Economic incentives for the wildlife trade and costs of epidemics compared across individual, national, and global scales

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Abstract

The wildlife trade drives biodiversity loss and zoonotic disease emergence, and the health and economic impacts of COVID-19 have sparked discussions over stricter regulation of the wildlife trade. Yet regulation for conservation and health purposes is at odds with the economic incentives provided by this multibillion-dollar industry. To understand why the wildlife trade persists despite associated biodiversity and global health threats, we used a benefit–cost approach using simple calculations to compare the economic benefits of the wildlife trade at the individual, national, and global scales to the costs of COVID-19, severe acute respiratory syndrome (SARS), and Ebola disease across scenarios of epidemic frequency. For COVID-19, benefits of the wildlife trade outweigh costs at individual scales, but costs far exceed benefits at national and global scales, particularly if epidemics were to become frequent. For SARS and Ebola, benefits outweigh costs at all scales, except if Ebola-like epidemics were to become frequent. The wildlife trade produces net benefits for people who depend on wildlife for food and income but incurs net costs on stakeholders at larger scales from increased epidemic risk. While our analysis omits a variety of costs and benefits that are difficult to quantify and contrast, our analysis is meant to illustrate the distributional outcomes across stakeholder groups that could result from increased wildlife trade regulation. Importantly, the feasibility of trade regulatory policies will depend on how these benefits and costs compare across groups and would therefore need to involve accessible and attractive alternative sources of food and livelihoods for those who depend on the wildlife trade.

Keywords

benefit–cost analysis, bushmeat, COVID-19, Ebola disease, pandemic, planetary health, policy, SARS, wild meat, wildlife markets
1 INTRODUCTION

Every year tens of millions of wild animals are hunted for direct consumption or traded as food (wild meat), or for use in traditional medicine, research, ornamental products, fur, pets, trophies, or to stock wildlife farms (Liew et al., 2021; Scheffers et al., 2019). These activities (hereafter: wildlife trade) threaten the persistence of thousands of wildlife species and populations (IUCN, 2019), and may also drive habitat loss via destructive hunting and collection methods (Symes et al., 2018; Wright & Muller-Landau, 2006). The unsustainable demand for functionally or commercially valuable species can also have ecosystem-wide impacts, with negative consequences on the provision of ecosystem services upon which human communities rely (Brashares et al., 2004; Ripple et al., 2016; Wolfe et al., 2005). These activities have also been directly linked to the emergence of pathogens that cause epidemics and pandemics such as AIDS, Ebola disease, severe acute respiratory syndrome (SARS), and COVID-19 (Andersen et al., 2020; Enserink, 2003; Pekar et al., 2022; Wolfe et al., 2005; Worobey et al., 2022). Specifically, the hunting, handling, and consumption of wild animals can increase the risk of pathogen emergence and zoonotic spillover through direct or indirect contact with infected wildlife (Alexander et al., 2018; Bezerra-Santos et al., 2021; Liew et al., 2021).

The past century has seen a surge in zoonotic epidemics, with devastating health and socioeconomic impacts (Evans et al., 2020; Morse et al., 2012). The 2002 SARS epidemic sickened over 8000 people and cost nearly US$ 55 billion to the world in lost economic activity (Evans et al., 2020; World Health Organization, 2003). Ebola disease outbreaks and epidemics have been responsible for more than 15000 human deaths over the last 45 years, in addition to millions of HIV, malaria, and tuberculosis cases that were left untreated due to impacts on the healthcare system of affected countries (CDC, 2014; Parpia et al., 2016). As of October 16, 2021, over 240.4 million people have become infected with the coronavirus that causes COVID-19, over 4.89 million people have died from this disease (Roser et al., 2020), and the world has entered the deepest economic recession in the post-World War II era (The World Bank, 2020). In addition to the human death toll and economic costs of epidemics, many more costs continue to be incurred by society, such as impacts on the education sector, widening of structural, racial and gender inequalities, food insecurity, mental illnesses, and civil unrest (Alon et al., 2020; Laborde et al., 2020; Pfefferbaum & North, 2020; UNDP, 2015; van Dorn et al., 2020).

Yet, despite the negative biodiversity and human health impacts, the wildlife trade remains widespread. The global trade in wild animals is valued at roughly US$ 13 billion annually (The World Bank, 2019a), and the consumption of wildlife supports the livelihoods and food security of millions of people in low-income countries (Nasi et al., 2011; Rivalan et al., 2007). For many people then, the benefits of the wildlife trade are enormously important. The costs and benefits associated with wildlife trade, and how they are distributed across global, national, and individual-level scales, may explain why the number of species threatened by trade continues to increase and zoonotic diseases such as COVID-19, SARS, and Ebola continue to emerge despite multiple wildlife trade regulatory efforts and global disease surveillance programs (Dobson et al., 2020; Scheffers et al., 2019).

The socioeconomic incentives for the wildlife trade vary across scales. Wildlife is a significant and accessible source of nutrition and income for rural households, as well as a highly profitable business for people trading wildlife in cities or across national borders (Brashares et al., 2011; Cawthorn & Hoffman, 2015; Xiao et al., 2021). In simple terms, individuals hunt various wildlife species for direct or local consumption of their meat or as live animals (Figure 1a), or to profit from regional and/or international demand for these products via wildlife markets or intermediaries (dealers and farmers; Figure 1b). Wildlife hunters, sellers, and consumers, who are in direct contact with wild animals, bear the most immediate risk of pathogen spillover from Infected animals (Karesh et al., 2005). Specifically, wild meat hunting, handling, and consumption can result in exposure to potentially lethal viruses such as Ebola (Figure 1c), while maintaining wild-caught or captive-bred wildlife in farms and markets may be conducive to the emergence of pathogens such as the ones that cause COVID-19 and SARS (Holmes et al., 2021; Karesh et al., 2005; Wolfe et al., 2005; Figure 1d). At least eight of the 27 reported Ebola outbreaks are linked to wild meat consumption (Alexander et al., 2015; Centers for Disease Control and Prevention [CDC], 2019a), and evidence suggests the first outbreaks of COVID-19 and SARS were associated with contact with wildlife at wildlife markets (Enserink, 2003; Maxmen, 2021; Pekar et al., 2022; Worobey et al., 2022). However, for hunters, sellers, and consumers, the perceived future health risks associated with the wildlife trade may be small compared to the present and continuous nutritional and economic benefits obtained from wildlife, particularly if pathogen spillover events are rare (Plowright et al., 2017).

Banning or more stringently regulating the wildlife trade is a highly controversial and debated topic, even among conservation and public health scientists (e.g., [Eskew & Carlson, 2020; Wang et al., 2020; Yang et al., 2020]). Most debated are the impacts on food security for individuals who depend on wild meat for subsistence, contrasted with the depletion of wildlife populations that could result from
unsustainable hunting, or contrasted with the food security crises that have followed the past zoonotic epidemics (Brashares et al., 2004; Huber et al., 2018; Niles et al., 2020; Ripple et al., 2016). Also debated is the loss of biodiversity and ecosystem services that would result from land clearances if domestic animal farming were to be the alternative to wild meat, contrasted with the impacts on biodiversity and ecosystem services resulting from unsustainable harvesting of wildlife populations and destructive collection methods (Bernstein et al., 2022; Booth et al., 2021; Ripple et al., 2016; Scheffers et al., 2019). Likewise, discussions revolve around the risk of zoonotic outbreaks originating from domestic animal farming as an alternative to wild meat, versus the risks of zoonotic pathogens spilling through human–wildlife interactions during wildlife hunting, consumption, and trade (Bernstein et al., 2022; Parry et al., 2014; Ripple et al., 2016; Wolfe et al., 2005).

Nevertheless, reducing the threat to wildlife populations and preventing future pandemics that emerge from the wildlife trade will certainly require targeted solutions toward effective regulation of the trade, particularly of unsustainable consumption that is not meant for nutritional subsistence, as well as stronger support for alternative and sustainable livelihood options, increased funding for wildlife trade enforcement, increased pathogen surveillance, improved outbreak responses, universal access to healthcare and vaccines, and speed of effective vaccine development (Daszak et al., 2020; Dobson et al., 2020; Petrovan et al., 2021; TRAFFIC, 2008). These targeted solutions, in turn, will require policy changes and additional financial resources, which national and international conservation organizations currently lack (Dobson et al., 2020). The COVID-19 pandemic has prompted discussions over the need to better regulate the wildlife trade, making clear the economic incentives and costs associated with this industry, and underscoring the challenges that conservation organizations face in combating the wildlife trade giant on their own (Bernstein et al., 2022; Ripple et al., 2016).

Here, we compare the benefits of continuing the wildlife trade without implementing additional regulations to the economic impacts of trade-associated zoonotic disease epidemics at the current rate of emergence (here COVID-19, SARS, and Ebola). We conduct this analysis at individual, national, and global scales, and focus on two questions: (1) How does the relationship between costs and benefits vary across scales? (2) How frequently would epidemics like these need to occur for the costs to outweigh the benefits at each scale? Our analysis is illustrative rather than comprehensive, as we omit a variety of costs and benefits associated with disease emergence.
and wildlife trade, respectively, that are incurred by society and are difficult to quantify and contrast, such as loss of biodiversity and ecosystem services, food insecurity, mental illnesses, and civil unrest, as well as nutritional and cultural benefits obtained from wildlife. We use simple calculations that, while limited by data availability (particularly at individual scales), are meant to illustrate the distributional outcomes across stakeholder groups that could result from increased regulation of the wildlife trade. Our study is meant to provide an economic perspective on a highly complex issue that has social, public health, and biodiversity conservation implications.

2 | METHODS

We employed a simple benefit–cost approach to examine how the economic benefits of the current wildlife trade compared to the public health costs of trade-associated zoonotic disease epidemics. We exercised a business-as-usual scenario and thus did not incorporate additional conservation costs of wildlife trade enforcement to represent past and current costs of epidemics. We compared the resulting net benefits of wildlife trade across individual, national, and global scales. Given that COVID-19, SARS, and Ebola disease have been associated with different links in the wildlife trade supply chain (Figure 1), we specifically compared the benefits associated with wildlife markets and trade to the costs of COVID-19 and SARS (Figure 1d), and compared the benefits associated with wild meat consumption and trade to the costs of Ebola disease (Figure 1c). For COVID-19, the benefit–cost comparison is provisional and restricted to 2020, as these costs are ongoing. We used costs associated with these epidemics as proxies for similar epidemics that could emerge in the future due to wildlife trade activities and modeled net benefits under different frequency scenarios.

We focused our analysis specifically on the livelihood benefits and main health and economic costs of the wildlife trade. To represent the costs for each of the three diseases, we used productivity loss due to illness (i.e., days of lost income), estimates of the direct costs of illness (e.g., diagnostic tests, personal protective equipment supplies for healthcare staff, costs associated with supportive and extensive care, and disease surveillance and response management [Bartsch et al., 2015; Tan-Torres Edejer et al., 2020]), and economic costs of the epidemics (gross domestic product [GDP] contractions). Our estimates of costs of COVID 19 are clearly only indicative and not precise. COVID-19 has forced governments around the world to mobilize stimulus payments and furlough schemes that across many countries will carry considerable costs to national economies in the coming years. Considering this, our estimate of costs is likely to be greatly underestimated. The human death toll of COVID-19, SARS, and Ebola is enormous, and the cost of human life is something the world is dealing with in terms well beyond financial. Here we do not delve into this very real and complex issue and even leave the value of a statistical life (VSL) behind, making our estimates extremely conservative. However, we provided an additional set of calculations in SM 2 which included the VSL as costs of premature mortality. Finally, we defined benefits as the income obtained from the wild animal trade by individuals (i.e., net profits), nations, and the world (i.e., the combined value of the legal and illegal wild animal trade; SM 1).

For COVID-19 and SARS, we focused on China for individual and national-scale analyses, because both diseases emerged in China (Andersen et al., 2020; Enserink, 2003). We used the 2020 costs and health estimates associated with COVID-19, although as of early 2022 the pandemic is still ongoing. For Ebola, we focused on the 2014 West African epidemic, and obtained individual and national-scale data for Liberia, one of the epicenters of this epidemic (CDC, 2014). We focused on this epidemic because although it is unclear whether the origin of this epidemic is directly linked to wild meat consumption (Alexander et al., 2015), it has been the largest of its kind and for which information at all scales was available.

We defined an individual as a single person, specifically a wildlife market seller or a wild meat seller, and assumed the person was not formally employed nor obtained unemployment benefits. At individual scales, we only considered productivity loss because direct costs of illnesses in China are typically covered by the Chinese government, and not by individuals (Li et al., 2020), and resources to pay for direct costs of Ebola cases in Liberia were covered by the local government, the World Bank and donations from charitable foundations (Bartsch et al., 2015; Huber et al., 2018). Likewise, at national and global scales we used estimates of GDP lost as economic costs and assumed productivity losses were included in these estimates. Although we assumed benefits at the individual scale (i.e., net profits) included individual nutritional benefits (e.g., animals not sold and consumed by the individual) (Jones et al., 2019), nutritional benefits at national and global scales were not accounted for in our calculations. We calculated the average annual benefits of wildlife trade and the costs of the COVID-19, SARS, and Ebola epidemics. For each benefit–cost comparison, we obtained the net benefits by subtracting costs from benefits. All values are reported in US$ 2020 (SM 1).

The costs of epidemics over the long run depend on their expected frequency. Because COVID-19 is only comparable in magnitude to the health and economic impacts of the 1918 Great Influenza Pandemic (Barro
et al., 2020), we initially assumed an annual epidemic frequency for a disease like this of 0.01. An epidemic like SARS has occurred once since 2002, thus we assumed an annual epidemic frequency of 0.05. For Ebola, 27 outbreaks have been reported since 1976 (Alexander et al., 2015; Centers for Disease Control and Prevention

| Disease               | Scale          | Benefits (US$)                                                                 | Costs (US$)                                                                 | Country/region |
|-----------------------|----------------|-------------------------------------------------------------------------------|-----------------------------------------------------------------------------|----------------|
| COVID-19 and SARS     | Individual     | • Income wet market (1392.6) (Qi et al., 2019)                                | COVID-19                                                                    | China          |
|                       |                |                                                                               | • Productivity loss (5.9x10^{-5}) (Li et al., 2020, Mizrahi et al., 2020, Roser et al., 2020) |                |
|                       |                |                                                                               | SARS                                                                       |                |
|                       |                |                                                                               | • Productivity loss (2.3 x10^{-5}) (Feng et al., 2009, Qi et al., 2019, World Health Organization, 2003) |                |
|                       | National       | • Income wildlife market (21.3 billion) (Arranz & Huang, 2020)                | COVID-19                                                                    | China          |
|                       |                |                                                                               | • Health costs (1.3 million) (Li et al., 2020; Roser et al., 2020)            |                |
|                       |                |                                                                               | • Economic costs (7.3 billion) (The World Bank, 2019b, 2020)                  |                |
|                       |                |                                                                               | SARS                                                                       |                |
|                       |                |                                                                               | • Health costs (502,336) (Beutels et al., 2009; World Health Organization, 2003) |                |
|                       |                |                                                                               | • Economic costs (513.2 million) (Evans et al., 2020)                         |                |
|                       | Global         | • Income legal wildlife trade (10.7 billion) (The World Bank, 2019a)         | COVID-19                                                                    | World          |
|                       |                | • Income illegal wildlife trade (2.5 billion) (The World Bank, 2019a)        | • Health costs (1.9 billion) (Roser et al., 2020)                            |                |
|                       |                |                                                                               | • Economic costs (67.3 billion) (The World Bank, 2019b, 2020)                  |                |
|                       |                |                                                                               | SARS                                                                       |                |
|                       |                |                                                                               | • Health costs (795,609) (Beutels et al., 2009, World Health Organization, 2003) |                |
|                       |                |                                                                               | • Economic costs (2.7 billion) (Evans et al., 2020)                           |                |
| Ebola disease         | Individual     | • Income from wild meat consumption (1070.8) (Bene et al., 2013, Jones et al., 2019) | • Productivity loss (3.8x10^{-4}) (Bene et al., 2013, Kratz et al., 2015, Centers for Disease Control and Prevention (CDC), 2019b, Jones et al., 2019) | Liberia        |
|                       | National       | • Income from wild meat consumption (45.6 million) (Jones et al., 2019)        | • Health costs (30,946) (Bartsch et al., 2015, Centers for Disease Control and Prevention (CDC), 2019b) | Liberia        |
|                       |                |                                                                               | • Economic costs (1.4 million) (UNDP, 2015)                                  |                |
|                       | Global         | • Income legal wild meat trade (944 million) (The World Bank, 2019a)          | • Health costs (77,016) (Bartsch et al., 2015, Centers for Disease Control and Prevention (CDC), 2019b) | World          |
|                       |                | • Income illegal wild meat trade (236 million) (The World Bank, 2019a)        | • Economic costs (71.5 million) (Evans et al., 2020, United Nations Special Envoy on Ebola, 2015) |                |

**Note:** Annual probability of disease occurrence of 0.01, 0.05, and 0.02 was factored into annual costs of COVID-19, SARS, and Ebola, respectively. All estimates reported in US$ 2020.
[CDC], 2019a), but only the West African epidemic spread globally, thus we assumed an annual frequency for an epidemic of this magnitude of 0.02. We then varied these assumptions to examine the frequency at which epidemics like COVID-19, SARS, and Ebola would need to occur for health costs to outweigh wildlife trade benefits at all scales. We chose six annual probabilities: 0.01, 0.02, 0.05, 0.1, 0.2, and 0.5, equivalent to one expected epidemic every 100, 50, 20, 10, 5, and 2 years, respectively. We factored each frequency scenario into the expected annual costs and then compared updated net benefits across scales.

2.1 Wildlife markets and COVID-19

2.1.1 Individual scale

Benefits of the wildlife trade: Comprehensive data for the profit of wildlife market sellers across China were unavailable, so we used the average annual profit of wet market sellers from Nanjing, China (US$ 1393) (Qi et al., 2019) as benefits. This approach means that earnings from non-wildlife products may be included in the estimates and thus may overestimate the profit margin of wildlife sellers (Rao et al., 2011; Zhu & Zhu, 2020; Table 1).

Costs of the wildlife trade: We estimated productivity loss from COVID-19 by multiplying the mean duration of COVID-19 symptoms in mild and severe cases (23.5 days; Mizrahi et al., 2020) by the average daily earnings of a wildlife market seller in China (see individual scale benefits; Li et al., 2020). We then multiplied this value by the incidence of COVID-19 in China during 2020 (66.6 per million; Roser et al., 2020) to account for the probability of a wet market seller becoming infected with COVID-19 once the disease emerged (SM 1, Table 1).

2.1.2 National scale

Benefits of the wildlife trade: We estimated the national income obtained from wildlife markets using the annual value of wildlife in the food, pet, and traditional Chinese medicine sectors (Arranz & Huang, 2020; Table 1).

Costs of the wildlife trade: To calculate health costs, we used 20% of China's COVID-19 cases as of December 31, 2020 (19,193) (Roser et al., 2020) as this was the average proportion of cases requiring medical treatment and hospitalization in 2020 (World Health Organization, 2020). We then multiplied this value by the cost of treating a COVID-19 patient in that same year (US$ 6827) (Li et al., 2020) (SM 1). To estimate economic costs due to COVID-19, we used China's expected GDP growth in 2020 prior to the emergence of the pandemic (US$ 14.34 trillion, 6.1%) minus the actual GDP growth during 2020 (US$ 14.48 trillion, 1%) (The World Bank, 2019b, 2020) (SM 3, Table 1).

2.1.3 Global scale

Benefits of the wildlife trade: We used the combined global value of the legal (US$ 10.7 billion) (The World Bank, 2019a) and illegal (US$ 2.5 billion) (The World Bank, 2019a) wild animal trade reported by the World Bank (The World Bank, 2019a), which estimates the value of the illegal trade as 25% of the total value of the legal trade (Table 1).

Costs of the wildlife trade: We used 20% of the world's COVID-19 cases as of December 31, 2020 (16.7 million; Roser et al., 2020) as this was the average proportion of cases requiring medical treatment and hospitalization in 2020 (World Health Organization, 2020). We then multiplied this value by the average cost of treating a COVID-19 patient in that same year in 11 of the 19 countries with the highest number of reported cases (90th percentile) for which cost per patient information was available (US$ 11,529) (SM 1). We estimated economic costs using the world's expected GDP growth in 2020 prior to the emergence of COVID-19 (US$ 87.7 trillion, 2.47%) minus the actual GDP growth during 2020 US$ 83.1 trillion, −5.2%) (The World Bank, 2019b, 2020; SM 3, Table 1).

2.2 Wildlife markets and SARS

2.2.1 Individual scale

Benefits of the wildlife trade: see methods for COVID-19 individual scale benefits.

Costs of the wildlife trade: We estimated productivity loss from SARS by multiplying the average duration of SARS symptoms (29-7 days) (Feng et al., 2009) by the average daily earnings of a wet market seller in China (see methods for COVID-19 individual scale benefits). We multiplied this value by the incidence of SARS in China (4.2 per million) (World Health Organization, 2003) to account for the probability of a wet market seller becoming infected with SARS once the disease emerged (SM 1, Table 1).

2.2.2 National scale

Benefits of the wildlife trade: See methods for COVID-19 national scale benefits.
Costs of the wildlife trade: We estimated health costs by multiplying the cost of treating a SARS patient (US$ 1886) (Beutels et al., 2009) by the number of cases in China (5327) (World Health Organization, 2003). We used the GDP lost due to the epidemic (US$ 10.3 billion; Evans et al., 2020) to estimate economic costs (Table 1).

2.2.3 | Global scale

Benefits of the wildlife trade: See methods for COVID-19 global scale benefits.

Costs of the wildlife trade: We estimated health costs by multiplying the total number of SARS cases worldwide (8437) by the reported costs of treating SARS patients in mainland China (US$ 1886) (Beutels et al., 2009), as China accounted for over 63% of the total cases (World Health Organization, 2003). We used the value of lost economic activity (US$ 54.8 billion; Evans et al., 2020) due to the epidemic as economic costs (Table 1).

2.3 | Wild meat trade and Ebola disease

2.3.1 | Individual scale

Benefits of the wild meat trade: We estimated the income from wild meat consumption using the average annual net income generated by wild meat hunters in Liberia (US$ 1071) (Bene et al., 2013; Jones et al., 2019; Table 1). These estimates include the net profits of hunters and include costs associated with hunting and animals not sold that were destined for personal consumption (Jones et al., 2019).

Costs of the wild meat trade: We estimated productivity loss by multiplying the average duration of Ebola symptoms (18 days) (Kratz et al., 2015) by the average daily earnings of a wild meat seller in Liberia (see methods for Ebola individual scale benefits; Bene et al., 2013; Jones et al., 2019). We multiplied this value by the annual incidence of Ebola in Liberia (1124 per million) (Centers for Disease Control and Prevention [CDC], 2019b) to account for the probability of a wild meat hunter becoming infected with Ebola once the disease emerged (SM 1). We then multiplied these costs by the fraction of epidemics that have been linked directly to wildlife hunting or wild meat consumption (i.e., 30%) (Alexander et al., 2015; Centers for Disease Control and Prevention [CDC], 2019a; SM 1, Table 1).

2.3.2 | National scale

Benefits of the wild meat trade: We estimated the national income obtained from wild meat consumption using the total annual value of wild meat in Liberia (US$ 45.6 million; Jones et al., 2019; Table 1).

Costs of the wild meat trade: We estimated health costs by multiplying the average cost of treating an Ebola patient (US$ 966; Bartsch et al., 2015) by the average annual number of cases in Liberia (5339; Centers for Disease Control and Prevention [CDC], 2019b). We estimated economic costs using the annual average GDP lost as a consequence of the epidemic (US$ 236.7 million; UNDP, 2015). We then multiplied all costs by 0.30 to account for the probability of epidemics resulting from wild meat consumption (Alexander et al., 2015; Centers for Disease Control and Prevention [CDC], 2019a; Table 1).

2.3.3 | Global scale

Benefits of wild meat trade: We estimated the combined global income obtained from wild meat consumption using the global annual value of the legal (US$ 944 million; The World Bank, 2019a) and illegal wild meat trade (US$ 236 million; The World Bank, 2019a), assuming the illegal trade accounts for 25% of the legal trade (The World Bank, 2019a; Table 1).

Costs of wild meat trade: We estimated health costs by multiplying the average annual number of Ebola cases worldwide (14,326; Centers for Disease Control and Prevention [CDC], 2019b) by the reported costs of treating Ebola patients in Liberia, Guinea, and Sierra Leone (US$ 896; Bartsch et al., 2015), as these countries accounted for over 99% of the total cases (Centers for Disease Control and Prevention [CDC], 2019b). For the economic costs, we used the value of lost economic activity in Liberia, Guinea, and Sierra Leone in 2015 (Evans et al., 2020) and the funds disbursed by international donors to address the epidemic (US$ 11.9 billion; United Nations Special Envoy on Ebola, 2015). We multiplied all costs by 0.30 to account for the probability of epidemics resulting from wild meat consumption (Alexander et al., 2015; Centers for Disease Control and Prevention [CDC], 2019a; Table 1).

3 | RESULTS

3.1 | Wildlife markets and COVID-19

Assuming an epidemic frequency of once every 100 years, wildlife market sellers that become ill with a disease like COVID-19 and survive, experience an average annual net benefit of US$ 1392 from continued wildlife trade (Figure 2, SM 4). For China, national-scale benefits of
wildlife markets would exceed the costs of COVID-19 by US$ 13.9 billion per year (Figure 2, SM 4), and global-scale costs associated with COVID-19 would exceed the benefits of the wildlife trade by US$ 56 billion per year (Figure 2, SM 4).

3.2 | Wildlife markets and SARS

Assuming an epidemic frequency of once every 20 years, wildlife market sellers that become ill with a disease like SARS and survive, experience an average annual net benefit of US$ 1393 from continued wildlife trade (Figure 2, SM 4). For China, the benefits of wildlife markets would exceed the costs of SARS-like epidemics by US$ 20.8 billion per year, and for the world, benefits would exceed the costs by US$ 10.4 billion per year (Figure 2, SM 4).

3.3 | Wild meat and Ebola

Assuming an epidemic frequency of once every 50 years, wild meat sellers that become ill with a disease like Ebola and survive, experience an average annual net benefit of US$ 1071 from continued wild meat consumption (Figure 2, SM 4). For Liberia, the national-scale benefits of wild meat consumption would exceed the costs of epidemics like Ebola by US$ 44.2 million per year (Figure 2, SM 4). For the world, benefits from the wild meat trade would exceed the costs of Ebola-like epidemics by US$ 1.1 billion per year (Figure 2, SM 4).

3.4 | Scenarios of epidemic frequency

COVID-19: Individual-scale benefits of wildlife markets consistently exceed costs associated with diseases like COVID-19 across all frequency scenarios of epidemic...
occurrence like COVID-19 would exceed the benefits of wildlife markets across all frequency scenarios of epidemic occurrence, except under scenarios in which these epidemics occur once every 50 and 100 years (Figure 3, SM 4). The costs associated with COVID-19-like epidemics on a global scale would exceed the benefits of the wildlife trade across all frequency scenarios of epidemic occurrence (Figure 3).

SARS: Average annual benefits of wildlife markets would outweigh the costs of epidemics like SARS across all scales and across all scenarios of epidemic occurrence (Figure 3, SM 4).

Ebola: Individual and national-scale benefits of bushmeat consumption consistently exceed costs associated with Ebola-like epidemics across all scenarios of epidemic occurrence (Figure 3). Global costs of these epidemics would exceed the benefits only if epidemics occurred approximately every 4 years (Figure 3).

4 | DISCUSSION

Our findings suggest that the costs and benefits of the wildlife trade vary widely across diseases, scales, and frequency of epidemic occurrence. At individual scales, the livelihood benefits of the wildlife trade appear to always outweigh the costs of becoming ill, no matter how frequent epidemics of each disease become. In contrast, at national and global scales the aggregate costs of disease would more often outweigh the benefits of wildlife trade for diseases like COVID-19, the costliest global pandemic in history. Our study indicates important inequities in the distribution of health and economic impacts of the wildlife trade. These inequities, in turn, help explain why the wildlife trade persists despite the immense and increasing biodiversity threats and global health burden associated with it, and they point to policy interventions that can reduce this burden fairly.

How frequently emerging zoonotic diseases become epidemics depends on a myriad of ecological, epidemiological, and socioeconomic factors, including the probability of pathogen spillover given contact, human population density, international trade and travel, and public health infrastructure (Morse et al., 2012; Plowright et al., 2017). If zoonotic diseases associated with the wildlife trade continue to emerge at similar or higher rates than in past decades, decisions to effectively regulate the trade may yield cumulative benefits over longer time scales. However, because predicting when spillover events will occur and how frequently these will become epidemics is extremely difficult (Morse et al., 2012; Plowright et al., 2017), thus enacting these policies may not be attractive for decision makers if policy results are not immediately apparent, or if other sources of pathogen exposure are possible (as is the case for Ebola disease (Alexander et al., 2015)). These uncertainties will naturally make policy decisions riskier, particularly if these come at a significant economic or livelihood cost (e.g., enforcement costs and lost income from wildlife trade). For example, our results suggest that Ebola-like epidemics would need to occur at a much greater frequency (even after accounting for costs of premature mortality [SM 2]) for costs to outweigh benefits (Figure 3) and drive policy decisions toward regulating wild meat consumption. However, for a pandemic like COVID-19, regulating wildlife trade would significantly reduce economic costs associated with the disease, even if a disease like this became a pandemic only once every 100 years (Figure 3; e.g., Dobson et al., 2020).

The average annual net costs of SARS, Ebola, and the first full year of COVID-19 combined are approximately US$ 58.8 billion per year (SM 5), which provides a rough estimate of society’s current willingness to pay for effective enforcement of the wildlife trade, as well as for the livelihood costs that such policies would impose on the stakeholders involved. Aside from reducing the risk of emerging diseases such as COVID-19, SARS, and Ebola, effective wildlife trade enforcement could significantly reduce the risks of extinction of thousands of species (Ripple et al., 2016; Scheffers et al., 2019). Notably, the feasibility of laws and policies aimed at regulating the wildlife trade will likely depend on the distribution of their potential benefits and costs across affected groups (e.g., hunters, traders, and susceptible populations). Effective regulation of the wildlife trade would require a significant increase in costs dedicated to enforcing regulations (e.g., Dobson et al., 2020), as well as programs focused on supporting sustainable harvesting of wildlife for nutritional purposes and creating alternative livelihoods and sources of income for those affected by such policies (Koh et al., 2021).

Our results are indeed underestimates of the actual costs and benefits of the current wildlife trade given that we did not include in our analysis the cultural benefits derived from wildlife trade activities, the nutritional benefits of wildlife at national and global scales (Douglas & Ali, 2014), nor the human death toll of trade-associated epidemics (however, see SM 2) or their impacts on mental health, food security, social disparities, and healthcare systems (Alon et al., 2020; Huber et al., 2018; Laborde et al., 2020; Pfefferbaum & North, 2020; van Dorn et al., 2020). Notably, after accounting for the financial costs associated with premature mortality (i.e., VSL), the benefits of the wildlife trade still outweighed the costs of the three epidemics in most scale-frequency combinations (SM 2), largely because of the effect of epidemic frequency on the expected costs of epidemics. Furthermore, we focused our analyses on two countries for
which information was available at individual and national scales (i.e., Liberia and China), and the value of wildlife, the economies, as well as the epidemiology and therefore costs associated with these diseases, will likely vary significantly across countries where wildlife trade is prevalent.

Lastly, we did not include in our analysis a scenario in which domestic animal farming is the only alternative to wild meat consumption. This scenario could potentially shift the net benefits across scales due to costs associated with disease outbreaks of domestic animals (e.g., foot and mouth disease, bluetongue, avian Influenza, etc.), the emergence of other zoonotic diseases (e.g., pandemic Influenza, foodborne diseases, coronaviruses, etc.), increased antimicrobial use and resistance from livestock, as well as loss of ecosystem services due to land conversions (Loh et al., 2015; Roe & Lee, 2021). Importantly, only a proportion of the economic benefits derived from the wildlife trade are associated with the consumption of wild meat (~9% (The World Bank, 2019a)) and an even smaller proportion of these benefits are associated with wild meat consumption for nutritional subsistence—evidence of which can be seen in the elevated costs of wild meat compared to domestic animal meat, particularly when sold in city markets (Xiao et al., 2021). This suggests that wildlife trade regulation does not preclude sustainable wild meat consumption.

Our findings reinforce those of others (Roe et al., 2020; Saylors et al., 2021) who suggest that reducing or regulating the wildlife trade would negatively impact individuals whose livelihoods depend on it for food and income. Our findings, as such, provide a rough estimate of the opportunity costs to these individuals if effectively regulating the trade were possible, and therefore an estimate of compensation required from national and global stakeholders who would benefit most from the prevention of pandemics like COVID-19. For example, through a global incentive or compensation mechanism similar to those used for climate change mitigation and nature conservation, payments could be directed toward programs that help wildlife hunters and sellers develop alternative livelihoods and food sources (Liew et al., 2021; Parry et al., 2014; Ripple et al., 2016).

There are multiple reasons to better regulate the unsustainable trade of wildlife worldwide, including reducing the extinction risk of thousands of species, preventing the loss of human lives, and promoting sustainable development (Ripple et al., 2016; Roe et al., 2020; Scheffers et al., 2019). The public health benefits of preventing future zoonotic disease outbreaks provide a powerful economic argument for better managing the wildlife trade. However, any policy and finance mechanism needs to account for private and social incentives at multiple scales, to avoid unfair distributional impacts of such policies.

AUTHOR CONTRIBUTIONS
LAdW: Conceived research idea, collected data, analyzed data, and wrote manuscript; BF: conceived research idea, and wrote manuscript; RN: conceived research idea and wrote manuscript; and THR: conceived research idea and wrote manuscript.

ACKNOWLEDGMENTS
LAdW was supported by a Gund Institute Postdoctoral Fellowship at University of Vermont. We also thank the Medina Fund and the Gund Institute for financial support, and Jesse Gourevitch and Tim Treuer who improved the manuscript with their comments.

CONFLICT OF INTEREST
The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT
All data and code for this research project are public and accessible at Figshare (DOI: 10.6084/m9.figshare.19760311).

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