystems, where seed-eating is prevalent, have a high abundance of rodents linked to diseases such as Lyme disease, Bartonellosis, and Hantavirus. Mesopredator-dominated communities, with species such as opossums, are associated with diseases like Leishmaniosis, Chagas disease, and rabies. Herbivore-dominated ecosystems are linked to tick-borne diseases and pathologies such as tuberculosis, brucellosis, and anthrax. Human activities have disrupted the original ecosystem dynamics, leading to situations where certain species become abundant. The higher the number of these species, the greater the level of their associated zoonotic diseases. The study recommends that ecosystem restoration efforts should be aware of these dynamics. It’s important to identify the current state of the area to be restored and evaluate if it’s possible to alter some of these dynamics. However, the article doesn’t provide practical advice on how to achieve this.

Hantavirus Cardiopulmonary Syndrome (HCPS) is a zoonotic infectious disease present in Brazil, which is transmitted to humans via the main rodent reservoir species, *Oligoryzomys nigripes* and *Necromys lasiurus*, both of which increase in abundance with deforestation (Prist et al. 2021) these are characteristic of the mesopredator or small seed-eating herbivore-dominated forest ecosystems, these are found in the most disturbed landscapes (Pires & Galetti 2023). Prist et al. (2021) compared sites with forest cover and disturbed forest and modeled predictions of HCPS infection rates based on rodent density and forest type. They concluded that restoring the degraded forests will result in reduced HCPS infection rates because of lower rodent densities.

An example of an emerging zoonotic disease in animals which may have the potential to infect humans in the future is the prion disease, Chronic Wasting Disease (CWD). CWD is seen as a zoonotic disease of concern as it may in the future be similar to the transmission of Bovine Spongiform Encephalopathy (BSE) which can cause Creutzfeldt-Jakob Disease in humans. CWD can infect deer, elk, moose and reindeer, and incidence and range of the disease is spreading in North America and Europe. Restoring, protecting and rewilding native predators such as big cats, wolves and bears can act as a control mechanism for reducing CWD through higher predation of infected animals and reducing potential vector populations (Escobar et al. 2020).

5.2.4 Removal and control of invasive alien species as ecosystem restoration to reduce zoonotic disease risk

Removal and management of invasive species as part of restoration can reduce zoonotic disease risk. Rai and Singh (2020) look at invasive alien plant species which can increase disease in humans mostly by acting as a suitable habitat for vectors of zoonotic disease. Many invasive aquatic plants have been linked to zoonotic disease outbreaks by creating favorable microhabitat conditions either on the plants themselves or by creating stagnant waterbodies for zoonotic vectors. One example is *Eichhornia crassipes* a water hyacinth which creates ideal habitat for mosquito larvae linked to Malaria and other mosquito-borne diseases as well as for snails which can lead to schistosomiasis outbreaks. Another example is the invasive plant species Lantana camara also known as Lantana or railway creeper which is an ideal microhabitat for *Glossina spp*. (tsetse fly), a vector for sleeping sickness. Rai and Singh (2020) recommend ecosystem restoration in collaboration which targets the reduction and removal of invasive plant species which are known as habitats for zoonotic disease vectors and hosts.

Picture 1. Invasive water hyacinth *Eichhornia crassipes* (insert above) creates suitable habitat for mosquito-borne disease and snail-borne disease such as schistosomiasis

Reaser et al. (2021) provide a case study of how invasive plant removal and management can be seen as an ecological countermeasure as part ecological restoration. The case study the use is of removal of the Japanese barberry plant and invasive species which creates ideal microhabitat for the tick-vector and mice-host of Lyme Disease. The Japanese barberry creates a shaded, dense, predator-protected, relatively moist habitat ideal for rodents and ticks, allowing both host and vector to proliferate. Removal of the invasive Japanese barberry therefore reduces that habitat and consequently abundance of rodents and ticks, therefore reducing the risk of transmission to humans.

Another article by Wilson et al. (2021) discussed how *Toxoplasma gondii* is lower in areas with lower population densities, i.e. pristine environments when compared to degraded or human-modified landscapes, which have higher *T. gondii* disease prevalence, this is thought to be because of the accompanying domestic cats and invasive feral cats in these environments. To reduce the risk of *T. gondii* risk to humans they suggest environmental restoration and effective population management of feral cats.

While the removal and eradication of invasive species can be time-consuming and costly, it is often considered feasible and practical on islands due to their smaller geographical areas and isolation. De Wit et al. (2017) examined neglected tropical diseases on islands with invasive mammal hosts, identifying feral cats and dogs, and non-native rodents as significant host reservoirs for the zoonotic diseases: leptospirosis, toxoplasmosis, and rabies. Ecosystem restoration on islands often involves the eradication or removal of non-native invasive species to protect biodiversity by restoring native fauna and flora, De Wit et al. (2017) see this as an opportunity to also reduce the risk of zoonotic diseases of invasive species, creating a win-win situation. They found that the removal of feral cats, dogs, and non-native rodents could considerably reduce the disease risk for leptospirosis, toxoplasmosis, and rabies on islands, arguing that this is a cost-effective measure when compared to public health spending on treating these diseases.

Complete invasive species removal is technically feasible on islands where there are definite seas boundary, but on mainland invasive species have no such restrictions and have the opportunity to constantly replenish and reinvade areas where they have been eradicated much more easily than on islands. To accept this new reality, the term “ecological novelty” is used by restoration ecologists to describe the situation in ecosystems, which are now composed of assemblages of species which did not co-evolve together, but through human induced land use changes, climate change and increased globalized movement of humans, animals and plants, are now living together. This is seen as a hallmark of the Anthropocene and those involved in ecosystem restoration may have to accept that these may be irreversible changes and that restoring an ecosystem to its baseline pre-disturbance state is unrealistic or impossible, removal of plant and large animal species may be possible but removal of invasive insect, parasite and microorganisms is unlikely. This has implications for zoonotic disease as new combinations of microorganisms, viruses, plants, animals, insects, and parasites have been linked to emerging zoonotic diseases and new zoonotic disease dynamics (Dunn & Hatcher 2015). However, this does not mean that this situation should be left to continue Dunn and Hatcher (2015) advocate that there is a need for biosecurity measures which can monitor and control invasive species of animals, plants and microorganisms. Biosecurity methods include international controls on the movement of plants and animals, monitoring of parasites and zoonotic disease, and eradication and reduction measures for invasive species.

Ecosystem restoration should incorporate biosecurity measures for invasive species (Dunn & Hatcher 2015), attempt for the eradication of invasive zoonotic disease host and vector species on islands (de Wit et al. 2017) and target the removal or reduction of invasive plants which create suitable environmental conditions for zoonotic disease and invasive animal hosts and vectors which have been linked to zoonotic disease in humans (Rai & Singh 2020).

5.2.5 Restoring amphibian and bat populations as insect-borne disease vector control.

Borzee et al. (2021) discussed how amphibians can be vectors for certain zoonotic diseases, such as mycobacteria and arboviruses, they are also potential vectors for emerging zoonotic diseases. These species are also a target for wildlife harvesting and trade in China. To reduce zoonotic disease risk, they recommend a ban on the wildlife trade of amphibians, protection and conservation of amphibians, and restoration of amphibian populations through captive breeding and rewilding. Another way that protecting amphibians can reduce zoonotic disease risk is that they also provide an ecosystem service as insect control, targeting insect-vectors such as flies and mosquitoes.

Bats and ecosystem restoration present an interesting topic. Bats can contribute to ecosystem restoration by dispersing the seeds of native fruits (Parolin et al. 2021), and pollination (Osofsky et al. 2023), both vital ecosystem services. They can control agricultural pests and also mosquito-borne and insect-borne vectors, thereby reducing the risk of zoonotic diseases (Osofsky et al. 2023). However, bats have also been associated with other diseases. The public's perception of bats being linked to diseases could pose a barrier to restoring bat populations as part of ecosystem restoration. Education campaigns can help address this issue (Parolin et al. 2021).

6 Ecosystem restoration may increase zoonotic disease risk in humans

One of the overall themes which emerged, which also answered one of my research questions (does ecosystem restoration increase zoonotic disease risk?) was the potential for ecosystem restoration to increase zoonotic disease risk especially on a local level but also on a continental scale. Similar concerns were raised for tick-borne disease, bat-borne disease, mosquito-borne disease, small mammal-born disease and monkey-borne disease. Similarities are that these are all animal vector-borne diseases, and that ecosystem restoration creates suitable habitats which may be close to humans, increasing the transmission risk. The subthemes which supported this were:

- Ecosystem restoration as agroforestry may increase zoonotic disease risk.
- Ecosystem restoration may increase wildlife harvesting and zoonotic disease.
- Ecosystem restoration may increase the risk of tick-borne zoonotic disease.
- Ecosystem restoration may increase mosquito-borne disease.
- Ecosystem restoration may increase bat-borne disease.
- Climate change may lead to higher risk of zoonotic disease in ecosystem restoration.

6.1 Ecosystem restoration as agroforestry may increase zoonotic disease risk.

Rosenstock et al. (2019) support the use of agroforestry as an ecosystem restoration tool to improve human health through enhancing ecosystem services such as, climate change mitigation, climate regulation, food security, soil and water protection and cycling and as a source of plant-based medicines, however they warn that there is a risk that agroforestry may increase the risk of zoonotic disease in humans on a local scale. Agroforestry is a mix of agricultural land, livestock, and fruit plants; thus, agroforestry landscapes resemble that of fragmented forest and forest peripheries both which have been linked to the emergence of zoonotic disease, through zoonotic spillover. Rosenstock et al. (2019) caution that agroforestry landscapes near intact forest may act as a habitat for wildlife which will be in closer proximity to humans and domesticated animals therefore increasing possible transmission of zoonotic disease. This appears to be the case in Malaysia, Bangladesh and Ghana where agroforestry has been linked to a rise in cases of Nipah virus, for example in Malaysia mixed fruit and pig-farming has increased transmission of Nipah virus as the bat-vectors feed on the fruit trees in close proximity to the pig farms. Similarly in Ghana, fruit tree farmers have an increased risks of exposure to bat-borne henipaviruses.

On the whole zoonotic disease is associated with reforestation in temperate more economically developed countries and zoonotic disease is associated with deforestation in economically less developed counties particularly in the tropics. Increased tree cover in the form of oil palm plantations have been linked to increases in mosquito-borne disease, highlighting the complex relationship between tree dominated agriculture and zoonotic disease risk (Morand & Lajaunie 2021).

Agroforestry in Sub-Saharan Africa has been linked to microhabitat formation for malaria vector-mosquitos in the form of tree holes which fill with water creating ideal breeding ground for mosquito larva. The mix of livestock grazing, and forest fragments has also been linked to creating ideal breeding ground for tsetse flies, increasing trypanosomiasis (Sleeping Sickness) risk in humans. One of the benefits of agroforestry is nutrient cycling increasing nitrate and phosphorus in the soil however this can also enrich freshwater sources with these nutrients supporting snail-vectors of schistosomiasis (Rosenstock et al. 2019).

6.2 Ecosystem restoration may increase wildlife harvesting and zoonotic disease.

The harvesting of wildlife for the wild animal trade and their subsequent sale in wet markets is seen as a possible means for the origin of emerging infectious zoonotic disease. To prevent the emergence of infectious zoonotic disease Galindo-González (2021) proposes the ban of live wildlife sales in wet markets along with large-scale ecosystem restoration. The ban on international wildlife in wet markets is important as there is the temptation of collecting wildlife from restored ecosystems.

Although deforestation and forest-fragmentation are still occurring in Myanmar, there are also successful ecosystem restoration and reforestation taking place. Restoration of Myanmar's forests will reduce zoonotic spillover. However, one area of concern for the potential of increased zoonotic disease risk is if local people use the restored forests and their abundant wildlife as a source for wildlife harvesting for local bushmeat consumption and wildlife trade to China. Evans et al. (2020) found that a wide range of species were collected for wildlife trade or bushmeat in Myanmar's The North Zamari Wildlife Sanctuary forests, including reptiles, birds, primates, large carnivores, rodents, bats and pangolins.

Evans et al. (2020) also conducted surveys of local people who harvest wildlife to evaluate zoonotic disease risk from handling wildlife and found that awareness was generally low for example 45% reported being injured and having an open wound but carried on handling the animals without precautions, 21% didn't know and 18% thought there was no health risk in such behaviors, only 7% thought that there would be a risk of infection. Worryingly 14% percent of those questioned admitted to eating an animal that they found already dead and 9% admitted having eaten a wild animal that was clearly sick. This sample of views shows that there is a large risk of transmission of zoonotic disease in people harvesting wildlife in Myanmar.

Evans et al. (2020) recommend raising awareness of the risks of wildlife harvesting in local populations, banning the sale of wildlife for exportation abroad and banning of wildlife harvesting in species such as primates which a very high risk of being vectors of an emerging infectious zoonotic disease. Banning wildlife harvesting in indigenous communities for food and medicinal use was seen as unviable. This study is of importance as it shows that in Southeast Asia wildlife harvesting is significant and that successful ecosystem restoration and subsequent recovery of wildlife in this region may lead to increased zoonotic risk, this also has implications for all ecosystem restoration in that the return of wildlife needs not to be seen as a resource that can be unsustainably used.

6.3 Ecosystem restoration may increase the risk of tick-borne zoonotic disease.

Ticks are vectors of many known transmittable diseases to humans including tick-borne encephalitis, Rocky Mountain Fever, and Lyme disease. Incidences of these diseases have been increasing significantly in North America and Europe. The increase of suitable habitat (woodlands) and their wildlife hosts are thought to be responsible for this increase (Pfäffle et al. 2013). This has implications for ecosystem restoration as will be discussed below.

An article by Köhler et al. (2023) article specifically looked at ecosystem restoration and tick-borne diseases, from the European perspective. The EU has recently passed the nature restoration law and together with biodiversity goals there is an aim to implement large scale ecosystem restoration projects. The article asked the question what the consequences are in

regard to tick borne diseases as a result of these planned ecosystem restoration projects. This question is similar to my thesis question what are the effects of ecosystem restoration on zoonotic disease in humans? The two main tick-borne diseases in Europe affecting humans are Lyme disease and tick-borne encephalitis. The theory is that as more ecosystems are restored there will be more tree cover which is the habitat for ticks and their ungulate hosts, (mainly deer and wild boar) however this relationship is not so simple there are many other factors that affect tick and deer abundance. Also, not all ecosystem restoration projects in the EU will be based on creating woodlands or forests.

Research by Linnell et al. (2020) also support this idea, as they show that wild ungulate populations especially roe deer and boar have increased in range and population because of reforestation, ecosystem restoration and the abandonment of agricultural land throughout Europe as a whole. These changes have the potential to increase the risk of several zoonotic diseases (Lyme disease, tick-borne encephalitis, tuberculosis, and Brucellosis) to humans through increased interaction between wild ungulates, livestock, and humans. Fencing off farm and grazing land is recommended to reduce ungulate-borne zoonotic disease risk to livestock and subsequently humans. Machtinger et al. (2024) show that similar processes are at work in the United States as a result of increased reforestation, ecosystem restoration and the abandonment of agricultural land, however they argue that tick-borne disease is not confined to ungulates alone and that many other common widespread species are hosts for ticks, including rodents, birds, opossums, and racoons. Machtinger et al. (2024) recommend a One Health approach which acknowledges that many wildlife species are potential hosts for ticks and that wildlife should be monitored for tick-borne disease.

Millins et al. (2016) found the same process being played out in the United Kingdom, an increase in woodland and ecosystem restoration has resulted in increases of vector-borne tick populations, densities and distribution, raising the risk of tick-borne disease such as Lyme disease, tick-borne encephalitis in the human population. Management strategies for reducing the risk of tick-borne disease include deer management through culling or fencing off of land; invasive species management such as the culling or eradication of non-native grey squirrels which are also hosts to ticks; tick surveys and pathogen testing; reducing suitable tick habitat alongside paths and trails in woodlands; and educating the public on the risk of tick-borne disease and personal protection measures.

A theme that emerged from the included articles was that articles discussing tick-borne disease mentioned that ecosystem restoration in the form of reforestation, the conversion of cropland to forest and urban greening have led to an increase in ticks and consequently tick-borne disease in North America and Europe (Bellato et al. 2021; Brennan et al. 2023). Although none of the studies investigating ticks-borne disease before and after a specific ecosystem restoration project, some for-example Boyer et al. (2022) did compare tick-density

in different environmental settings and found that tick abundance and consequently tick-borne disease was higher in forested areas, some of which had been restored or reforested environments, from which it can be assumed that forest restoration will have similar characteristics.

Boyer et al. (2022) compared tick abundance in several sites with different environmental conditions and found that the highest abundance was in the restored reforested site. This is a high-quality comparative study which supports the evidence that reforestation and ecosystem restoration does seem to increase zoonotic tick-borne disease risk in Europe.

Boyer et al. (2022) concluded that from their comparative study they found that open parks with mowing lawns with little leaf litter cover pose negligible risk of humans acquiring tick-borne disease, however they found that the site which was allowed to recover naturally without human intervention had the highest risk for catching a tick-borne disease. I would argue that this makes the case that hands off restoration near urban areas is not ideal and that restored areas especially in the peri-urban and urban areas need to be managed with an eye towards tick borne disease.

A similar study by Bellato et al. (2021) found comparable results. Their article talks about how restoration will increase green areas in peri-urban and urban areas, so they examined two green natural park areas near a densely populated urban areas, Turin Italy, and found many tick species to be abundant and the risk of zoonotic tick-borne disease to be high, this serves as evidence of probable future high disease risk in restored peri-urban and urban environments.

Ticks can be infected by several diseases with the ability to infect humans, such as Lyme disease and tick-borne encephalitis. Ticks feed on the blood of many different host species ranging from lizards and birds to small and large mammals. Much focus is on the larger animals such as deer which can harbor numerous ticks on the same body and are highly mobile. This leads to increased infection risk with the diseases between the ticks, other hosts and humans. Not all ticks are vectors of disease, Boyer et al. (2022) found that there were differences in microorganisms in the ticks with range of around 10-20% of ticks infected by a zoonotic pathogen.

The spread of tickborne diseases as a result of reforestation and ecosystem restoration is not confined to Europe and North America. Fang et al. (2015) investigated tickborne disease in China and how this is following a similar trend as in Europe and North America. Highlighting again the connection between tick and restoration reforestation or grassland restoration. And that restoration programs should be aware of these risks.

Ecosystem restoration especially the greening of urban and peri-urban areas will hopefully according to the goals of the restoration increase the number and diversity of wildlife, unfortunately including many species which can potentially harbor ticks. To address the concerns of future spread of tick-borne disease Bouchard et al. (2023) produced risk-maps in a region in Canada, using disease and tick surveillance as well as vulnerability of the human population determined by their knowledge and adoption of preventive behaviors. This allowed the authors to map and identify populations at high risk for TBD in the region. This approach can be used in the planning of ecosystem restoration and urban and peri-urban greening, so that at risk populations can be identified and vulnerability can be reduced through education of protective measures. This could help in the planning of ecosystem restoration projects as they should be located in areas identified with low risk of TBD.

Hanh et al. (2018) investigated tick-borne disease risk to humans in Washington County, Minnesota, USA, they found that lawns, park and garden areas near woodland have the highest incidence of ticks. The recommended clearing brush and log piles from recreational and residential properties near woodlands. They also recommended fencing off areas to prevent deer being visiting parks and gardens will also reduce the risk of tick-borne disease. In addition, people in these areas should use personal prevention methods against tick bites.

Tick borne disease tick borne disease looks set to become an increasing problem for populations in Europe and North America and if the large-scale restoration envisioned by the UN and EU takes place the risk of tick-borne disease decreases, this is an example of one of the ecosystem disservices however the benefits of other ecosystem services could be argued to outweigh the risks of tick-borne disease.

A comparative study by Brennan et al. (2022) in the USA, looked at tick density in restored forest where thinning strategy was used to promote growth of native species, it was found these areas had lower tick density due to more sunlight and drying out which is a relatively unsuitable microclimate for tick, which prefer shaded, moist undergrowth, thinning is recommended for forest restoration. This could be a useful tool for controlling tick-borne disease in forested ecosystem restoration areas. Another study by Mols et al. (2022) found that deer avoid areas close to human-used trails in recreational areas therefore tick abundance was also lower near these trails. They suggest that recreational woodlands should maintain hiking trails and encourage people to stay on them to reduce the risk of tick-borne disease. From this it can be inferred that ecosystem restoration and reforestation projects if open to the public should incorporate walking trails and discourage roaming off these designated trails.

Wimms et al. (2023) investigated prairie grassland restoration in the USA, and found how this is leading to an increase in ticks even though this was not expected, and surprisingly for a

number of potential zoonotic disease species there were larger populations in grasslands compared to forests. That ecosystem restoration of Prairie grasslands also increased tick populations shows that the risk is present in more than just temperate forest restoration projects.

None of the articles in the search results contained information about tick borne disease in tropical areas. This is an area that which needs to be researched in the future especially as large-scale ecosystem restoration projects are set to occur in the tropics this would also have implications for climate change and the spread of invasive take species into North America and Europe as a result of higher temperatures.

Wood and Lafferty (2013) discussed biodiversity and Lyme Disease, they acknowledge that reforestation and ecosystem restoration has spread Lyme disease but also that there is growing evidence that biodiversity is a good protector against many zoonotic diseases, through the dilution effect. They argue that scale and context is important for whether biodiversity is a protection against tick-borne disease. But overall, they found that there is no strong evidence to support biodiversity as a means of reducing Lyme disease risk, as the wildlife are reservoir hosts for the ticks. They suggested introducing wolves and other apex predators to control deer populations as a tick-borne disease reduction method.

Interestingly a study conducted in South America suggested that ecosystem restoration could be a potential tool to reduce tick borne disease risk from capybara, (Polo et al. 2018). The article talks about capybara and their ticks as Brazilian spotted fever, they discuss using reforested riparian land to stop them from moving into sugar cane and other agricultural areas where their birth rate is higher due to increased food supply. Riparian restoration can act as a zoonotic disease control, they also say that this should be done in areas where capybara have not yet reached. This again shows the importance of taking local geographical biological conditions into account when planning ecosystem or environmental restoration no one fits all solution is available. This highlights the need for people familiar with the area to undergo restoration being involved in the process, it is not as simple as mandating reforestation and assuming that this will reduce zoonotic disease as in many localized cases this is not the case. Hopkins et al. (2022) discuss Lyme disease in this context in that the effects of restoration may have unpredictable impacts on local populations however they also state that ecosystem restoration and reforestation can also reduce tick borne disease through the dilution effect, this again highlights complexity of the issue, and they suggest that much needed research into the effects restoration need to be carried out.

Europe serves as a good example of a region where ecosystem restoration is set to increase on a large scale as a result of the EU's aims of restoring 20 of degraded ecosystems by 20230. These restoration goals are to be legally binding to all member states. As discussed earlier,

reforestation and increase of wildlife hosts and vectors are thought to be the driving mechanism behind the increase of Lyme-disease and other tick-borne diseases in Europe. Tomassone et al. (2018) identify other zoonotic diseases which could spread because of large-scale ecosystem restoration in Europe, they term these neglected zoonotic disease as they argue that unlike Lyme-disease these are not well known or researched diseases and large-scale ecosystem restoration could result in the spread, disease surveillance and more research is needed to reduce and mitigate these potential zoonotic diseases. These include Bartonella a pathogen spread by fleas acting as a vector, the host of infected fleas are rodents, including rats, mice, voles and squirrels all of which are expected to increase through ecosystem restoration, reforestation and urban greening.

6.4 Ecosystem restoration may increase mosquito-borne diseases

Medeiros-Sousa et al. (2015) looked at mosquito species abundance in an urban park which had been restored from fragmented forest and agricultural land, they found that this area was a breeding ground for many mosquito species which are vectors for mosquito borne zoonotic disease. The setting was in Sao Paulo Brazil a large urban area. It was found that that these restored environments had an increased risk of mosquito vector borne zoonotic disease. Recommendations were that people visiting the park should take precautions and that mosquito vector bone control should be incorporated in the management of this and similar areas. *A.aegypti* and *A. albopictus*, were present in the park both of which are potential chikungunya vectors. The report found a high diversity of mosquito species. This study shows that peri-urban and urban greening in tropical South America has the potential to increase mosquito-borne zoonotic disease.

Ali et al. (2019) discuss different forest types in Trinidad, South America, including secondary forests, which are forests that have been disturbed or degraded in the past and have recovered or restored. This is an example of forest restoration. The article does not specifically focus on restoration as a theme, but it is useful as it shows that the Mayaro virus, its host reservoir and vectors, are present in high abundance in secondary forests. It can be inferred that forest restoration has increased the habitat for Mayaro virus host and vectors, and that secondary restored forests, as well as other forest types, increase the transmission risk to human populations. The study used ArcGIS software to conduct a proximity analysis and found that urban areas and human populations within a 1 km buffer zone at the edges of the forests are at increased risk of mosquito-borne disease, including Mayaro. This article is important as it demonstrates how proximity analysis can be conducted for specific zoonotic hosts and vectors in order to calculate and identify human populations at increased risk of disease transmission. Exclusion zones of human settlement or increased vector and host control, or mitigation measures can be focused on areas identified as high risk. This article is also relevant as it demonstrates how monitoring and sampling of vectors can be an effective

tool to estimate presence and distribution of potential zoonotic disease. The Mayaro Virus Disease (MAYVD) is an emerging zoonosis transmitted by mosquitoes. It is endemic to Central and South America. The primary reservoirs for this virus are primates, and the main vectors are mosquitoes of the *Haemagogus* species. MAYVD causes arthralgic syndromes, and its symptoms are similar to those of Zika, Dengue, and Chikungunya, which are also mosquito-borne diseases prevalent in the region. There have been localized outbreaks of MAYVD, and it has the potential to become a pandemic.

Awuku-Sowah et al. (2023) conducted interviews with a diverse group of individuals involved in mangrove restoration, including environmental journalists, health workers, and local residents. The residents mentioned that due to measures taken to mitigate mosquito-borne diseases, they do not view these diseases as unmanageable. They also do not perceive an increase in mosquitoes as a problem, as they can take precautionary measures. The respondents also noted that the mosquitoes in the mangroves were larger, slower, and less likely to bite humans than the smaller, faster mosquitoes found in urban areas. This was suggested because the mangrove mosquitoes have an increase in birds to feed off and are not as nutrient deficient as urban mosquitoes, where humans are presumably the target. A limitation of this study is that this information is subjective. However, it is useful as it reveals the local population's attitudes towards mangrove restoration. They are not opposed to it on the basis of potential zoonotic disease risk from mosquito-borne diseases. The informants, including the health workers, acknowledged that there is a large number of mosquitoes in the mangroves but believe that they are not necessarily infected with Malaria or other diseases. The health and other benefits of the restored mangroves seem to override any concerns with an increase in mosquito-borne disease, and there was already a mosquito problem before the mangroves were restored.

Although only this one qualitative study looked at attitudes to restoration project, of mangroves in Ghana, its showed that the respondents were aware of the potential for mosquito borne disease to increase, however they did not see it as a reason to stop restoration as they valued the other ecosystem services which were enhanced such as food fish security and wood, storm protection, and as a nursery for fish.

6.5 Ecosystem restoration may increase bat-borne disease risk

Bats and ecosystem restoration present an interesting topic. Bats can contribute to ecosystem restoration by dispersing the seeds of native fruits (Parolin et al. 2021), and pollination (Osofsky et al. 2023), both vital ecosystem services. They can control agricultural pests and also mosquito-borne and insect-borne vectors, thereby reducing the risk of zoonotic diseases (Osofsky et al. 2023). However, bats have also been associated with zoonotic diseases. The public's perception of bats being linked to diseases could pose a barrier to restoring bat

populations as part of ecosystem restoration. Education campaigns can help address this issue (Parolin et al. 2021).

However, Goncalves, Galetti and Streicker (2021), warn of the risks of tropical ecosystem restoration and reforestation and wildlife rewilding as it has the potential to increase bat-borne zoonotic risk in humans and livestock, through creating suitable habitat and intermediate vectors sources for vampire bats, in human dominated landscapes. They argue that rewilding and restoration projects in regions where vampire bats are present need to take into account the potential for rabies outbreaks and surveillance and monitoring of both human, livestock and wildlife should be incorporated in such projects. Suggested infection prevention control measures could include vaccinating large wildlife such as tapirs before they are released in rewilding projects, as well as monitoring vampire bat populations, which could be managed through sterilization when rabies outbreaks are detected. There are ethical considerations that need to be taken when releasing animals as part of ecosystem reconstruction rewilding, in that safeguards must be made when releasing animals into environments where there is the potential for them to become infected with zoonotic disease or to infect already established wildlife or local human populations (Thulin & Rocklinsberg, 2020) as recommended by Goncalves, Galetti and Streicker (2021) vaccinating animals before being released in rewilding projects can help alleviate such concerns. Stronen, Iacolina and Ruiz-Gonzalez (2019) also warn of the potential of novel zoonotic diseases to emerge through rewilding of animals into human modified landscapes as part of restoration efforts.

Hughes et al. (2023) briefly discuss the importance of preserving cave habitats, so that bat habitats are not disturbed, and bat populations are healthy, stressed bats are more likely to succumb from disease and die where they may be eaten by intermediate species which could act as transmission to human populations, or then look for other places to roost putting them in closer contact with domesticated animals and humans. Therefore, although not mentioned in the article it can be inferred that restoring cave ecosystems will have positive benefits for reducing zoonotic disease risk in humans.

6.6 Climate change may lead to higher risk of zoonotic disease in ecosystem restoration

Restoration of wetlands in the UK has been supported by policymakers as part of climate change mitigation and resilience efforts, in that wetlands protects against flooding and rising sea levels. Currently there is no risk in an increase in zoonotic disease from mosquito-borne disease from wetland restoration, unlike in many other countries, as the UK is free from mosquito-borne diseases. (Medlock & Vaux 2015). However, future climate change predictions in which the UK gets warmer and wetter, would result in wetlands in the UK as possible habitats for mosquito vectors of diseases such as Malaria, West Nile Virus, Rift Valley Fever Virus, Dengue Fever, Chikungunya, and Yellow fever. (Medlock & Leach 2015). The possible

risk of these diseases becoming established in the UK is high as potential vector species of mosquitoes are present in the UK (Medlock & Vaux 2015).

This is not restricted to wetlands and mosquito-borne disease as other zoonotic and insect-vector-borne diseases could also become established in the UK as a result of climate change such as Leishmania from sandflies and tick-borne diseases. (Medlock & Leach 2015). This potential establishment of zoonotic disease in host and vector species in a future warmer and wetter UK has implications for ecosystem restoration, as current restoration projects should take these into account when planning and designing stages in order to mitigate these threats as well as monitoring and disease surveillance measures put in place to detect these zoonotic diseases if and when they do arrive. Governmental public health authorities are already developing guidance for the Environment Agency and wetland managers on how these risks can be managed and mitigated during a zoonotic disease outbreak. (Medlock & Leach 2015).

The unknown effects of climate change on zoonotic disease dynamics on ecosystem restoration, especially wetland restoration and urban greening calls for monitoring of climate-sensitive infectious zoonotic and vector disease, adaptation and mitigation, and a resilient public health system prepared to respond to zoonotic disease outbreaks (Rocklöv et al. 2023).

Goncalves et al. (2021) modelled future climate change scenarios on the distribution of bats in South America, finding that bats which are adapted to colder mountainous habitats may go extinct or decline, whereas bats adapted to warmer temperatures increase their range. They promote ecosystem restoration to connect habitats which will help bats adapt to climate change but caution that there could be an increase in zoonotic disease since bats are highly mobile and will move to more suitable habitats which may overlap with human populations bringing with them the increased risk of bat-borne disease.

7 Tools and strategies for management of ecosystem restoration to reduce zoonotic disease risk.

Ecosystem restoration should be conducted with an awareness for the potential increase in zoonotic disease risks. The literature suggested numerous ways to mitigate or reduce the risk of zoonotic disease. These include removal of invasive species, reinstating top-down predator controls, managing microhabitats conducive to disease, disease and wildlife surveillance, monitoring, predicting and awareness, prevention, and risk reduction behaviors in local populations. GIS and modelling software can help predict and map risk areas and create modelling scenarios for potential disease outbreaks. There is a need for ecosystem restoration projects to include surveillance, forecasting, and vulnerability mapping for zoonotic disease. This section of the thesis includes examples from the articles of the literature search results.

Although ecosystem restoration may be seen as low-tech and nature based, advances in technology can aid in reducing the risk of zoonotic disease in humans.

7.1 Vector-borne disease surveillance using diagnostic laboratory analysis

Ecosystem restoration in areas where ticks are present, it would benefit health stakeholders from surveillance on tick-borne diseases present in the restored areas ticks. Bellato et al. (2021) conducted surveillance on tick-borne diseases in various urban green areas in Turin, Italy and found using laboratory analysis that in some locations sampled ticks were infected with tick-borne disease, Borrelia burgdorferi (24.1 % of sampled ticks harboured the virus), *Anaplasma phagocytophilum* (2.9 %), and Spotted Fever Group rickettsiae (30.4 %). Tick-borne encephalitis virus was not present in the sampled ticks. This kind of study shows that as tick-borne disease has been associated with ecosystem restoration there are surveillance and laboratory analysis tools that can be used to identify which diseases are present and take appropriate preventative and mitigation measures such as educating the population on personal protection methods.

7.2 Proximity analysis and zoonotic disease vector and host distributions using GIS

Concerned about the possibility of a future outbreak of Mayaro virus disease (MAYVD) on the island of Trinidad, Ali et al. (2019) and wanting to provide valuable data for mitigation of such an outbreak by mapping the distribution of Mayaro virus vector species of *Haemagogus* mosquitoes, such data would allow for effective vector control in the occurrence of an outbreak. The distribution, presence and species composition of *Haemagogus* mosquitoes in 22 sampling sites in several different representative forest types were recorded as well as conducting Proximity analysis using Geographic Information Systems (GIS) software ArcGIS, this tool was used to determine the distance between *Haemagogus* mosquito locations and the surrounding urban communities. Using traditional insect sampling methods and GIS technology they were able to identify communities most at risk from a Mayaro virus or other mosquito-borne disease. This study serves as an example of how ecosystem restoration projects could use mosquito vector abundance and distribution and GIS aided Proximity analysis to mitigate and prepare for mosquito-borne zoonotic disease outbreaks. Proximity analysis of distance between urban populations and zoonotic disease vectors in restored ecosystems could be used to identify and monitor at risk populations and allow for effective targeting of preventative and control measures (Ali et al. 2019; Diao et al. 2022).

7.3 Zoonotic disease risk-mapping

To address the concerns of future spread of tick-borne disease Bouchard et al. (2023) produced risk-maps in a region in Canada, using disease and tick surveillance as well as vulnerability of the human population determined by their knowledge and adoption of

preventive behaviors. This allowed the authors to map and identify populations at high risk for tick-borne disease in the region. This approach can be used in the planning of ecosystem restoration and urban and peri-urban greening, so that at risk populations can be identified and vulnerability can be reduced through education of protective measures. This could help in the planning of ecosystem restoration projects as they could be located in areas identified with low risk of tick-borne disease.

7.4 Predicting, forecasting and modelling of zoonotic disease vector and hosts species distributions using GIS

Diao et al. (2022) used Geographic Information Systems (GIS) and wildlife population modeling to create different scenarios for the future possible distribution of raccoon dogs, in Shanghai, China, based on different forest and urban ecosystem restoration plans to green the city. They used the data to extrapolate the population of raccoon dogs based on varying degrees of urban greening scenarios. Racoon dogs are a host for zoonotic diseases such as rabies, and Lymes disease as well as parasites such as tapeworms. Raccoon dogs are increasing their range in Shanghai and other Chinese urban areas because of ecosystem and urban greening efforts. This increases the zoonotic disease risk to humans in urban environments. Diao et al. (2022) concluded that urban greening by restoring the urban natural environment will result in increased raccoon dog populations by providing suitable habitat. Increased human and raccoon dog interaction therefore has the potential to increase zoonotic disease risk in Chinese urban areas.

7.5 Using GIS and Land Use and Land Cover Change analysis (LUCC) to predict areas at high risk for the emergence of a new zoonotic disease

Using Geographic Information Systems ArcGIS and anthropogenic land use and land cover change (LUCC) prediction data. Cao et al. (2022) were able to create models of potential wilderness loss to identify areas at high risk for the emergence of a new zoonotic disease so as to identify these areas for ecosystem restoration prioritization.

7.6 Zoonotic disease early-warning systems using vulnerability mapping and epidemiological forecasting

Eco-environmental early-warning systems can be developed for many environmentally sensitive diseases, such as leptospirosis and other zoonoses. These early warning systems are an effective tool to monitor changes in the ecosystem and environment that create conditions favorable for a disease outbreak. Epidemiological forecasting can be used to predict and control leptospirosis outbreaks, which can produce vulnerability mapping and early warning forecasts. Convertino et al. (2022) explored how to predict leptospirosis outbreaks using topographic wetness and rainfall data.

Convertino et al. (2022) also discussed the implications of restoration programs that alter local topography, such as the creation of wetlands, ponds, etc. which are likely to flood, when high rainfall occurs. Leptospirosis is a neglected tropical zoonotic disease that causes symptoms which are very similar to those of meningitis, hepatitis, yellow fever, haemorrhagic fever, and dengue fever. Leptospirosis is caused by bacteria that can infect many different species of animals, rodents being the most important hosts for transmission to humans. Humans can contract leptospirosis through contact with the urine or feces of infected animals, or with soil or water that is contaminated with them. Leptospirosis thrives in wet conditions, and weather events such as flooding and high rainfall increase the habitat available for the bacteria. However, these conditions also drive rodents to seek shelter in homes and farms, which consequently increases the risk of human exposure and transmission. Convertino et al. (2022) argues that ecosystem restoration planning in areas endemic for leptospirosis should consider the disease dynamics related to hydrological morphology. This implies that care should be taken to restore ecosystems in a way that reduces flooding risk, or at least does not increase it or create habitats such as ponds and wetlands that are susceptible to flooding near populated areas.

7.7 Zoonotic disease surveillance following ecosystem restoration

An example of the need for zoonotic disease surveillance following ecosystem restoration is provided by Giraudoux et al. (2019) who discuss how ecosystem restoration and reforestation programs in Gansu Province, China, may lead to the reemergence and increased zoonotic risk in a disease once eradicated in the region. Human alveolar echinococcosis is caused by infection with *Echinococcus multilocularis* a pathogenic helminthic zoonosis. Transmission is thought to occur via transmission of wild rodent population to humans via the intermediate species of foxes and dogs. Ecosystem restoration in the region has resulted in an increase in wild rodent and red fox populations and there is the potential for this to spread to domesticated dogs and finally to humans. Although this has not yet been documented the authors recommend disease surveillance systems for *Echinococcus multilocularis* in dogs and Human alveolar echinococcosis in humans so that if the disease does reemerge action can be taken to safeguard the local population.

Johnson et al. (2023) discuss Passive acoustic monitoring (PAM) as an effective surveillance tool for detecting the present of zoonotic disease hosts and vectors in an area. Bioacoustics can be used to identify and detect the sounds produced by many animal species that are, reservoirs, hosts or vectors for zoonotic disease, including primates, birds, rodents, large mammals, amphibians and bats. In addition, acoustic monitoring can also be used to monitor human activity, which has implications for disease transmission, in the restored area, through recognizing voices and other manmade sounds of such as chainsaws and forestry equipment, as well as detecting livestock and domestic animals. Acoustic monitoring can therefore act as

an effective surveillance and monitoring tool for human and domesticated animal activity as well as wildlife.

8 Discussion

8.1 Significance of the results

On the whole zoonotic disease is associated with reforestation in temperate more economically developed countries and zoonotic disease is associated with deforestation in economically less developed counties particularly in the tropics (Morand & Lajaunie 2021). These two trends have important implications for ecosystem restoration and were supported by the results of this integrative literature review.

The main results found that ecosystem restoration especially in the tropics and forested wildness areas can prevent emerging infectious zoonotic diseases (Everard et al. 2020; Glidden et al. 2021; Keesing & Ostfeld 2021; Sandifer et al. 2015). The mechanism through which this is hypothesized to work is through strengthening ecosystem regulation of disease though high biodiversity mediated dilution effect and through the prevention of zoonotic disease spillover (Everard et al. 2020; Glidden et al. 2021). Large scale ecosystem restoration is seen as a protective measure against a future zoonotic pandemic disease (Robinson et al. 2022; Wang et al. 2022). High priority target areas are fragmented tropical forest habitats and the periphery of remaining primary forests and intact wilderness areas (Buřivalová et al. 2023; Cao et al. 2022; Guégan et al. 2023; Mohan et al. 2021; Okeke et al. 2022; Robinson et al. 2022; Shyamsundar et al. 2021). However, ecosystem restoration can also lead to the increase and spread of already known and endemic zoonotic diseases through increased wildlife resulting in higher animals to human transmission risk (Rosenstock et al. 2019). The most researched example being the spread of Lymes Disease in Europe and North America. (Köhler et al. 2023; Pires & Galetti 2023; Reaser et al. 2021). The mechanisms through which these are hypothesized to work is through an increase of available habitat resulting in increased abundance of wildlife and subsequent increased risk of transmission of zoonotic disease in humans. This problem is compounded by human induced trophic changes such as reduction or extermination of large apex predators such as wolves and bears which would otherwise keep deer and other wildlife populations in check, free of such top-down restraint's deer, and other animal numbers are higher than they would be otherwise, resulting in high incidence of zoonotic disease (Glidden et al 2021; Pfäffle et al. 2013; She et al. 2023; Wallach et al. 2015). High at-risk areas identified for an increase of zoonotic disease because of ecosystem restoration are peri-urban and urban areas where high wildlife and population densities would increase the risk of transmission of zoonotic disease through

increased human-animal interactions (Bellato et al. 2001; Bouchard et al. 2023; Hanh et al. 2018; Medeiros-Sousa et al. 2015; Thorn et al. 2021).

There is evidence to suggest that ecosystem restoration projects seem to carry with it the risk of zoonotic disease outbreaks. The primary risks appear to be an increase in tick-borne diseases and closer contact between wildlife and humans (Glidden et al 2021; Pfäffle et al. 2013; She et al. 2023; Wallach et al. 2015). Despite these risks, restoration projects should proceed due to their numerous benefits (Speldewinde et al 2014; Wang et al. 2022; Yin et al. 2021). However, it's important for planners to be aware of potential risks. While the overall impact is positive, there could be an increase in certain risks. These can be reduced and mitigated to ensure the success of restoration projects without compromising human health. Precautions can be taken to mitigate these risks. In the Northern Hemisphere, where tick-borne diseases are prevalent, education campaigns focusing on prevention could be beneficial (Millins et al. 2016). In areas where wetland restoration could lead to an increased risk of vector-borne diseases from mosquitoes, mosquito control measures need to be implemented (Medlock & Leach 2015; Medlock & Vaux 2015). There's also a concern that a rise in wildlife populations might tempt people to consume bushmeat. In regions where bushmeat is consumed, awareness campaigns about zoonotic risks are necessary, along with monitoring of markets and regulations to prohibit wet markets (Evans et al. 2020; Galindo-González 2021).

To gain public support for large-scale restoration projects, one strategy could be to create recreational areas. These spaces would offer health benefits to the public. However, there's a potential downside: an increased risk of zoonotic diseases. One of the advantages of urban restoration projects is that they provide recreational spaces, which have numerous health benefits for local populations. However, this could lead to more interactions between humans and animals, potentially increasing the risk of disease transmission. Therefore, it's crucial to implement education campaigns and vector control measures, considering that people will be using these spaces. A health impact assessment on recreation is also necessary. People should be allowed to use these spaces, but it should be done safely. It's the responsibility of the restoration project planners to mitigate this risk (Medeiros-Sousa et al 2015).

The impact of large-scale restoration projects on the incidence of zoonotic diseases in human populations is currently uncertain due to a lack of scientific evidence (Shanks et al. 2022) Therefore, the precautionary principle should guide restoration efforts. This principle can be integrated with environmental and health assessments for each project. On an individual level, restoration projects could potentially increase the incidence of local diseases. However, if large-scale restoration is achieved, for instance, if the UN meets its target of restoring 30% of land by 2030, and the EU fulfills its more ambitious plan of restoring almost all ecosystems by 2050 (European Commission 2022) the health benefits of reducing zoonotic diseases may become apparent. We may need to restore a significant number of areas or

percentage of land before we can observe the effects on pandemic prevention and a reduction in larger disease outbreaks. Of course, if these measures prevent outbreaks, we may never know for sure. Long-term data would be needed to determine whether wide-scale restoration could lead to a reduction in pandemic diseases and disease outbreaks. For now, we must proceed with caution and adhere to the precautionary principle.

Two main ideas emerge from this discussion. The first is the direct interaction of zoonotic diseases and the disruption caused by a specific disease, along with strategies to combat it. The second is the broader concept of ecosystem services, which includes disease control. The evidence supporting these services is somewhat vague, so it might be beneficial to focus on specifics. Large-scale ecosystem restoration may reduce zoonotic disease interactions due to enhanced ecosystem functions, structures, and processes. These are extremely complex and not fully understood. Even if the suppression of zoonotic diseases cannot be explicitly demonstrated, the overall effect may still be present. This is particularly true if we consider ecosystem services and functions. Improvements in air quality, soil quality, water quality, etc., can indirectly reduce zoonotic diseases. Therefore, both direct and indirect factors are at play.

As already mentioned there seems to be more evidence for the increase in zoonotic risks related to ecosystem restoration, this was not what I expected, my own bias was that I assumed it would have a positive effect, this is because of the often-cited benefits of ecosystem services and the shown effects of degraded land and deforestation on zoonotic disease risk increasing. However, proving a negative may be harder, if the restoration does not cause an increase in zoonotic disease, it may not be noticed. Comparative studies investigating zoonotic disease risk before and after a ecosystem restoration project would provide valuable information.

8.2 Recommendations and guidelines for ecosystem restoration projects

Below are some useful questions which could be recommended using to guide participants of ecosystem restoration projects in regard to implications for zoonotic disease risk. These should be specific to the local context of the area that will undergo restoration.

- Is there a zoonotic disease risk problem?
- Has this been caused or exacerbated by land use change or environmental degradation?
- Is it possible to identify the mechanism of the disease risk?
- Can specific restoration measures be taken to reduce or eliminate the disease risk?
- Is it possible to measure the effects of the restoration measures, so as to evaluate if the restoration measures were successful?

- If successful share the results/knowledge.
- Can the success be replicated elsewhere?
- Can the restoration measures be maintained?

Guidlines for those conducting ecosystem restoration which could help reduce or mitigate zoonotic disease risk and strengthen disease regulation and zoonotic infectious disease prevention and control, include:

1. Adopt a theoretical framework to guide the restoration project, Planetary health One Health, Landscape immunity-approaches and ecosystem services and disservices are all complementary and suitable for ecosystem restoration. These frameworks recognize the anthropogenic causes of ecosystem degradation are driving changes in ecological functions of disease regulation and increased interaction between zoonotic disease wildlife hosts and vectors and domesticated animals and humans. When choosing a hierarchical spatial scale, choose what is relevant, (planetary scale, national scale, regional, or local scale) to the zoonotic disease outcomes. Sustainable development can also be included as well as adopting the precautionary principle to mitigate and manage adverse effects pre-emptively. Applying the concept of ecosystem services, the higher the biodiversity in a restoration project the stronger the infection prevention and control value of the dilution effect. Therefore, restoration projects should strive for high biodiversity. (Bawa et al. 2021; Bouchard et al. 2023; Felappi et al. 2020; Harrison et al. 2020; Hopkins et al. 2020; Lawler et al. 2021; Machtinger et al.2024; McNeely 2021; Nishi & Hashimoto 2022; Reaser et al. 2021; Rocklov et al. 2023; Rosenstock et al. 2019; Shanks et al. 2022; Vaz et al. 2017; Yin et al. 2021, Wang et al. 2022).

2. The higher the biodiversity in a restoration project the stronger the infection prevention and control value of the dilution effect. Therefore, restoration projects should strive for high biodiversity (Everard et al. 2020; Glidden et al. 2021; Keesing & Ostfeld 2021; Sandifer et al. 2015).

3. Ecosystem restoration should be focused on restoring fragmented forests in order to reduce zoonotic spillover risk (Buřivalová et al., 2023; Cao et al. 2022; Guégan et al. 2023; Mohan et al. 2021; Okeke et al. 2022; Robinson et al. 2022; Shyamsundar et al. 2021).

4. Ecosystem restoration should aim to restore apex predators to restore top-down trophic controls of herbivores and rodents which act as vectors and hosts of zoonotic disease (Everard et al. 2020; Filgueiras et al. 2021; Glidden et al 2021; Pires & Galetti 2023; She et al. 2023).

5. Ecosystem restoration should involve removal or eradication of invasive species, especially plant species which are known habitat for zoonotic host and vectors (De Wit et al. 2017; Rai & Singh 2020; Reaser et al. 2021; Wilson et al. 2021).

6. Ecosystem restoration should support amphibian and bat populations which act as insect-borne zoonotic disease vector control (Borzee et al. 2021; Osofsky et al. 2023).

7. Ecosystem restoration which involves agroforestry should identify and monitor for increases in zoonotic disease and take appropriate measures to reduce the risk in the local population. Special attention should be given to bat-borne diseases such as Nipah virus. (Morand & Lajaunie 2021; Rosenstock et al. 2019).

8. Ecosystem restoration should educate the local population on the zoonotic disease risk of wildlife harvesting and efforts made to prevent the harvesting of wildlife for exportation abroad (Evans et al. 2020; Galindo-González 2021).

9. Mosquito-borne zoonotic disease should be monitored, and appropriate mosquito control measures should be incorporated into ecosystem restoration in areas endemic to mosquito-borne zoonotic disease (Ali et al. 2019; Lliso et al. 2022; Medeiros-Sousa et al. 2015; Medlock & Leach 2015; Medlock & Vaux 2015; Rai & Singh 2020).

10. Reduce common reservoir hosts where they are over abundant. There seems to be a link between high biodiversity and lower disease transmission to humans, plants, and animals. The suggested mechanism for this link is the dilution effect. Reservoir hosts (the species most likely to be infected and spread disease) tend to be more abundant in damaged environments, i.e. rats, mice, mosquitoes. Therefore, one principle that could guide ecosystem restoration would be that the higher the biodiversity in a restoration project the higher/stronger the infection prevention and control value. Therefore, restoration projects should strive for high biodiversity. (Reaser et al. 2021; Pires & Galetti 2023; Prist et al. 2021).

11. Rewilding and restoration projects in regions where vampire bats are present need to take into account the potential for rabies outbreaks and surveillance and monitoring of both human, livestock and wildlife should be incorporated in such projects. Suggested infection prevention control measures could include vaccinating large wildlife such as tapirs before they are released in rewilding projects, as well as monitoring vampire bat populations, which could be managed through sterilization when rabies outbreaks are detected (Goncalves, Galetti & Streicker 2021).

12. Proximity analysis of distance between urban populations and zoonotic disease vectors in restored ecosystems could be used to identify and monitor at risk populations and allow for effective targeting of preventative and control measures (Ali et al. 2019; Diao et al. 2022).

13. Conduct surveys or interviews with people living in or near the ecosystem restoration project on their knowledge of zoonotic disease risk and prevention measures. Such information would be useful for identifying groups with poor or incorrect knowledge on zoonotic disease risk transmission allowing for public health education and promotion programs to target these groups. (Evans et al. 2020)

14. Hanh et al. (2018) investigated tick-borne disease risk to humans in Washington County, Minnesota, USA, they found that lawns, park and garden areas near woodland have the highest incidence of ticks. The recommended clearing brush and log piles from recreational and residential properties near woodlands. They also recommended fencing off areas to prevent deer being visiting parks and gardens will also reduce the risk of tick-borne disease. In addition, people in these areas should use personal prevention methods against tick bites.

15. Ecosystem restoration can be carried out using a participatory integrated assessment (PIA) approach which is multisectoral collaboration and communication, between businesses, policymakers, local populations all of which should be involved in finding solutions to any zoonotic disease issues that may arise. (Huang et al. 2015).

8.3 Gaps in the knowledge and further research questions

Apart for Lyme disease (Köhler et al. 2023) and hantavirus (Prist et al. 2021) there were few articles which were disease specific, most articles talked about zoonotic diseases in general or gave various examples of zoonotic diseases but did not focus specifically on one. This was surprising as I was expecting more articles about wetland restoration and malaria, or another mosquito borne disease. Further research looking at a specific zoonotic disease, for example Dengue risks before and after an ecosystem restoration would be useful. Such studies would provide valuable information which could be used for disease infection and control and public health efforts. There is a need for a database or body of research that specifically and explicitly investigates the impact of ecosystem restoration and specific zoonotic diseases. This would be beneficial for both ecosystem restoration stakeholders, environmentalists, governments and those working in the health care field. If an ecosystem restoration project could be proven to reduce the risk of infection to humans, this could be used by environmentalists to gain public and governmental support acting as justification for the

restoration and would offer public health stakeholders a nature-based solution to zoonotic disease prevention and control. On the other hand, if an ecosystem restoration project can be proved to increase a specific zoonotic disease risk of infection in humans this could allow health authorities in areas with similar restoration projects to take mitigation, surveillance and prevention measures to reduce the disease risk to the local population.

Surprisingly, there is little mention of rewilding and species introductions, especially in the tropics, as reintroduction of wildlife is often part of ecosystem restoration. The restoration of original species, including those that have locally gone extinct, could alter the dynamics of zoonotic diseases. This is an area that requires future research, particularly to monitor rewilding efforts in restored ecosystems. Further research in this area could help promote the cause of rewilding efforts worldwide. For example, studies could investigate zoonotic disease risk in local human populations before and after the rewilding of wolves or other apex predator. This type of research would increase understanding of the effects of apex predators on zoonotic disease regulation and could be used by rewilding stakeholders to gain public support for introduction of animals seen by the public as dangerous.

While there were many articles focused on ecosystem restoration and tick-borne disease, especially Lyme disease, in Europe and North America, there were no articles discussing ecosystem restoration and tick-borne disease in tropical and sub-tropical regions. Tick-borne diseases are not confined to the temperate northern hemisphere. Many tick diseases, such as bond tick, which is a vector for various diseases, occur throughout the tropics. This is a crucial area of research that needs to be explored, particularly the effects of tropical reforestation and ecosystem restoration on the risk of tick-borne disease transmission in humans. If large-scale restoration occurs in the tropics, will it follow the same trend of increased tick-borne disease as seen in Europe and North America? This is a question that needs to be addressed to safeguard health from a potential increase in tick-borne disease in the tropics due to reforestation and ecosystem restoration.

While mentioned by Borzee et al. (2021) there was surprisingly no articles discussing birds, bats, fish, or amphibians, such as frogs, as vector control for insect-borne zoonotic disease. Successful environmental restoration would provide a habitat for creatures such as birds and frogs capable of insect-vector control. This could be a fruitful area for future research to focus on as it could provide more support for ecosystem restoration as a tool for reducing zoonotic insect-vector diseases.

Another gap in the literature results of this thesis was there was no information on the effects of ecosystem restoration, zoonotic disease and animal migration. Could ecosystem restoration projects provide suitable stop-over points for migrating species, especially birds which potentially can be infected with zoonotic diseases such as bird flu or carry ticks? Would these

restored areas then have the potential to attract species capable of transmitting disease to local populations? This question is especially relevant to urban greening and urban environmental restoration efforts as high-density populated areas could be vulnerable to a zoonotic disease outbreak caused by migrating birds.

This leads to another area of future research concerning urban areas. For instance, consider large-scale urban environmental restoration and urban greening in tropical and sub-tropical mega-cities like Bangkok, Thailand or Sao Paulo, Brazil, with populations in the 10s of millions. Conditions like these have never existed before in human history, so there are many unknowns. Would largescale urban greening lead to an increase in urban wildlife or insect vectors. Millions of humans living in high density with tropical animals is a relatively new phenomenon with implications for human health and zoonotic disease risks.

Another gap in the literature results of this thesis was there was no information on the effects ecosystem restoration on carrion animals such as vultures and jackals, which eat dead animal carcasses. Carrion species could be expected to increase in number and diversity in restored areas, as these animals remove the bodies of dead animals, including those who have died from zoonotic disease, they could have a disease regulating function. So, a further area of research could be investigating if ecosystem restoration increases carrion animal numbers, and do they have a positive or negative effect on zoonotic disease?

There were few studies in this thesis integrative literature research results that focused on the effects of climate change. The effects of climate change on future and existing restored ecosystems need to be investigated in relation to zoonotic disease. How will changes in the future because of climatic changes in rainfall, temperature, and extreme weather events, effect zoonotic disease risk would be a useful area of research to support governmental and public health stakeholder response to climate change by prevention measures, mitigation and resilience.

As highlighted by the gaps in knowledge and further research areas discussed, there is a general lack of research focusing specifically on ecosystem restoration and zoonotic disease risk. There should be more comparison studies on different zoonotic diseases especially evolving before and after restored ecosystems or comparing areas with restored ecosystems to controls in degraded ecosystems. Such research could help build an evidence base to guide ecosystem restoration efforts with a focus on improving human health. In the health field intervention studies would be very valuable to see if restoring ecosystems does indeed reduce zoonotic disease in the local population, however these kinds of studies may be very complex and difficult to execute, due to the complex nature of interactions between disease, humans and the environment, but would be invaluable to guide future restoration projects on the on the risk of zoonotic disease dynamics.

Wegner et al. (2022) acknowledge that there is still debate between links between wildlife zoonosis and newly emerging infectious diseases in humans caused by spillover effect, they argue that this is because it would be very difficult to detect the origin and emergence of such a disease in real time, as there are so many complicated factors involved the but recommend adopting the precautionary principle. The precautionary principle needs to be adopted and that we should assume that the following socio-economic drivers of increased wildlife origin infectious disease are livestock driven tropical deforestation, livestock production in and wildlife hunting and trade.

8.4 Limitations

This thesis was authored alone, this provides some limitations to the results of this integrative literature review that needs to be acknowledged. Working alone places limitations to the amount of data that can be analyzed due to time constraints and workload, and the large number of included articles, 77 in total, meant I was not able to evaluate the strength and quality of each research paper. One person analyzing the results is also not ideal as it limits different perspectives, expertise and viewpoints which could be added by a second author. Working alone also impacts the subjectivity of this thesis; my personal conscious and unconscious biases could have influenced my interpretation of the results and article selection. Having a second author would have involved discussion and consensus on interpretation of results and key findings and themes. Having one author also affects quality assurance, as working alone may have increased the risk of overlooking important data or make errors in data extraction or analysis. Peer review and collaboration with a second author would have improved the accuracy and reliability of the literature review.

9 Conclusions

We won’t be returning to the Holocene era anytime soon. We are now in the Anthropocene, which means ecosystem restoration will not be able to turn back time to a pristine state. The environment is evolving into a new mix, with invasive species, introduced or restored species, climate change, different plant and animal assemblages, and increased human influence. We must come to terms with this new situation; we are in uncharted territory.

Large-scale ecosystem restoration will not take us back in time. Other global trends, such as population increase, urbanization, and globalization, are continuing. Therefore, we must apply the precautionary principle and assume that there will be some increase in zoonotic diseases. However, if we don’t undertake large-scale restoration, the precautionary principle suggests that new diseases will emerge, and endemic outbreaks will occur as a result of continued ecological degradation. We must navigate these new circumstances with caution

and foresight, preventing, managing and mitigating any zoonotic disease disservices as a consequence of ecosystem restoration. While strengthening the ecosystem services of disease regulation and protection against zoonotic disease risk in humans.

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Figures

Tables

Appendices

Appendix 1: List of the 77 articles reviewed in the integrative literature review, each with a designated theme analysis, which assisted in identification, analysis and synthesis of the data (For full references refer to the thesis reference section).

Ali et al. 2019: Mosquito-borne disease, Mayaro virus disease (MAYVD), GIS modelling and surveillance,

Awuku-Sowah et al. 2023: Ecosystem services and disservices, Mosquito-borne disease

Bawa et al. 2021: Biodiversity, One Health

Bellato et al. 2021: Tick-borne disease, zoonotic disease surveillance,

Borzee et al. 2021: Amphibians as vector control

Bouchard et al. 2023: Zoonotic disease risk-mapping, Tick-borne disease

Boyer et al. 2022: Tick-borne disease

Brennan et al. 2022: Tick-borne disease

Buřivalová et al. 2023: Zoonotic spill-over, habitat fragmentation

Cao et al. 2022: Habitat fragmentation, zoonotic spill-over, dilution effect, forecasting and modelling

Convertino et al. 2022: Zoonotic disease early-warning systems, vulnerability mapping, epidemiological forecasting, Leptospirosis

De Wit, et al. 2017: Invasive species

Diao et al. 2022: Predicting and modelling, urban ecosystem restoration

Dunn & Hatcher 2015: Invasive species

Escobar et al. 2020: Chronic Wasting Disease, Apex predators

Evans et al. 2020: Wildlife trade and bushmeat

Everard et al. 2020: Biodiversity, dilution effect, ecosystem functions

Fang et al. 2015: Tick-borne disease

Felappi et al. 2020: One Health

Filgueiras et al. 2021: Habitat fragmentation; ecosystem functions

Giraudoux et al. 2019: Zoonotic disease surveillance, human alveolar echinococcosis

Galindo-González 2021: Wet markets, wildlife trade and bushmeat

Glidden et al. 2021: Biodiversity

Gonçalves, et al. 2021a: Bats, climate change,

Gonçalves, et al. 2021b: Bats

Guégan et al. 2023: Habitat fragmentation, zoonotic spill-over, dilution effect

Hahn et al. 2018: Tick-borne disease

Harrison et al. 2020: Habitat fragmentation, zoonotic spill-over, tropical peatlands

Hopkins et al. 2022: Planetary Health, evidence-base

Huang et al. 2015: Wetland restoration, participatory integrated assessment (PIA) approach

Hughes et al. 2023: Bat-borne disease

Johnson et al. 2023: Bioacoustic surveillance

Keesing & Ostfeld 2021: Biodiversity, zoonotic spill-over, dilution effect

Köhler et al. 2023: Tick-borne disease, biodiversity

Lawler et al. 2021: Biodiversity, One-Health, Planetary Health

Linnell et al. 2020: Tick-borne disease

Lliso et al. 2022: Ecosystem services and disservices

McNeely 2021: One-Health, biodiversity

Machtinger et al. 2024: Tick-borne disease

Medlock & Leach 2015: Climate change, mosquito-borne disease

Medlock & Vaux 2015: Climate change, mosquito-borne disease, tick-borne disease

Medeiros-Sousa et al. 2015: Mosquito-borne disease

Millins et al. 2016: Tick-borne disease

Mohan M. et al. 2021: Habitat fragmentation, dilution effect, reforestation

Mols et al. 2022: Tick-borne disease

Morand & Lajaunie 2021: Agroforestry

Nishi & Hashimoto 2022: Landscape approaches

Okeke et al. 2022: Zoonotic spill over, habitat fragmentation and deforestation, ecosystem restoration as pandemic prevention

Osofsky et al. 2023: Bat-borne disease

Parolin et al. 2021: Bat-borne disease

Pfäffle et al. 2013: Tick-borne disease

Pires & Galetti 2023: Apex predators, ecosystem functions

Polo et al. 2018: Tick-borne disease

Prist et al. 2021: Apex predators, ecosystem functions

Rai & Singh 2020: Invasive species

Ranjan 2021: Mosquito-borne disease, habitat fragmentation, zoonotic spill-over, agroforestry

Reaser et al. 2021: Landscape approaches, invasive species

Robinson et al. 2022: Zoonotic spill over, habitat fragmentation and deforestation, ecosystem restoration as pandemic prevention

Rocklöv et al. 2023: Climate change

Rosenstock et al. 2019: Habitat fragmentation, agroforestry

Sandifer et al. 2015: Biodiversity

Shanks et al. 2022: One Health

She et al. 2023: Apex predators, ecosystem functions

Shyamsundar et al. 2021: reforestation, habitat fragmentation, ecosystem restoration as pandemic prevention

Speldewinde et al. 2015: Ecosystem services and disservices, biodiversity

Stronen et al. 2019: Rewilding

Thorn et al. 2021: Ecosystem services and disservices, urban ecosystem restoration

Thulin & Röcklinsberg 2020: Rewilding

Tomassone et al. 2018: Tick-borne disease

Vaz et al. 2017: Ecosystem services and disservices

Wallach 2015: Apex predators

Wang et al. 2022: One Health, habitat fragmentation, zoonotic disease surveillance, ecosystem restoration as pandemic prevention

Wegner et al. 2022: One Health, pandemics

Wilson et al. 2021: Toxoplasma gondii, invasive species

Wimms et al. 2023: Tick-borne disease

Wood & Lafferty 2013: Tick-borne disease

Yin et al. 2021: Ecosystem services and disservices, ecosystem restoration as pandemic prevention