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Viewpoint

Preventing the Next Pandemic through a Planetary Health Approach: A Focus on Key Drivers of Zoonosis

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Abstract: The ever-increasing global health impact of SARS-CoV-2—the etiological agent of coronavirus disease 2019 (COVID-19)—coupled with its socio-economic burden, has not only revealed the vulnerability of humanity to zoonotic pathogens of pandemic potential but also serves as a wake-up call for global health communities to rethink sustainable approaches towards preventing future pandemics. However, since the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) convened experts have declared that future pandemics are likely to be zoonotic in origin, it is imperative that we understand the key drivers of zoonosis such as biodiversity loss, climate change, wildlife consumption, and population mobility, as well as the scientific evidence underpinning them. In this article, we underscore the correlations of these drivers with the emergence and re-emergence of zoonosis. Consequently, we highlighted the need for multidisciplinary collaboration under the planetary health approach between researchers across the fields of environmental and human health to fill the knowledge and research gaps on key drivers of zoonosis. This is to prevent or limit future pandemics by protecting the natural systems of the Earth and its resources and safeguarding human and animal health.

Keywords: planetary health; zoonosis; climate change; biodiversity loss; population mobility; pandemics

1. Introduction

The term 'zoonosis' (zoonoses-plural) refers to an infectious disease that can be transmitted from vertebrate animals (wildlife or domestic) to humans [1]. Wildlife is a natural reservoir host for zoonotic pathogens, including bacteria, viruses, fungi, and protozoan parasites, known to cause various kinds of diseases of public health significance [2]. Concern about wildlife–human pathogen transmission—a process termed 'spillover' or 'anthropozoonosis'—has grown over the years and in light of the ongoing COVID-19 pandemic [3].

As confirmed by an epidemiological study, approximately 61% of communicable diseases affecting humans are zoonotic in nature, while approximately 75% of emerging infectious diseases in circulation are of wildlife origin [4,5]. The World Health Organization (WHO) reported that zoonoses account for an estimated one billion cases of illness and a million cases of deaths across the world per annum, concomitant with a huge socio-economic burden; this was further revealed by the COVID-19 pandemic [6]. A recent analysis by Bernstein and colleagues estimated approximately $200 billion financial loss due to emerging zoonoses across the world per annum [7].

Both developed and developing countries experience zoonotic infections, grouped according to their etiological agents, transmission cycles, and reservoir hosts [8,9]. Rapid circulation of zoonotic diseases within human populations has been linked with intensified ecosystem services such as animal domestication, animal husbandry, deforestation, and habitat encroachment. These activities are increasing human–domestic animal interactions with wildlife, where they pose both direct and indirect impacts on public health and individual well-being in societies [10,11].

Direct impacts are characterized in terms of morbidity and mortality metrics in humans, while indirect impacts extend to the effects of emerging zoonoses on both health professionals and the public [10]. A significant amount of inhabitants in rural areas who are in proximity to the forests with their livelihood linked to forest ecosystems and those with religious or traditional attachment to wildlife, are primarily vulnerable to zoonotic pathogens [12]. Constant interactions with wildlife could not only increase the susceptibility to zoonotic infections but also lead to contamination of food, water, fruits, and vegetables, and this is regarded as a significant food-borne risk factor [12–14].

Zoonotic diseases have been the antecedent of multiple repeated epidemics in human settlements across the globe [12,14]. In endemic locations, zoonotic diseases such as H7N9 influenza, salmonellosis, West Nile fever, and coronavirus infections are responsible for significant human morbidity and mortality as well as large economic losses that constitute more than hundreds of billions of US dollars over the past 20 years [13,15–17]. When the Ebola virus spread across many African countries in 2014, it was called a 'major epidemic' because it resulted in a decline in foreign investments, loss of domestic productions, and decrease in employment opportunities [18]. According to the evidence, the Ebola virus evades both innate and adaptive immunity with grave pro- inflammatory responses in affected individuals [18].

As a result of this outbreak, approximately 11,323 people died out of the 28,646 cases documented in West Africa [19]. This example of the Ebola virus epidemic highlights the impact of zoonotic diseases that ranges from individual's infection to a drop in livestock production and farm commodities with shrinking economic growth in general.

Addressing the profound public health threat and socio-economic burden of zoonosis requires a global solution-oriented, collaborative, and system-based approach as a panacea. One important example is the planetary health approach—launched by the Rockefeller Foundation in 2015 but with ancestorial origins in indigenous communities. The planetary health approach aims to ensure the stability of the Earth's natural systems coupled with sustainability of human environments. This to be achieved by ting and tackling the diverse threats arising from persistent anthropogenic activities. The prevalence of emerging and re-emerging zoonotic infectious diseases has been associated with various anthropogenic and socio-economic factors, which necessitated the need for this approach. In this article, we provide a comprehensive review of the impact of biodiversity loss, climate change, population mobility, and wildlife consumption on the emergence and re-emergence of zoonosis. Finally, we recommend the need for multidisciplinary research studies adopting a holistic planetary health approach to prevent future zoonotic diseases of pandemic potential.

2. Epidemiology of Zoonoses

Since 1976, outbreaks of the Ebola virus have been repeatedly reported in Africa, causing 47% to 90% of case fatalities in men [20]. From 2014 to 2016, the Ebola virus epidemic of bat origin affected African countries with serious consequences in Nigeria, causing high fatality rates (Figure 1) in Guinea, Liberia, and Sierra Leone [20]. On the other hand, the intestinal parasitic infection, Giardiasis, caused by the tiny protozoa *Giardia intestinalis*, has caused diarrheal disease outbreaks in the United States due to contaminated soil, food, and drink from infected people and animal reservoir hosts [21]. As a US nationally notifiable disease, the Centers for Disease Control and Prevention (CDC) surveillance report on Giardiasis since the outbreak in 2006–2008 [21] showed a 2.9% increase in reported cases from 19,239 in 2006 to 19,704 in 2007, followed by a 3.3% decrease to 19,140 in 2008 [21].

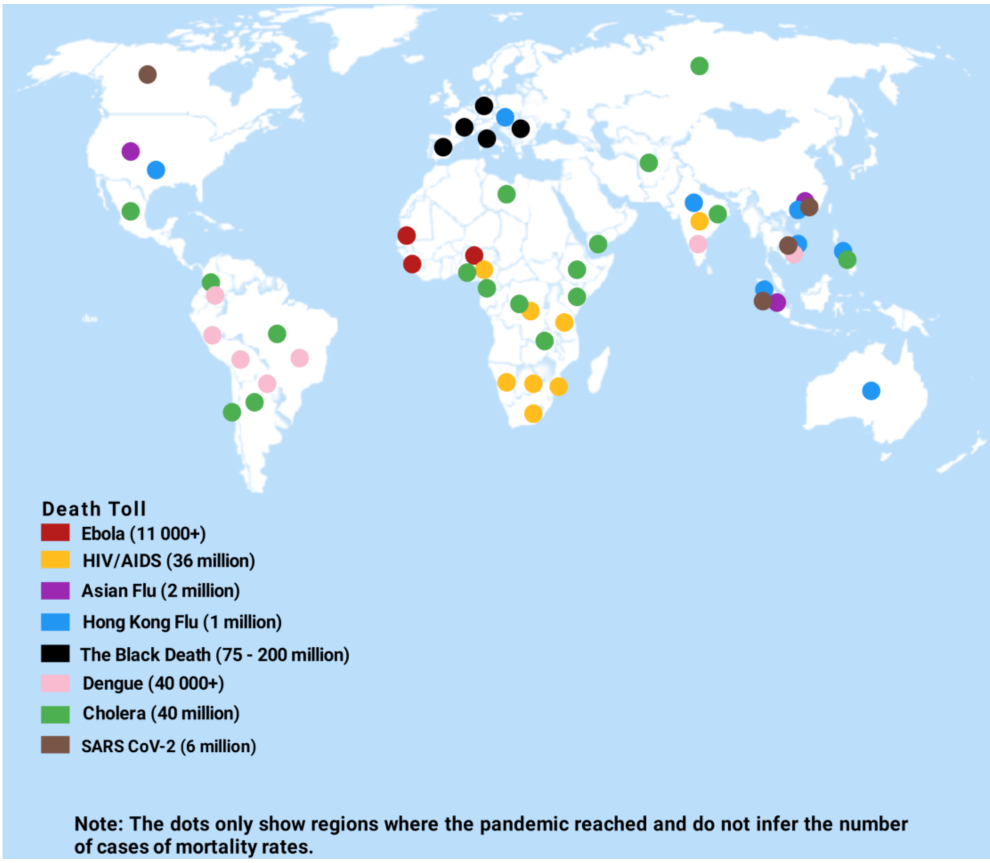

Figure 1. Geographical distribution of zoonosis across different regions.

Another food-borne infection with more than 2 million estimated cases of Campylobacter enteritis occur yearly in the United States. This represents 5–7% of gastroenteritis cases with a large animal reservoir in poultry 100%, including turkeys, chickens, and waterfowl, yet with asymptomatic infections [22]. Between November 2002 and February 2003, China reported 305 cases of atypical pneumonia of an unknown etiology in Guangdong Province, with 5 fatalities [23]. In February 2003, a physician in the said province fell ill with atypical pneumonia, visited Hong Kong, and stayed overnight at a hotel. The agent that caused his severe acute respiratory syndrome, SARS, was transmitted to at least ten people, who subsequently initiated outbreaks in Hong Kong, Singapore, Vietnam, and Canada [23].

From 2019 to 2020, the pandemic of coronavirus disease (COVID-19) caused by SARS-CoV-2 has been identified as a zoonotic disease. However, no animal reservoir host has been found yet, so this classification is premature [6]. It is proposed that COVID-19 should instead be classified as an emerging infectious disease of animal origin [6]. Since the first case was reported from Wuhan, a city in Hubei Province of China, at the end of 2019, cases have been reported from all continents (Figure 1). Globally, more than 500 million confirmed cases of COVID-19 were recorded at the time of writing [24].

In the United States and Europe, seroprevalence surveys have suggested that, after accounting for potential false positives or negatives, the rate of prior exposure to SARS-CoV-2, as reflected in seropositivity, exceeds the incidence of reported cases by approximately 10 times or more [25].

3. Brief Classification of Zoonoses Based on Aetiological Agents, Transmission Cycles, and Reservoir Hosts

Zoonoses can be classified based on:

Aetiological Agents:

- Bacterial, e.g., tuberculosis and brucellosis;
- Viral, e.g., rabies and dengue;
- Fungal, e.g., histoplasmosis and cryptococcosis;
- Rickettsial and chromydial, e.g., scrub typhus and ornithosis;
- Parasitic, e.g., toxoplasmosis, schistosomiasis, cysticercosis, and trichinellosis.

Transmission Cycles:

- Sylvatic Cycle: transmission that involves non-human primates such as monkeys and mosquitoes; whereby the mosquito species transmit the disease from non-human primates to humans, notably those working in the jungle, e.g., monkeypox.
- Synanthropic cycle: transmission that involves synanthropes—species whose population is highly dependent on variables influenced by humans—such as rodents, lizards, and birds, e.g., tularemia and plague [26].
- Human Cycle: transmission that involves man to man or man to animals, e.g., human tuberculosis and giardiasis.

Reservoir Hosts:

- Anthropozoonoses: these are diseases of domestic and wild animals that occur naturally independent of man and get transmitted from animal to human, e.g., Rabies, Tularemia, Rift Valley fever, and Leptospirosis.
- Zooanthroponoses: these are diseases of pathogens that are normal reservoirs in a human host and can be transmitted to other vertebrates, e.g., human tuberculosis and amoebiasis [27].
- Amphixenoses: these are diseases of pathogens whose reservoir hosts can be both humans and lower vertebrates, and thus diseases can be transmitted in both directions, e.g., *Staphylococcal* and *Streptococcal* diseases [28].

4. Biodiversity Loss and Zoonoses

Biodiversity—the diversity of microorganisms, plants, animals, and the genes they contain, coupled with the ecosystems they form—is increasingly under pressure from uncontrolled exploitation and ever-increasing anthropogenic activities including deforestation, urbanization, and intensified agricultural practices, which are driving it into precipitous decline [29,30]. The main implication of this (Figure 2) has been attributed to an increase in the emergence of infectious diseases, particularly diseases that are usually transmitted from animals to humans, i.e., zoonoses [30].

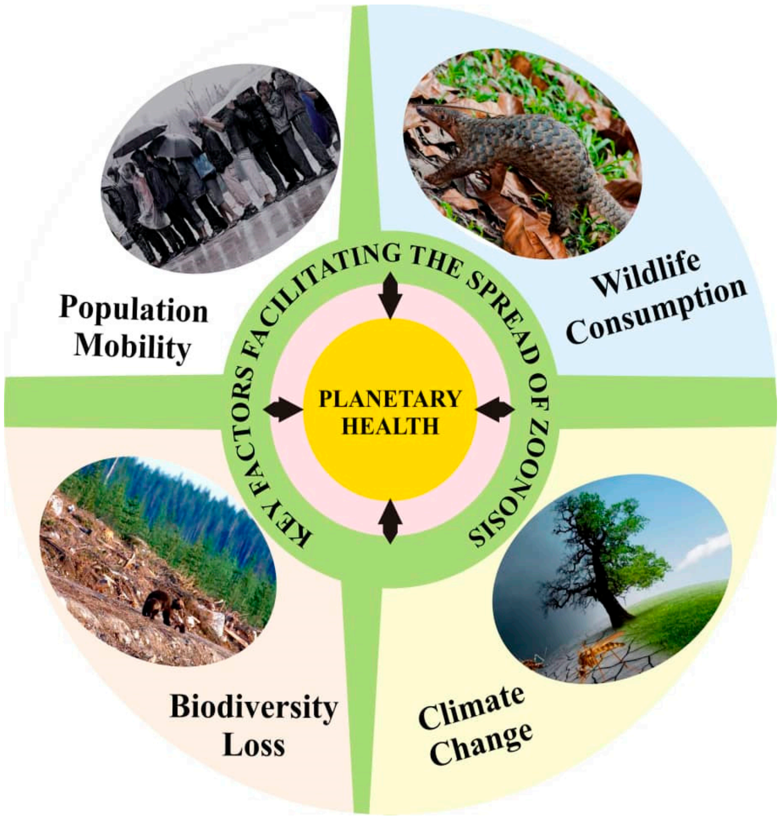

Figure 2. Key Factors Facilitating the Spread of Zoonosis.

Zoonotic pathogens, including bacteria, viruses, fungi, and protozoan parasites, are a normal occurrence in biological systems—establishing an indeterminate relationship with their reservoir hosts, i.e., wildlife, which has persisted over eons of evolution [2]. However, human encroachment into natural biodiversity through anthropogenic activities and ecosystem services can disrupt this established relationship and further drive the transmission of pathogens from wildlife to humans, i.e., spillover [3]. Over the years, there have been different consensuses on how biodiversity affects the spread of zoonoses, but the most well-known one is the hypothesis of the 'dilution effect' of Ostfeld and Keesing [31,32].

According to these researchers, the risk of disease and pathogen transmission is much lower in highly rich biodiverse species. This is due to the availability of diverse communities to harbour competent hosts for any known pathogen, thereby causing a significant reduction in host exposure and susceptibility to such pathogen [31,32]. Most importantly, the dilution effect will only occur when more diverse communities of species result in a lower rate of transmission of pathogens to hosts [32]. This can be in the form of regulating the populations of susceptible hosts or interference with the pathogen transmission process [32].

Although the hypothesis for the dilution effect has been subjected to contentious debate by several researchers, especially when considering the zoonoses of humans; observational and experimental studies published in recent years have increasingly documented the relationship between the dilution effects of zoonoses on humans. This evidence supports the fact that host diversity inhibits the abundance of circulating pathogens in human settlements [33]. Evidently, three different studies conducted in the United States established a positive correlation between low bird diversity and the increased risk of West Nile encephalitis infections in humans [34–36].

In their study, Suzan and colleagues reported a strong correlation between a reduction in small mammal diversity and the prevalence of the Hantavirus infection in Panama [37]. Similarly, in a meta-analysis of more than 200 assessments investigating the link between biodiversity and infectious diseases in wildlife and humans using more than 60 host–

parasite systems, Civitello & colleagues [33] reported strong evidence for the dilution effect. These findings corroborate the hypothesis that loss of biodiversity increases the abundance of zoonotic parasites, subjecting humans to the risk of disease.

5. Climate Change and Zoonoses

Climate change is another factor affecting the spread of zoonoses. It is a well-known fact that anthropogenically induced climate change—especially geo-climatic variations and global warming—due to the emission of greenhouse gases (GHGs) is one of the greatest threats facing the living components of the Earth's biosphere. Its impact on the epidemiology of zoonotic diseases is evidenced by alterations in the interactions, distribution, and dynamics of hosts, vectors, and pathogens [38].

Climate change is facilitating the emergence, re-emergence, and transmissibility of zoonoses, especially those caused by vector-borne zoonotic pathogens and transmitted by arthropod vectors such as mosquitoes, ticks, biting midges, and fleas [30]. Rapid fluctuations in the mean temperature of the earth over the years have created favorable conditions for arthropod vectors and their zoonotic pathogens to thrive in terms of breeding, survival, and infectivity [39]. Supportively, research studies have established the relationship between climate change and the emergence of zoonoses (Figure 2).

A positive correlation of human plague (Black death) in the western United States (Figure 1) has been linked to extreme weather events, temperature anomalies, and Pacific Decadal Oscillation (PDO) from climate change, as reported by Ari and colleagues [40]. Research studies on global infectious diseases and climate change also reported a positive relationship between the El Niño–Southern Oscillation (ENSO)—an extreme weather event—and the outbreak of plague, Hantavirus, Rift valley fever, and other emerging zoonoses [41,42]. In another study, researchers found a significant correlation between the surges in Hantavirus infection in the United States and El Niño-related weather events. These events have been predicted to become more intense in the coming decades [43].

The global incidence of dengue—a disease transmitted by mosquito vectors [44] which is highly prevalent in tropical and subtropical regions (Figure 1)—has increased by more than 10-folds in the last few decades [45]. This is not surprising as the temperature has direct and indirect impacts on vector breeding and prevalence. The current trend of climate change is more evidenced by the global mean increase in surface temperature of 1.09 °C (0.95–1.20 °C) between 2011 and 2020 [46].

This, coupled with the projected 0.2 °C (±0.1 °C) increase in global mean temperature per decade and the 1.4–4.4 °C mean temperature rise before the end of this century under high and low Co_2 emission scenarios [46], is a serious cause for concern with respect to zoonoses. This is because increased global warming and geo-climatic variations have a propensity to drive the emergence and prevalence of zoonoses among human populations, as reported by scientific researchers [38,46].

6. Population Mobility and Zoonoses

The increasingly intensive and intricate interactions of people, animals, and pathogens across local and global landscapes all point to an ever-increasing risk of zoonotic diseases (Figure 2). An actual pandemic potential may threaten the lives of millions of animals and people with devastating consequences [47]. Changes in human population density, movement, lifestyle habits, and food preferences have all altered the dynamics of zoonotic disease onset and served as pathogen transmission drivers over time [48]. As the human population increases, the influence of increased urbanization, combined with higher incomes, has led to the massive alteration of previously isolated and seldom-visited regions into ever more intense livestock and agricultural production zones [49].

This expansion into areas with a greater abundance of wildlife has resulted in the emergence of various zoonoses directly associated with agricultural practices. These diseases include henipaviruses (pigs and horses), the Middle East respiratory syndrome-coronavirus (CoV) (camels), Crimean-Congo hemorrhagic fever virus (ostriches), and other tick-borne bunyaviruses such as the severe fever with thrombocytopenia syndrome virus (livestock) [50–52]. The irregular measles periodicity in Niger is caused by yearly rural-to-urban cyclical migration linked to the agricultural cycle [53,54], in contrast to the regular periodicity in historical Europe [55].

Infectious disease transmission is a complex system defined by integrated ecological transmission and demographic-social dynamics [56]. However, space and mobility are critical elements in disease origin, propagation, and dynamics. These demonstrate that integrating the social system with the transmission and ecological systems can lead to a more holistic view of disease dynamics [56]. According to Padmanabha and colleagues [57], microbursts of dengue infection in Colombia are driven by movements that result in frequent introductions into heterogeneous urban populations. Individuals may transmit infectious diseases when they travel across a landscape from a long range. The annual migration to fine-scale mobility [58], and studies of migration and mobility in general, are important to understand the risk of infection and epidemic transmission [59].

7. Wildlife Consumption and Zoonoses

The consumption of wildlife meat as a protein source has become rather prevalent in the last few decades. This is evident from a study conducted by Nielsen and colleagues [60] on the use of wild meat (bushmeat) in 24 countries across Africa, Latin America, and Asia. According to this study, 39% of the sampled households (7978) consumed wild meat at least once a year [60]. Based on their inference from these data, the authors proposed that more than 150 million households (i.e., 230–833 million people) in the global south hunt for wildlife as a dietary habit at least once a year. This, of course, depicts the dependence of man on wildlife as a food source. Although wildlife has provided itself as an abundant protein source, it has also been implicated as a reservoir for zoonotic pathogens [61]. It is important to note that lower socio-economic status due to limited financial resources facilitates ecosystem services such as hunting as a source of income. These are important factors triggering human-to-animal interactions and the emergence of zoonosis in human settlements (Figure 2). For example, in tropical areas of low and middle-income countries (LMICs) with low socio-economic status, the need for survival often outweighs the risk of infection, and communities often depend extensively on wildlife hunting, either for sale or consumption. This is contributing significantly to the risk of infectious diseases of wildlife origin in underprivileged communities.

The significance of this can be seen in a study conducted by Taylor and colleagues [4], which revealed that, of 1415 species of disease-causing organisms described, 61% are zoonotic. Common examples of diseases caused by these organisms include severe acute respiratory syndrome (SARS) and the Ebola virus disease [62]. The tendency of wildlife consumption to facilitate zoonoses and disease outbreaks is observed in two ways: the activities associated with the trade of wildlife (such as hunting, handling, butchering, processing, and preparation of carcasses); and the consumption of wildlife animals as food (which is known to spread zoonotic pathogens such as the Ebola virus, monkeypox virus, and Sudan virus to humans) [62,63].

It is verified that hunting, handling wild meat, and related activities increase human–animal contact (from bites and scratches), which facilitates the spread of zoonoses [62]. This has been seen in diseases such as brucellosis, rabies, influenza, and hantaviruses [62]. In addition, the activities and conditions of the wildlife trade are risk factors for novel virus spillover. Such actions and conditions include the cramming of diverse wildlife into stressful conditions with poor biosafety and regular close contact between wildlife, domestic animals, and humans [64]. An example of this is observed in the case of the H7N9 influenza outbreak [65].

8. Addressing Zoonoses via a Planetary Health Approach: Justification for Action

Planetary health is a concept that dissects the impact of anthropogenic activities on all forms of existing life and the ecosystem. This concept was launched in 2015 by the

Rockefeller Foundation to advocate for the integration of socio-economic, health, and environmental knowledge for the benefit of all life forms [66]. The concept explicitly illustrates the relationship between human and animal health in a balanced environment [67].

Population mobility and biodiversity loss are being shaped by climate change. The effect of a changing climate is evidenced by the prevalence of zoonotic infectious diseases and the unsustainability of the human environment [66]. Planetary health recognizes these threats and advocates for co-creating stewardship of our planet to protect our health [66]. While planetary health is being used synonymously with other holistic concepts of health such as One Health and Eco-Health [67], Tajudeen and colleagues [68] have highlighted the differences between these concepts. Unlike the two other concepts, with the sole aim of optimizing the health of humans, animals, environments, and plants, the planetary health approach is mainly anthropocentric and takes a multilateral and multisystem approach to understand the health impact of all ecosystems' interconnectedness and interdependency on each other (Figure 2) [68]. The primary focus of this approach is mitigating and addressing the diverse threats to the health and general well-being of humans while also ensuring the sustainability of human civilization [66]. Additionally, the vitality of these planetary ecosystems is echoed in the totality of health for the entire mankind. By highlighting the link between human health and ecological changes, critically analyzing the challenges, and proposing sustainable solutions for the next generation [69], a sustainable health goal can be achieved. Human health cannot be separated from the health of the planet [66,70], and an increase in anthropogenic activities that disrupt the equilibrium of the Earth's biosphere directly has a lasting impact on the health of every individual living organism, including the human and animal hosts (reservoir and non-reservoir) and pathogens.

A deeper perspective on host–pathogen interactions has emerged under the planetary health concept. The evolutionary analysis under the 'Stockholm Paradigm' highlighted that humanity has opened Pandora's Box for increased circulation of pathogens that only required contact opportunities with susceptible but previously unexposed hosts to initiate infection [71]. The dual crises of climate change and anthropogenic ecological disruption facilitated the movement of hosts and pathogens to new geographical locations. Consequently, this exposure and interactions of one or a few hosts with highly specialized pathogens in localized settings may result in the emergence of new disease variants, most of which are zoonotic in origin. This evolutionary threat of pathogens to immunologically naive hosts may carry a large risk in the context of global public health and socio-economic burden [71]. Hence, the 'Stockholm Paradigm' addresses the climate-related hazards of emerging diseases with a focus on four ecological concepts, including ecological fitting, the geographical mosaic theory of co-evolution, taxon pulses, and the oscillation hypothesis. This paradigm aims at providing meaningful insight into understanding past, present, and predicted diseases. By adhering to the DAMA (Document, Assess, Monitor, and Act) protocol, we can anticipate mitigating outbreaks of emerging disease by D; documenting unknown pathogens in reservoir hosts and using new technologies and modeling platforms to A; assess the genetic status of pathogens of public health potential. Consequently, we can M; monitor the identified pathogens to inform about any known changes in pathogen population arising from anthropogenic activities and ecological disruption, and A; act collaboratively by involving concerned stakeholders and sectors across the field of public health and environmental health. This can involve the use of new technologies for data gathering, analysis, and formulating sustainable action plans to cope with these challenges [71].

Overall, the overarching application of the planetary health concept and Stockholm Paradigm in the fight against emerging infectious diseases will be realistic if a sustainable equilibrium is to be attained between humans and various ecological factors affecting the reservoir hosts, vectors, and pathogens dynamics.

9. Planetary Health and Drivers of Zoonoses

The emergence of zoonoses in recent times has been identified as a complex process due to the varying factors or drivers highlighted above (Figure 2). These drivers provide conditions that allow selected pathogens to expand and adapt to a new ecological niche. Urbanization with population mobility is the dominant demographic trend in the 21st century, linking planetary health to drivers of zoonotic disease [72]. Climate models for greenhouse warming predict that geographical changes will occur for some water-borne (e.g., cholera) and vector-borne (e.g., malaria, yellow fever, dengue, and leishmaniasis) diseases [40,42]. These changes will be driven largely by an increase in precipitation, leading to favorable habitat availability for vectors, intermediate hosts, and reservoir hosts; or warming that leads to the expansion of ranges in low latitudes, oceans, or mountain regions.

Two phenomena indicate that climate change will likely have a greater impact on key human diseases [42]. The continued variability and changes in anthropogenic factors that affect planetary health will continue to persist. Zoonotic disease emergence often occurs in stages, with an initial series of spillover events, followed by repeated small outbreaks in people, and then pathogen adaptation for human-to-human transmission [3]. Each stage might have a different driver and therefore a different control measure [42]. Hahn and colleagues [73] reported that Human Immunodeficiency Virus-1 (HIV-1) emerged from chimpanzees in Africa and spread to humans repeatedly before its global spread (Figure 1).

The initial phase of emergence was facilitated by bushmeat hunting and was the primary driver of its emergence. The second phase of emergence was driven by increased urbanization and road expansion in Central Africa beginning in the 1950s [73]. This allowed for population mobility and dispersal of index cases harboring prototype HIV-1 infections that were transmissible from person to person [74].

10. Recommendations: Planetary Health as a Panacea for Zoonoses

The causes of pandemics are often the causes of climate change and loss of biodiversity, two long-term issues that have not been resolved throughout the COVID-19 pandemic [75]. Against the backdrop of approximately 200 emerging disease hazards addressed yearly by the WHO, the COVID-19 pandemic reflected the unhealthy and unbalanced connections within the world we live in [76]. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) convened experts who declared that future pandemics are likely to be zoonotic in origin [77]. The debate around biodiversity loss and wildlife-origin zoonoses, the hidden cost of socio-economic development, and globalization over the last century requires collaboration and considering indigenous worldviews. Specifically, a worldview that recognizes the interdependence within and throughout our world and promises a pathway forward for the western world to heal its broken relationship with nature in upstream ways [78,79].

Indigenous peoples' millennia-old knowledge understood the interconnection of all living species and their environment, a framework increasingly acknowledged and embraced within the concept of "planetary health" [80]. In fact, planetary health is not "new" in the context of how our ancestors understood the web of life in the ecological theatre. Through a planetary health prism, integrationist approaches with a commitment to cultural competencies and the interconnectedness of factors, both negative and positive, can empower individuals and communities—especially the underprivileged ones, who are most vulnerable to zoonoses. The path to zoonotic disease prevention requires consolidative efforts, including a more comprehensive understanding of the limitations of previously implemented global health initiatives [81].

Preventing spillover without dealing with its bidirectional root causes is a never-ending battle [82]. Combating the emergence of zoonoses, especially in resource-limited settings such as developing African countries, can be mitigated by a planetary health approach. This allows for intersectoral collaboration, which leads to cost-resource sharing among translational fields within the concerned ministries. This would eventually improve the preparedness and response to the outbreak [69]. Reconciliation with indigenous peoples and other groups that have experienced historical patterns of synergizing western science with indigenous ways of protecting ecological integrity is also crucial to these partnerships [82].

Although there are unquestionable dangers of pathogen spillover related to wildlife consumption, policies aimed at reducing these risks are only part of the solution in pandemic prevention, as explained in this paper. As disease emergence and dynamics continue to change, there is a need for increased global (pre-spillover) surveillance measures such as the identification and monitoring of potential spillover hotspots [83]. There is also a need for periodic and dynamic risk assessment of high-risk settings where human and animal populations are in close contact. This should be performed without stigmatizing the consumption practices and livelihoods of underprivileged communities that rely on wild resources [82].

Before action, consultation with community leaders and stakeholders is required to ensure that policies are responsive to local disease exposures (and activities that may contribute to them) while being attentive to local needs [84]. Under the indigenous knowledge system, planetary health can develop highly ethnocentric narratives for vulnerable communities and encourage the engagement of local stakeholders. This is coupled with multiple supportive and diversified resources that may assist in the design of zoonotic disease programs for detection and treatment. Prioritizing robust public health programs that enhance local to global planetary health that project on building healthy ecosystems for a more equitable, and sustainable future [82].

Thus, well-developed theoretical and methodological frameworks are critically needed in zoonotic research and development. This with the goal of informing future actions that move beyond a geographically bounded perspective to a more holistic systems-based multilateral approach [85]. Preventing future pandemics requires substantial, highly focused investments from governmental, intellectual, technical, and policy perspectives. This can only be driven by the call to fill a crucial scientific and socio-ecological niche reflected in biosecurity operations at the local and global levels [85–88].

11. Conclusions

Zoonotic disease susceptibility is determined by a plethora of internal and external variables that vary throughout time and geography. As the planet faces several cumulative stressors on ecological systems, knee-jerk policy responses and fragmented solutions to zoonotic disease prevention necessitate context-sensitive and effective interventions based on awareness of local community vulnerabilities. The complexity of macro-level disease risk, the underscoring heterogeneity of social changes, and contextual biological-immune mechanisms leading to zoonotic infections—all these interdependent factors are recognized from a planetary health perspective.

Scientists have a moral obligation to prioritize research that helps the public good and the conservation of biodiversity within the Earth's biosphere. Moreover, there is a need to challenge long-held disciplinary boundaries where necessary toward a more holistic interdisciplinary understanding of pandemic complexities in a nonlinear manner, comparable to zoonoses, driven by multiple factors operating within distinct ecological ranges. Navigating the paradox of pathogen-human-vector/animal connectivity is a challenge for the prevention of zoonotic diseases. However, since interaction and connection between different species and the environment constitute the foundation of all life, a more holistic world view that moves beyond major drivers of zoonoses to understanding the ecological connectivity in pandemic prevention is a local and global imperative.

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