





Viewpoint

# Zoonotic Spillover in an Era of Rapid Deforestation of Tropical Areas and Unprecedented Wildlife Trafficking: Into the Wild

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**Abstract:** Rapid deforestation and unprecedented wildlife trafficking are important factors triggering the rate of zoonotic spillover from animals to humans. Consequently, this leads to the emergence and re-emergence of zoonotic infectious diseases among the human population. Deforestation is an important ecological disruption that leads to the loss of biodiversity. The loss of biodiversity results in the persistence of highest-quality hosts of zoonotic pathogens dominating the low-diversity communities, a process termed the dilution effect. Activities like intensive farming and logging that resulted in deforestation bring vulnerable people in close contact with these highest-quality reservoir hosts (wildlife). As a result of this vulnerability, there is an increased risk of spillover, leading to zoonotic infection in humans and eventually disease outbreaks during human–human transmission. One prominent example of a disease of wildlife origin is the ongoing SARS-CoV-2 (Severe Acute Respiratory Syndrome–Coronavirus 2), even though the original source has not been found. Another important factor facilitating the risk of spillover and emergence of zoonotic infectious diseases is wildlife trafficking. This involves illegal hunting and trading of wildlife and their products, which increases the risk of spillover as a result of exchange of bodily fluids and bloodmeals between humans and wildlife during the hunting and butchering of animals' carcasses. Consequently, little or no hygiene protocol and poor handling practices during the wildlife-trade chain expose poachers, consumers, and local market sellers to the risk of zoonotic diseases. Despite the interventions on deforestation-induced spillover and wildlife trafficking-associated spillover, there are still knowledge and research gaps that need to be addressed towards preventing the outbreaks of future zoonotic infectious diseases. In response to this, there is a need for interdisciplinary and intersectoral collaborations among researchers from various fields as well as sectors in minimizing the risk of zoonotic spillover driven by deforestation and wildlife trafficking at the human–animal–environmental nexus. In addition, there is a need for integrated and unified evidence-based policy formulation that puts an end to deforestation and wildlife trafficking, especially in tropical areas such as Africa and Asia.

**Keywords:** zoonotic spillover; wildlife trafficking; infectious diseases; hygiene protocol; poor handling practices



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## 1. Introduction

The rapid spread and ever-increasing global health burden of “Severe Acute Respiratory Syndrome (SARS) Coronavirus 2” (SARS-CoV-2), the etiological agent of the 2019 coronavirus disease (COVID-19), have led researchers to place significant interest in addressing this outbreak rather than developing interventions to tackle its source, i.e., zoonotic spillover, to prevent the outbreak of future zoonoses of pandemic potential. By definition,

zoonoses are infectious diseases (caused by pathogens including bacteria, viruses, fungi, and parasites) that are naturally transmitted between humans and vertebrate hosts (usually domestic animals and wildlife) [1,2]. Zoonosis is one of the most widely known public health threats, accounting for increased morbidity and mortality concomitantly with a huge socio-economic burden across the world [1,2]. According to the first quantitative analysis on infectious diseases, “Risk factors for human disease emergence”, zoonosis accounts for 75% of emerging infectious diseases and 61% of all communicable diseases, which is responsible for a billion cases of human illnesses and millions of deaths across the world per annum, and this is evident from the COVID-19 pandemic [3]. Consequently, it has also been reported that an estimated \$1.3 billion is lost to foodborne zoonotic diseases per annum worldwide [4].

The emergence and re-emergence of zoonotic infectious diseases, such as Severe Acute Respiratory Syndrome Coronavirus (SARS-CoV), Ebola Virus Disease, and Monkeypox at the interface between humans, animals, and their environment are being driven by complex ecological changes from rapid deforestation, linked with the dilution effect hypothesis (which states that a high-quality host of zoonotic pathogens tends to dominate the low-diversity community that could facilitate pathogen transmission risk) and unprecedented trading and/or trafficking of wildlife associated with poor hygiene practices and stress on wildlife [5,6]. This is leading to cross-species transmission of pathogens from infected wild vertebrates to humans, a process termed zoonotic spillover. Unfortunately, zoonotic spillover is on the rise due to little attention paid to it in the context of deforestation and wildlife trafficking, while an integrated, unified, and evidence-based policy on zoonotic spillover prevention has not been effectively formulated at the global level [5]. To effectively minimize the risk of zoonotic spillover to prevent future pandemics, there is a need for interdisciplinary collaborations among researchers to address the knowledge and research gap by providing evidence-based results required for effective policy formulation. In the case of deforestation and wildlife trafficking, the impacts on the emergence of zoonosis in the human population require a new approach. Consequently, an evidence-based policy on drivers of zoonotic spillover that takes into consideration the health risks of zoonotic diseases arising from deforestation and wildlife trafficking needs to be formulated. This paper highlights the impact of activities from the wild, including deforestation and wildlife trafficking, on zoonotic spillover in the human population, particularly in the tropical areas of Asia and Africa, as well as other affected areas. Finally, we present recommendations to minimize the risk of spillover to reduce the emergence and re-emergence of zoonotic infectious diseases of pandemic potential (Table S1).

## 2. Materials and Methods

In this narrative review, we conducted a web-based search of peer-reviewed journal articles published in English from 2001 to 2022. In our search, relevant databases and free-web article searches from PubMed (<https://pubmed.ncbi.nlm.nih.gov/>; accessed on 2 January 2022), ScienceDirect (<https://www.sciencedirect.com>; accessed on 4 January 2022), Wiley (<https://www.wiley.com/en-us>; accessed on 5 January 2022), and Google Scholar (<https://scholar.google.com>; accessed on 12 January 2022) were considered for suitable articles. The following keywords were used during the web and databases searches: “Zoonosis”, “Spillover”, “Wildlife Trafficking”, “Zoonotic Infectious Diseases”, “Land-use Changes”, “Dilution Effect”, and “Viral Zoonosis”. The list of references from relevant articles was checked for additional articles used in the review. A cumulative number of 35 articles were considered for the final review. All articles included in the final review established incontrovertible proof that deforestation and wildlife trafficking are important factors triggering the zoonotic spillover event in the human population.

## 3. Deforestation and Zoonotic Spillover

Deforestation, which is regarded as the anthropogenic clearing of forested land, is one of the most important causes of biodiversity loss. Unfortunately, this trend has increased

greatly over the past decades and it is also directly linked with the following emerging zoonotic infectious diseases caused by Hendra and Ebola viruses [7]. It has been reported that land-use changes, such as deforestation, have the propensity to induce environmental stressors on wildlife [8]. This usually happens during the process of ecological disruption, leading to the migration of wild vertebrates from their lost habitat to another ecological niche. As a result, their exposure and susceptibility to novel pathogens from disease vectors are thus affected. Furthermore, the rate of cross-species transmission of pathogens, especially during anthropogenic activities like hunting and logging that could result in human contact with wildlife, is facilitated [8].

However, the “dilution effect” theory has offered more clarity in understanding the emergence of zoonotic infectious diseases in the human population as a result of biodiversity loss from anthropogenic activities like deforestation [6,9]. According to this theory, the rate of infectious disease transmission is low in highly conserved biodiversity characterized by higher species diversity. This is due to the availability of incompetent reservoir hosts to dilute the infection rates between the competent hosts and the human host [6,9]. Following this theory, it can be well understood that the rate of zoonotic spillover in higher species diversity will be very much lower, while in a lesser species diversity, the rate of spillover will be much higher.

Over the years, the linkages between deforestation, zoonosis infectious disease dynamics, and the dilution effect have been reported in scientific literature. In one of the hypotheses from the study of Murray and Daszak, deforestation has been reported to affect the emergence of zoonotic infectious diseases as a result of increased contact between humans and circulating pathogens from a lost habitat [10]. In their experimental study in Panama, Suzan and colleagues reported an increase in the prevalence of hantavirus as a result of the reduction in small mammal diversity [11]. Rulli and colleagues also revealed the positive correlation of outbreaks of Ebola virus diseases in Central and West Africa with ecological changes from deforestation, leading to a spillover of zoonotic pathogens and novel infections in human communities in proximity to the lost habitat [12]. Furthermore, the emergence of Nipah and Hendra has been linked with forest destruction, which affects the distribution of the reservoir host and the rate of zoonotic spillover [3].

#### 4. Wildlife Trafficking and Zoonotic Spillover

Another important driver of zoonotic spillover in the human population is unprecedented wildlife trafficking. Wildlife trafficking is regarded as smuggling, poaching, capturing, and trading of wild animals and plants, including their products, in contravention of national or international law [13]. This is one of the most widely spread lucrative criminal activities across the globe, with a financial estimation of US\$20 billion per annum [13,14]. Over the past decades, a global increase in demands for wildlife and their products (horn, scales, bile, bone), either for consumption or the use of their products in traditional medicine, have led to uncontrolled exploitation and illegal trading of wildlife [13]. This is driving the biodiversity into spiraling decline, thereby increasing the risk of zoonotic spillover to humans. The illegal trading of wildlife, especially reptiles, mammals, and birds, is prominent in Africa and Asia, and hygiene standards are usually not considered during trading. This subjects poachers, consumers, and market sellers to the risk of zoonotic diseases [15]. Importation and exportation of illegally traded animals between countries are facilitating the risk of zoonotic spillover and the outbreak of zoonotic infectious diseases. It has been reported that the outbreak of monkeypox outside Africa is due to the importation of African rodents into the United States [16]. African rodents have spread the virus to pet prairie dogs, which, in turn, spilled over the virus to humans, causing an epidemic [16].

In their recent review, Hilderink and colleagues highlighted the different phases involved in wildlife trading (legally or illegally performed) and their correlation with zoonotic spillover [17]. The first phase, which deals with the hunting, trapping, and butchering of the carcasses of wildlife, exposes humans to the direct transmission of zoonotic pathogens through contact with bodily fluids from wildlife bites, scratches, and poor handling prac-

tices of their products, as well as indirect transmission from the environmental reservoir or surfaces contaminated with infectious droplets from wildlife [17]. In one of the 2007–2009 reports by the Ministry of Health and Ministry of Agriculture in Saudi Arabia, an equivalent of 11,069 animal bites on humans was reported. However, some of these bites cases were from wild animals, including wolves, foxes, and monkeys known to transmit rabies (a viral zoonosis caused by lyssavirus) to humans. This resulted in increased zoonotic infections in Saudi Arabia [18]. Although other domestic animals such as dogs and cats are considered an important host for rabies virus, bats have also been identified as reservoir host [19]. In the regions of the world, such as Africa and Asia, where the rate of wildlife trafficking is high, 95% of human deaths are caused by rabies [19]. Other zoonotic viruses such as monkeypox virus, simian retroviruses, Alkhurma virus, and MERS-CoV (Middle East Respiratory Syndrome Coronavirus) can also spread through contact with bodily fluids and waste products of animals [17]. For example, a study by Han and colleagues suggested that MERS-CoV infection in humans usually occurs through contact with a dromedary camel's bodily fluid products (such as blood or tissues) or the use of their products, such as urine, for medicinal purposes [20].

The second phase is the transportation of wildlife between countries. In this process, multiple exotic species are brought in close contact, thus creating an avenue for interspecies transmission of zoonotic pathogens [17,21]. Moreover, trading these animals in the live market subjects humans to the risk of zoonosis from spillover events due to poor hygiene practices [21]. This might have been the case with SARS-CoV-2 which may have spilled over to the human population, possibly through the horseshoe bat (the reservoir host) or pangolin (the unharmed intermediary host) traded in the Wuhan wet market in China [1]. Evidently, a report by Lam and colleagues revealed that SARS-CoV-2 has 85.5% to 92.4% sequence similarity with coronaviruses in pangolins [22]. In another report by Zhou and colleagues, the authors revealed that SARS-CoV-2 has a 96% sequence similarity with bat coronaviruses [23]. These reports support the fact that SARS-CoV-2 is zoonotic in origin and that viral spillover in the human population might have occurred during human contact with the reservoir host or the intermediary host shedding the virus. In a recent analysis by Nga and colleagues [24], the authors reported a close sequence similarity of coronaviruses identified in Malayan and Chinese Pangolins with coronaviruses isolated from confiscated pangolins in Vietnam, due to illegal trading [24]. In 2003, the outbreak of SARS-CoV in Guangdong Province was linked with civets, a widely traded animal in the province, which harbor coronaviruses with 99% similarity to the strain identified during the outbreak [25]. Thus, this reinforces the zoonotic origin of the SAR-CoV outbreak in Guangdong and the possibility of zoonotic spillover from civets (the intermediary host) to humans during the wildlife trade.

The third phase of wildlife trading is the sale of wildlife and their products. This increases humans' vulnerability to the risk of spillover during butchering due to constant exposure to the blood and bodily fluids of infected wildlife containing zoonotic pathogens [17]. Avian influenza outbreaks have been linked with the trading of wild birds and wildlife products in the wet market [26].

The consumption and use of wildlife products is the last phase of wildlife trading [16]. Increased demands for animal-source food, such as bushmeat and the insatiable demand for wildlife products for use in the biomedical and pharmaceutical industry in drug formulation are contributing factors to zoonotic disease transmission. This, coupled with the rapid usage of these products in traditional medicine has increased the rate of zoonotic spillover to humans and the emergence of zoonotic infectious diseases [26]. For example, viral zoonoses, such as Ebola Virus and Human Immunodeficiency Virus, HIV-1, have been linked with the consumption of bushmeat [27,28]. This is because of pathogens' ability to survive in undercooked/raw meats. Furthermore, the consumption of raw/undercooked meat of snakes and frogs and the use of their bile in traditional medicine have played an important role in facilitating the spread of sparganosis, a foodborne zoonotic disease, in human settlement [29].

## 5. Conclusions and Recommendation to Minimize the Risk of Zoonotic Spillover from Deforestation and Wildlife Trafficking

The above evidence established the fact that deforestation and wildlife trafficking are two important drivers of zoonotic infectious diseases through their role in facilitating zoonotic spillover into the human population. These wild activities (deforestation and wildlife trafficking) are known to drive epidemics, as in the case of the Ebola outbreak in the Democratic Republic of the Congo and the SARS-CoV outbreak in Asia, and this might have been the case with the SARS-CoV-2 pandemic, although a direct correlation has not been established as research is still ongoing [12,16]. Addressing the risk of zoonotic spillover to prevent the emergence of zoonotic infectious diseases of pandemic potential requires a multidisciplinary approach like One Health, which recognizes zoonosis as a health crisis occurring at the interface of humans, animals, and their environment. Under the One Health approach, researchers from multiple disciplines, including veterinarians, wildlife experts, ecologists, public health scientists, conservationists, epidemiologists, social scientists, microbiologists, and lawyers, should collaborate on the need for ecological restoration, banning of illegal wildlife trade, and regulating legal wildlife trade to minimize the risk of zoonotic spillover in human populations. With support from the government and funding from international donors, evidence-based research on zoonotic infectious diseases regulating services from the natural biodiversity should be conducted among researchers to address the research and knowledge gap on this aspect. An example of how the One Health approach has been adopted in addressing zoonosis is evidenced by the project's of the United State Geological Survey (USGS), One Health's, approach to wildlife disease and environmental change [30]. Following the first United State of America workshop "One Health Zoonotic Disease Prioritization (OHZDP)" organized by the Centers for Disease Control and Prevention (CDC) in collaboration with the US Department of Agriculture (USDA) and the US Department of the Interior (DOI) in 2017 to address the threat of zoonosis in the US, six zoonotic diseases, such as zoonotic influenza, salmonellosis, West Nile Virus, plague, emerging coronaviruses (SARS and MERS), rabies, brucellosis, and Lyme diseases, were prioritized [30,31]. Of these eight priority diseases, the United State Geological Survey (USGS) conducts multidisciplinary projects establishing a partnership with health organizations like the US Department of Health and Human Services and the CDC, as well as researchers from the field of animal health, human health, and environmental health to work on seven of these diseases, with coronaviruses included. One important area of focus of USGS researchers is factors that drive devastating spillover from wildlife to human populations [30]. So far, the outcomes from USGS research have contributed to the existing body of knowledge that allows us to understand the ecological factors facilitating spillover risk from wildlife to humans and the human health impact of re-emerging zoonosis, coupled with how spillover can be prevented [30].

While it is evidenced that deforestation is an important key player driving zoonotic spillover, as discussed in the previous section [11,12], an incentive-based approach (this approach works by providing inducements to encourage farmers to halt activities that enhance deforestation, reduce emissions from deforestation, and promote conservation), market-based incentives (this aims to encourage behavioral change by providing farmers with economic incentives, especially through the market signals, such as logging certification), and an eco-based policy (this aims at preventing environmental problems such as deforestation by legislating only what is permitted) should be fostered to put a stop to deforestation to effectively ensure the conservation of biodiversity. However, future research should focus more on investigating the spillover event caused by deforestation and other land-use changes (urbanization, agricultural encroachment, and wetland modification) from a landscape perspective, as there are fewer studies on this aspect [5]. Consequently, there is still more to understand on how ecological disturbance and biodiversity loss from deforestation affect the emergence of zoonotic infectious diseases in the non-human host, how we can determine which of the reservoir hosts can effectively transmit the pathogen to humans, and the kind of land-use changes that maximize the risk of zoonotic spillover



from non-human hosts as well as the ones that minimizes it [5]. Obviously, while few studies have identified deforestation as a driver of spillover, in regions of the world such as Africa and Asia, where the rate of deforestation and other land-use changes are high [32], the community will be vulnerable to the risk of zoonotic spillover, as supported by the “dilution effect” theory. It is therefore recommended that the public health community should work with colleagues in the environmental sector to monitor deforestation and develop a unified integrated surveillance system at the human–animal–environmental nexus, not only to track and identify pathogens, but also to respond to them as soon as they emerge.

The second factor facilitating the risk of zoonotic spillover to the human population is wildlife trafficking, which has been on the rise over the past few years. Between 2012 and 2016, more than 11 million live wild animals were traded, and between 2000 and 2019, about 900,000 pangolins were poached [33,34]. This high demand for wildlife is an indication that wildlife trading is likely to persist for years. If this persists, there will be an increase in the circulation of zoonotic pathogens and the emergence of zoonotic infectious diseases in our world. As a result, this will continue to jeopardize the effort of the global health community to bring these zoonotic pathogens under control, as evidenced in the case of emerging SARS-CoV-2 variants of concern. To address this threat, an international organization, such as the World Organization for Animal Health (WOAH) or International Health Regulations (IHR), should work with the Convention on International Trade in Endangered Species of Wildlife Fauna and Flora (CITES) on placing a strict ban on the trading of endangered species while regulating and monitoring the trading of species (especially mammals and birds that host a large number of pathogens) that pose a significant global health risk without compromising the food security at the local scale [35]. Furthermore, international policy and wildlife law enforcement aimed at placing a strict ban on wildlife trafficking should be developed at a global scale with consensus from each country around the world. This can be in the form of setting up a transnational agreement in monitoring illegal wildlife trafficking along borders and ports. While wildlife trafficking is associated with corruption at the port of entry, such as the maritime seaport, Tajudeen and Oladunjoye [13] have recommended a way forward to address the rising corruption at this port. At the local level, public health workers should work with environmental scientists and wildlife ecologists to educate the local communities on conservation promotion; the risk of zoonotic spillover; safe handling practices of animals, including their waste products; hygiene protocols; the implication of wildlife trafficking; and measures to curb this act while also involving them (local communities) in the fight against wildlife trafficking. If anything, the COVID-19 pandemic has made us realize the need for zoonotic spillover prevention. However, to prevent the emergence of future zoonoses of pandemic potential, it requires the need to prevent or mitigate the factors (deforestation and wildlife trafficking) triggering zoonotic spillover in the human population. Nothing better captures the reality of disease outbreaks than the popular fundamental principle of modern health care: “Prevention is better than cure”, and the COVID-19 pandemic has further heightened the importance of this warning.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/challe13020041/s1>, Table S1: Selected viral zoonotic infectious diseases associated with human infections.

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