POLICY FORUM

ECOLOGY AND ECONOMICS: COVID-19

Ecology and economics for pandemic prevention

Investments to prevent tropical deforestation and to limit wildlife trade will protect against future zoonosis outbreaks

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For a century, two new viruses per year have spilled from their natural hosts into humans (*1*). The MERS, SARS, and 2009 H1N1 epidemics, and the HIV and coronavirus disease 2019 (COVID-19) pandemics, testify to their damage. Zoonotic viruses infect people directly most often when they handle live primates, bats, and other wildlife (or their meat) or indirectly from farm animals such as chickens and pigs. The risks are higher than ever (*2*, *3*) as increasingly intimate associations between humans and wildlife disease reservoirs accelerate the potential for viruses to spread globally. Here, we assess the cost of monitoring and preventing disease spillover driven by the unprecedented loss and fragmentation of tropical forests and by the burgeoning wildlife trade. Currently, we invest relatively little toward preventing deforestation and regulating wildlife trade, despite well-researched plans that demonstrate a high return on their investment in limiting zoonoses and conferring many other benefits. As public funding in response to COVID-19 continues to rise, our analysis suggests that the associated costs of these preventive efforts would be substantially less than the economic and mortality costs of responding to these pathogens once they have emerged.

REDUCING DEFORESTATION

Tropical forest edges are a major launchpad for novel human viruses. Edges arise as humans build roads or clear forests for timber production and agriculture. Humans and their livestock are more likely to contact wildlife when more than 25% of the original forest cover is lost (*4*), and such contacts determine the risk of disease transmission. Pathogen transmission depends on the contact rate, the abundance of susceptible humans and livestock, and the abundance of infected wild hosts. Contact rates vary with the perimeter (the length of the forest edge) between forest and nonforest. Deforestation tends to create checkerboards, whereupon we see a maximum perimeter at a 50% level of forest conversion. Thereafter, the abundance of domestic animals and humans rapidly exceeds that of wild animals, so although we expect transmission to decline, the magnitude of any resultant outbreak is higher (*4*). Habitat fragmentation complicates this because it increases the length of the perimeter. Roadbuilding, mining and logging camps, expansion of urban centers and settlements, migration and war, and livestock and crop monocultures have led to increasing virus spillovers. Hunting, transport, farming, and trade of wildlife for food, pets, and traditional medicine compound these routes of transmission and closely track deforestation. For example, bats are the probable reservoirs of Ebola, Nipah, SARS, and the virus behind COVID-19. Fruit bats (Pteropodidae in the Old World, the genus *Artibeus* in the New World) are more likely to feed near human settlements when their forest habitats are disturbed; this has been a key factor in viral emergence in West Africa, Malaysia, Bangladesh, and Australia (*5*–*7*).

The clear link between deforestation and virus emergence suggests that a major effort to retain intact forest cover would have a large return on investment even if its only benefit was to reduce virus emergence events. The largest-scale example of directed deforestation reduction comes from Brazil between 2005 and 2012. Deforestation in the Amazon dropped by 70%, yet production of the region's dominant soy crop still increased (*8*). International contributions, complemented by an Amazon Fund, of about $1 billion supported land-use zoning, market and credit restrictions, and state-of-the-science satellite monitoring. Brazil's program reduced forest fragmentation and edge at a lower cost than could have been achieved by carbon-pricing approaches (*9*).

Several estimates of the effectiveness and cost of strategies to reduce tropical deforestation are available (*8*, *9*). At an annual cost of $9.6 billion, direct forest-protection payments to outcompete deforestation economically could achieve a 40% reduction in areas at highest risk for virus spillover [see supplementary materials (SM)]. Multiple payment-for-ecosystem-services programs demonstrate the effectiveness of this approach. At the low end, widespread adoption of the earlier Brazil policy model could achieve the same reduction for only $1.5 billion annually by removing subsidies that favor deforestation, restricting private land clearing, and supporting territorial rights of indigenous peoples. All require national motivation and political will. Strong public support for similar deforestation-prevention policies may emerge in other countries recovering from COVID-19's devastation.

WILDLIFE TRADE SPILLOVER

Global demand for wildlife causes people to enter forests to collect wildlife for sale in markets in urban and rural areas. In cities, where people have diverse options for protein, bushmeat is a luxury bought to show status, and occasionally for cultural reasons. COVID-19 is the huge price society now pays for such encounters with wild species.

Wildlife markets and the legal and illegal wildlife trade bring live and dead wild animals into contact with hunters, traders, consumers, and all those involved in this commerce. Trade follows global consumer demand. The United States is one of the biggest global importers of wildlife, including for the massive exotic pet industry (*10*). The transit conditions, lack of health screening at import, and warehouses that store animals before and after import are similar to live animal markets, all conducive to spreading diseases.

Some countries have wildlife farming industries intended to prevent overhunting of wild species while meeting market demands for protein and appealing to cultural traditions. In China, wildlife farming is a ~$20 billion industry employing some 15 million people (*11*). With the February 2020 announcement by the Standing Committee of the National People's Congress of a ban on wildlife consumption for food and related trade in China, there are ongoing discussions on phasing out this industry. The justification is that it creates risks for disease emergence and

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that the health and safety regulations associated with farming wild animals are often insufficient. Laws to ban the national and international trade of high-risk disease reservoir species, and the will to sustain their enforcement, are necessary and precautionary steps to prevent zoonotic disease. Regulations must keep primates, bats, pangolins, civets, and rodents out of markets.

International conventions such as the Convention on International Trade in Endangered Species of Fauna and Flora (CITES) deal with only a part of the problem. They, regional networks, and national agencies monitoring wildlife trade and enforcing regulations are severely underfunded. Regional wildlife enforcement networks (WENs) could be strengthened to form part of an effective response frontier to future pandemic prevention. The annual budget of one WEN, hosted by the Association for Southeast Asian Nations, is $30,000 (see SM). CITES's annual budget is a mere $6 million. Its secretariat has recently stated that zoonotic diseases are outside of CITES's mandate; they are certainly outside its current budget. Helping to prevent the next outbreak might include raising WENs' budgets for regional responses while at the same time developing globally coordinated protocols to increase the WENs' capacity in wildlife health screening. Although there is no global agency with a remit to conduct surveillance on the wildlife trade, we estimated the costs of such an effort by considering the annual operating budget of the World Organization for Animal Health (OIE), which has a remit to assess disease risk in livestock trade without conducting testing. We then added costs of large-scale disease surveillance in wildlife, scaled to the global volume of wildlife trade (see SM).

Restricting access to wildlife for food and other uses must consider indigenous peoples and those in remote communities for whom wildlife provides essential protein. In some parts of the world, reliance on migratory wildlife such as caribou and salmon motivates stewardship of large expanses of habitat. Although the right to traditional diets should be upheld, people can nonetheless be at risk from harvesting wildlife. These are food security issues that governments and development agencies should confront. Where needed, they must include education and awareness on animal handling, sanitation, and disease transmission as well as sustainable wildlife management and support to develop village-level alternative foods. Legal hunting and marketing of wildlife that meets basic nutritional requirements sustainably can be regulated to reduce the risk of emerging pandemics. Over time, culturally sensitive measures could ensure indigenous people's access to healthy diets and reduce pandemic risks.

Summary of prevention costs, benefits, and break-even probability change

ITEM	VALUES (2020 $)
Expenditures on preventive measures	
Annual funding for monitoring wildlife trade (CITES+)	$250–$750 M
Annual cost of programs to reduce spillovers	$120–$340 M
Annual cost of programs for early detection and control	$217–$279 M
Annual cost of programs to reduce spillover via livestock	$476–$852 M
Annual cost of reducing deforestation by half	$1.53–$9.59 B
Annual cost of ending wild meat trade in China	$19.4 B
TOTAL GROSS PREVENTION COSTS (*C*)	**$22.0–$31.2 B**
Ancillary benefit of prevention	
Social cost of carbon	$36.5/tonne
Annual CO_2 emissions reduced from 50% less deforestation	118 Mt
Ancillary benefits from reduction in CO_2 emissions	$4.31 B
TOTAL PREVENTION COSTS NET OF CARBON BENEFITS (*C*)	**$17.7–$26.9 B**
Damages from COVID-19	
Lost GDP in world from COVID-19	$5.6 T
Value of a statistical life (*V*) adjusted for COVID-19 mortality structure	$5.34 M or $10.0 M
Total COVID-19 world mortality (Q_D) forecast by 28 July 2020, 50th percentile with 95% error bounds	590,643 [473,209, 1,019,078]
Value of deaths in world from COVID-19 = $Q_D \times V$ Lowest ($5.34 M × 2.5th percentile mortality forecast)	$2.5 T
Middle ($10 M × 50th percentile mortality forecast)	$5.9 T
Highest ($10 M × 97.5th percentile mortality forecast)	$10.2 T
TOTAL DISEASE DAMAGES (*D*):	
Lowest ($5.34 M × 2.5th percentile mortality forecast)	**$8.1 T**
Middle ($10 M × 50th percentile mortality forecast)	**$11.5 T**
Highest ($10 M × 97.5th percentile mortality forecast)	**$15.8 T**

The break-even change in annual probability of pandemic satisfies $C = \Delta P \times D$, where P_0 = benchmark probability of pandemic; P_1 = probability of pandemic with prevention efforts in place; $\Delta P = P_0 - P_1$; and $\%\Delta P = (\Delta P/P_0) \times 100$.

If $P_0 = 0.01$, C = \$30.7 B, and D = \$11.5 T (most likely scenario, ignoring ancillary benefits of CO_2 reductions), prevention results in net benefits if it decreases P by 26.7% to $P_1 = 0.00733$. Using other values of C, D, and P results in $\%\Delta P$ ranging from 11.8% to 75.7%; only one scenario has a $\%\Delta P$ exceeding 50%. See supplementary materials.

EARLY DETECTION AND CONTROL

There is substantial underreporting of exposure to zoonotic diseases. Correcting this would provide major opportunities for prevention. Nipah virus was discovered in 1998, originating in fruit bats, and caused a massive outbreak of respiratory illness in pigs and lethal encephalitis in people in Malaysia (*6*). Sentinel surveillance in Bangladesh hospitals revealed multiple annual case clusters and outbreaks with an average case fatality rate of 70%.

Similarly, SARS and COVID-19 emerged as outbreaks of respiratory disease in Guangdong and Wuhan, China, respectively. Serological surveys of people in rural Yunnan province showed that 3% had antibodies to similar virus species from their principal reservoir, horseshoe bats (*Rhinolophus* spp.) (*12*).

To quantify and reduce the risk of spillover of pathogens requires viral discovery in wildlife and testing of human and livestock populations in regions of high disease emergence risk. For example, the Wellcome Trust VIZIONS program tested wildlife, humans, and livestock for known pathogens in rural Vietnam. The U.S. Agency for International Development (USAID) PREDICT project analyzed the spillover of viruses in people with high wildlife contact in 31 countries. PREDICT included community education programs to raise awareness of zoonotic risk and reduce contact with wildlife. It worked to prevent spillover through identification of high-risk behaviors and used serology surveys to examine seasonal patterns of risk. Interventions included use of bamboo skirts to reduce Nipah virus contamination of palm sap, increased biosecurity at livestock farms to reduce wildlife-livestock-human contact, promotion of handwashing, and wearing of personal protective equipment when in close contact with wildlife. It reduced the capacity of wildlife to shed virus at interfaces by closing high-risk bat caves.

Costs of measures to prevent spillover vary. USAID PREDICT spent $200 million over 10 years. This cost compares favorably with the $1.2 billion for the Global Virome Project, a 10-year project designed to identify 70% of the unknown potentially zoonotic viruses in wildlife globally. Although we have proof of concept for the discovery of disease with potential for emergence, for the identification of active spillover, and for programs that reduce risk, research is needed to quantify the return on investment for these programs. Pilot programs should prioritize indicators that allow better assessment of the costs and benefits of risk reduction (see SM).

After spillover, a second critical window of opportunity is the prevention of larger outbreaks (*2*). Early cases of HIV/AIDS, hantavirus pulmonary syndrome, Nipah virus, SARS, and COVID-19 went undetected for weeks, months, or years (HIV) before pathogen identification. Lags in identification have decreased, but this varies geographically. In lower-income countries, large outbreaks with substantial mortality often go undiagnosed, particularly when symptoms mimic those of other known diseases. Pilot projects are under way in clinics in many rural regions to identify the etiology of cases with similar symptoms (syndromic surveillance). For example, a pilot project costing $200,000 per year for syndromic surveillance for Nipah virus in Bangladesh hospitals resulted in a factor of 3 increase in the detection of spillover events (*13*). The U.S. National Institute of Allergy and Infectious Diseases is launching a series of Centers for Research in Emerging Infectious Diseases. Contracts for this work are expected at $1.5 million per year, focusing on specific high-risk viral zoonoses in emerging disease hotspots. Detection and control programs targeting outbreaks in their early stages would result in considerable savings by reducing morbidity and mortality. A priority is to identify indicators of risk reduction as pilot programs roll out and to calculate the costs, cost savings, and benefits of expanding them.

FARMED ANIMAL SPILLOVER

Livestock are critical reservoirs and links in emergent diseases. H5N1 influenza came across the human-wildlife interface (wild bird → poultry → human transmission chain), as did H1N1 influenza (bird → pig → human). Many livestock-linked outbreaks have reached the cusp of pandemic emergence, such as Nipah virus (fruit bat → pig → human) and swine acute diarrhea syndrome coronavirus (bat → pig) (*14*). These links are well recognized and are the focus of pandemic prevention packages proposed by the U.S. Congress (H.R. 3771). There are well-researched veterinary health plans such as the World Bank's One World One Health farm biosecurity intervention program, designed to reduce H5N1 influenza risk. With costs in the tens of billions of dollars, proposals dealing with livestock's roles in pandemics are among the most advanced and ambitious of those being seriously considered. We have known about these risks longer (e.g., influenza) and can control farm biosecurity more easily than wildlife contact in trade or at forest edges.

CONCLUSIONS

The actions we outline can help to prevent future zoonotic pandemics before they start. Monitoring alone would realize substantial cost savings, even in the context of pandemic outbreaks much less severe than COVID-19 (*14*). The gross estimated costs of the actions we propose total $22 to $31 billion per year (see the table). Reduced deforestation has the ancillary benefit of around $4 billion per year in social benefits from reduced greenhouse gas emissions, so net prevention costs range from $18 to $27 billion per year. In comparison, COVID-19 has shown us the immense potential cost of a pandemic. The world may lose at least $5 trillion in GDP in 2020, and the willingness to pay for the lives lost constitutes many additional trillions (see SM). These costs exclude the rising tally of morbidity, deaths from other causes due to disrupted medical systems, and the loss to society of foregone activities due to social distancing.

To justify the costs of prevention, a year's worth of these preventive strategies would only need to reduce the likelihood of another pandemic like COVID-19 in the next year by about 27% below baseline probability in the most likely scenario, even ignoring the ancillary benefits of carbon sequestration. We explored eight alternative scenarios with varied assumptions drawn from the highest and lowest values of both prevention costs and pandemic damages, and assuming that extreme pandemics occur either once every 100 years or once every 200 years. In all scenarios but one, prevention need only reduce the probability of a pandemic by less than half, and in one case the break-even percent probability reduction is as low as 12% (see SM). We estimate the present value of prevention costs for 10 years to be only about 2% of the costs of the COVID-19 pandemic.

We recognize that we have provided no more than a sketch of the key components of an economically feasible set of ecological pandemic prevention strategies. Limits on the availability of information limit our ability to conduct a more exhaustive analysis. Instead, we tally readily available information to evaluate how likely it is that an investment of the costs of pandemic prevention would yield positive net benefits to the world. Our calculations are conservative in the direction of making it hard to find that prevention is likely to be worthwhile—and yet that is our finding. Future studies could narrow uncertainties in the costs and efficacy of those strategies and pinpoint the most cost-effective suite of actions. A full cost-benefit analysis of pandemic prevention could track the flows of prevention costs over time, allow for intertemporal dependences, and model the pandemics prevented as products of a distribution of disease events that are not all as severe as COVID-19. Our findings make clear that this research effort is warranted, because the net benefits of stopping pandemics before they start could be enormous.

We recognize that as the world emerges from the COVID-19 pandemic, economic priorities may shift to deal with soaring demands from unemployment, chronic diseases, bankruptcies, and severe financial hardship of public institutions. Nonetheless, there is substantial evidence that the rate of emergence of novel diseases is increasing (*2*, *3*) and that their economic impacts are also increasing. Postponing a global strategy to reduce pandemic risk would lead to continued soaring costs. Given the barrage of costly emerging diseases in the past 20 years, we urge that stimulus and other recovery funding include the strategies we have laid out to reduce pandemic risk. Society must strive to avoid some of the impacts of future pandemics. ■

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