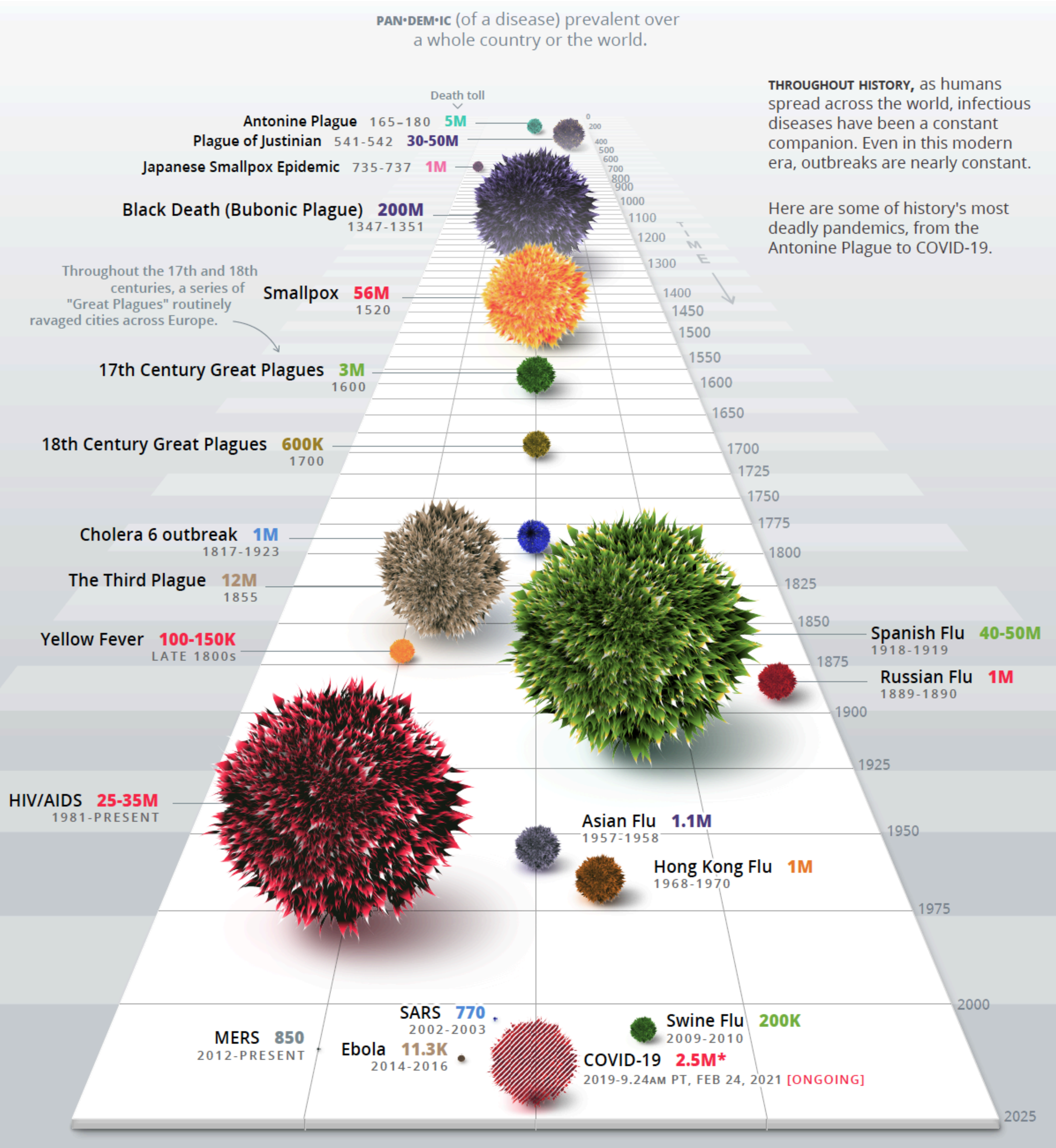
Could a future pandemic come from the Amazon?

The Science and Policy of Pandemic Prevention in the Amazon

HISTORY OF PANDEMICS



CREDIT: VISUAL CAPITALIST

Executive Summary

Yes, the next pandemic could very well come from the Amazon. Pandemics have arisen roughly every 20 years over the past century and a half. The Amazon has characteristics - high diversity of wildlife virus hosts and rising deforestation rates – common to hotspots for future emerging diseases. Yet currently the Amazon is considered a low spillover area. In this report, we suggest key actions to keep spillover low in the Amazon and reduce the risk of the basin being the source of future pandemics.

Pandemics are usually caused by viruses transmitted to humans from wildlife, especially rodents, birds and bats. Tropical forests are the richest source of pandemic-causing viruses, and deforestation and fragmentation brings people and wildlife into close contact. With its amazing diversity of vertebrates, especially bats, combined with rising deforestation rates, the Amazon is a potential source of future pandemics.

Global economic losses in the tens of trillions of dollars, the loss of millions of lives and untold social disruption resulting from COVID-19 suggest that investing billions of dollars in preventing pandemics is a sound investment. The Amazon, much of which is still a high forest cover and low spillover region, offers cost-effective opportunities to reduce deforestation and at the same time help meet Sustainable Development Goals for people across the region, restore respect for indigenous lands and protected areas, and protect regional climate. The regional benefits of these actions merit national investments, which should be complemented by international funding to help prevent the next pandemic. The Amazon must be a high priority for global efforts to prevent future pandemics.

Policy Recommendations:

- **Establish strong coordinated, cross-cutting deforestation control policies among Amazon countries**
- **Strengthen indigenous land rights**
- **End illegal incursions into the Amazon forest**
- **Improve health, sanitation and development practices in high population areas**
- **Discourage wildlife trade**
- **Commit adequate funding**

Could a future pandemic come from the Amazon?

Mariana M. Vale (1), Pablo A. Marquet (2), Derek Corcoran (2), Carlos A. de M. Scaramuzza (3), Lee Hannah (4), Andrew Hart (5), Jonah Busch (4), Alejandro Maass (5), Patrick R. Roehrdanz (4), Jorge X. Velasco-Hernández (6)

1 Universidade Federal do Rio de Janeiro, Brazil
2 Pontificia Universidad Católica de Chile
3 Instituto Internacional de Sustentabilidade, Rio de Janeiro, Brazil
4 Conservation International
5 Centro de Modelamiento Matemático (CMM), Universidad de Chile
6 Instituto de Matemáticas UNAM-Juriquilla

DOI: 10.5281/zenodo.4606591

Contents

CONSERVATION INTERNATIONAL

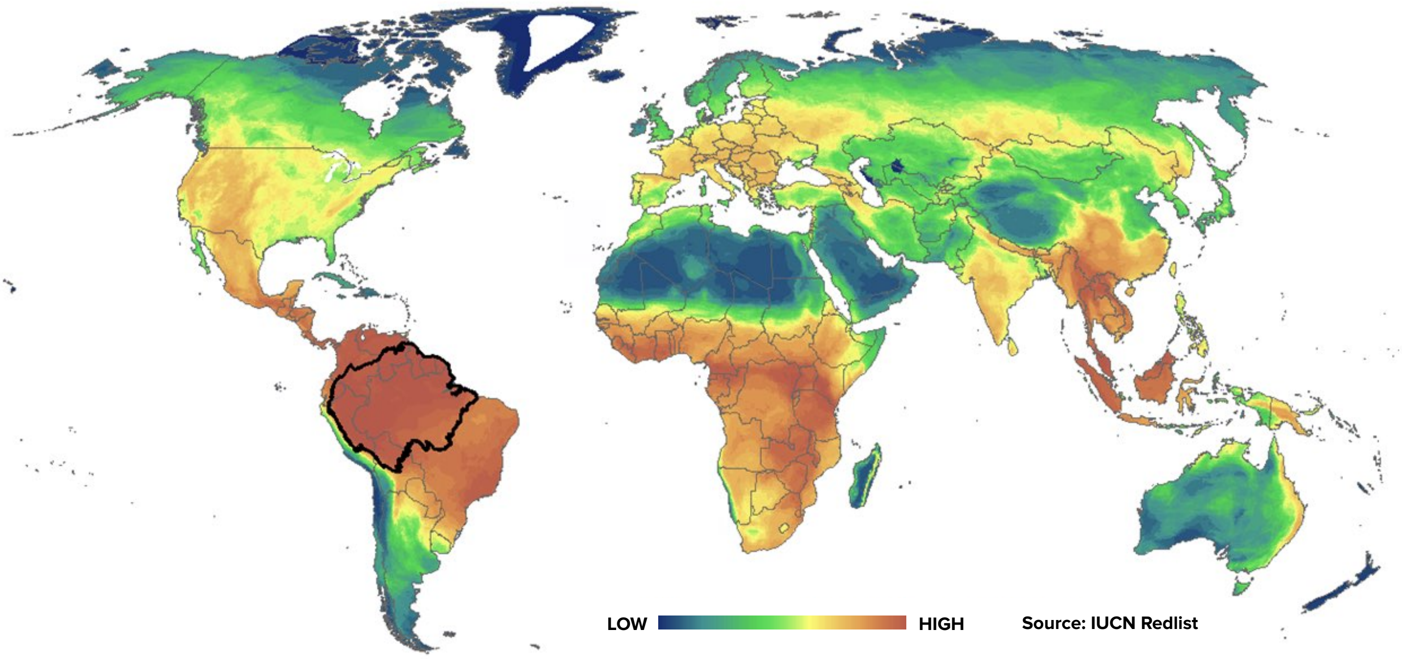
Origins of Pandemics

Modern pandemics are caused by viruses and are on the rise. Most pandemic-causing viruses come directly or indirectly from wildlife, spill over to people and are then passed human-to-human. Pandemic-causing viruses are zoonotic, meaning they come from an animal host (Woolhouse & Gowtage-Sequeria 2005), with new pathogens being discovered at a rate of three to four species per year (Woolhouse & Antia 2008). This process of disease emergence has already caused numerous pandemics, including COVID-19 and HIV/AIDS. As people move deeper and deeper into tropical forests, opportunities for contact between people and tropical animals -- and for viruses to move from animals to people -- are increasing.

Deforestation is a major driver of pandemics (Loh et al. 2015) (**Figure 1**), linked to more than 30% of new diseases reported since 1960 (IPBES 2020), including Ebola in Africa, Nipah in Malaysia, and Hendra in Australia (Looi & Chua 2007, Plowright et al. 2015, Leendertz et al. 2016, Rulli et al. 2017, Olivero et al. 2017, Castro et al. 2019). Transmission of pathogens depends not only on increased contact rate between wildlife and humans, but also on the abundance of potentially infected wild hosts (Faust et al. 2018). Most zoonosis arise from mammals, with a particularly high proportion reported for rodents, bats and primates (Han et al. 2016, Olival et al. 2017, Johnson et al., 2020). Additionally, the likelihood of spillover is higher in species associated with disturbed habitats (Gibb et al. 2020).

Figure 1. **Deforestation drives pandemics.** Healthy landscapes with intact forests have low virus spillover, while heavily modified landscapes have simplified ecosystems that favor species that can transmit viruses to people.

MAMMAL SPECIES RICHNESS



`Figure 2. **Diversity of possible mammal hosts.** The Amazon is particularly rich in mammals (top), especially bats, which have been implicated in the emergence of numerous deadly viruses worldwide. The spillover model in this study simulates virus transmission based on bat diversity and other factors.

The Amazon encapsulates these pressing global issues, combining a high diversity of animal hosts, areas of highly intact, lightly populated forest where spillover is low, and areas of high deforestation where spillover rapidly increases. Brazil's Amazonian forest and environmental protection laws and their enforcement have shown that development and reducing deforestation (and the risk of pandemics) are not mutually exclusive. It is the type of development that determines both the development benefits and the disease emergence risk in the region.

The Amazon and Pandemics

The Amazon has high levels of diversity of mammals and bats (**Figure 2**), which have been implicated as source wildlife reservoirs in many deadly emerging infectious viruses elsewhere, such as Ebola virus, SARS-CoV, MERS-CoV, Nipah virus, Hendra viruses, and, most recently, SARS-CoV-2 (Han et al. 2015, Platto et al. 2021, Zhou et al. 2020). In the Amazon, there is a well-established link between deforestation and increased vector-borne diseases such as yellow fever, Mayaro, Oropouche and malaria (Vasconcellos et al. 2001, Vittor et al. 2006, Vasconcelos & Calisher 2016, Chaves et al. 2018, MacDonald & Mordecai 2019, Castro et al. 2019, Ellwanger et al. 2020). The Amazon remains the world's least studied region for the prevalence of pathogens in wildlife (Olival et al. 2017). A single study, however, isolated at least 187 different species of viruses in Amazonian vertebrates, two-thirds of which have been confirmed to be pathogenic to humans (Vasconcellos et al. 2001).

Brazil has demonstrated that it is possible to reduce deforestation without sacrificing development goals. In 2004, the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm) was launched to reduce deforestation rates and establish regional conditions for a transition towards a sustainable development model. This set of coordinated public policies and public/private actions reduced deforestation in the Brazilian Amazon by about 70% between 2005-2012 (Nepstad et al. 2014, Arima et al. 2014, Assunção et al. 2015, Cunha et al. 2016, Busch & Engelmann 2017) (**Figure 3**). In the same period, GDP in the Amazon increased by 141% (IBGE 2020), and soy production grew by 70% (Nepstad et al. 2014). Policies included creation of protected areas, indigenous land recognition, and market and credit restrictions, farm embargos and administrative hurdles on municipalities with high illegal annual deforestation rates (Nepstad et al. 2014).

YEARLY DEFORESTATION (THOUSAND KM²)

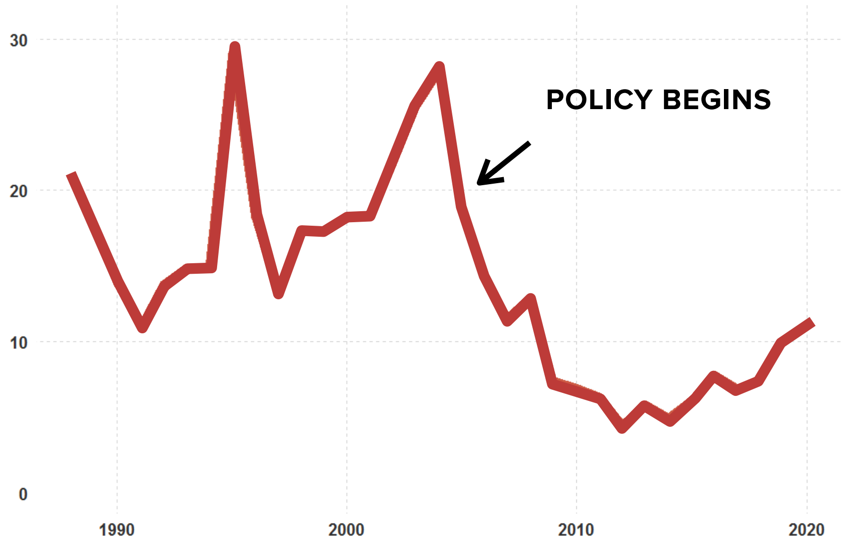


Figure 3. **Deforestation in the Brazilian Amazon though time**. Deforestation in the Brazilian Amazon dropped in 2005, as a consequence of the Brazilian program for monitoring and control of deforestation in the Amazon (PPCDAm) launched in 2004, but has been on the rise since 2012 (Source: Brazilian National Institute for Space Research, INPE).

Changes to environmental legislation in 2012 (the Native Vegetation Protection Law) and poor implementation of environmental laws in recent years have steadily undermined this success, however, leading to a recent rise in deforestation and fires in the Brazilian Amazon (Soares-Filho et al. 2014, Ferrante & Fearnside 2019). Poor environmental performance resulted in the discontinuation of the Amazon Fund program in the country (Karagiannopoulos 2019), impacting relevant governmental and non-governmental efforts to fight deforestation and promote sustainable development at scale. The renewed deforestation surge increases the risk of intensification of diseases already endemic in the Amazon, and of disease emergence from wildlife-human interactions, with pandemic potential. Fast growing Amazonian capital cities such as Manaus and Belem are well connected through direct flights to major international population centers such as São Paulo and Rio de Janeiro in Brazil, Miami in the United States and Lisbon in Portugal. This context poses a key question for science and policy makers: **Will current deforestation trends make the Amazon the next Emerging Infectious Disease hotspot?** This report uses the results of a new model of disease emergence applied to the Amazon to review the pandemic risk associated with different development pathways and patterns. We point out new policies that may be needed to reduce the risk of future disease emergence in the region, and suggest how existing or former policies may be important in protecting the region and the world from future devastating pandemics.

Models of Pandemic Origin

Several research groups have produced maps of spillover of pandemic-causing viruses globally, based on current forest cover. Perhaps the best known defines global **Emerging Infectious Disease (EID) hotspots** (**Figure 4**; Allen et al 2017). An international team of scientists is currently modeling spillover across the tropics into the future.

Emerging Infectious Disease (EID) Hotspots

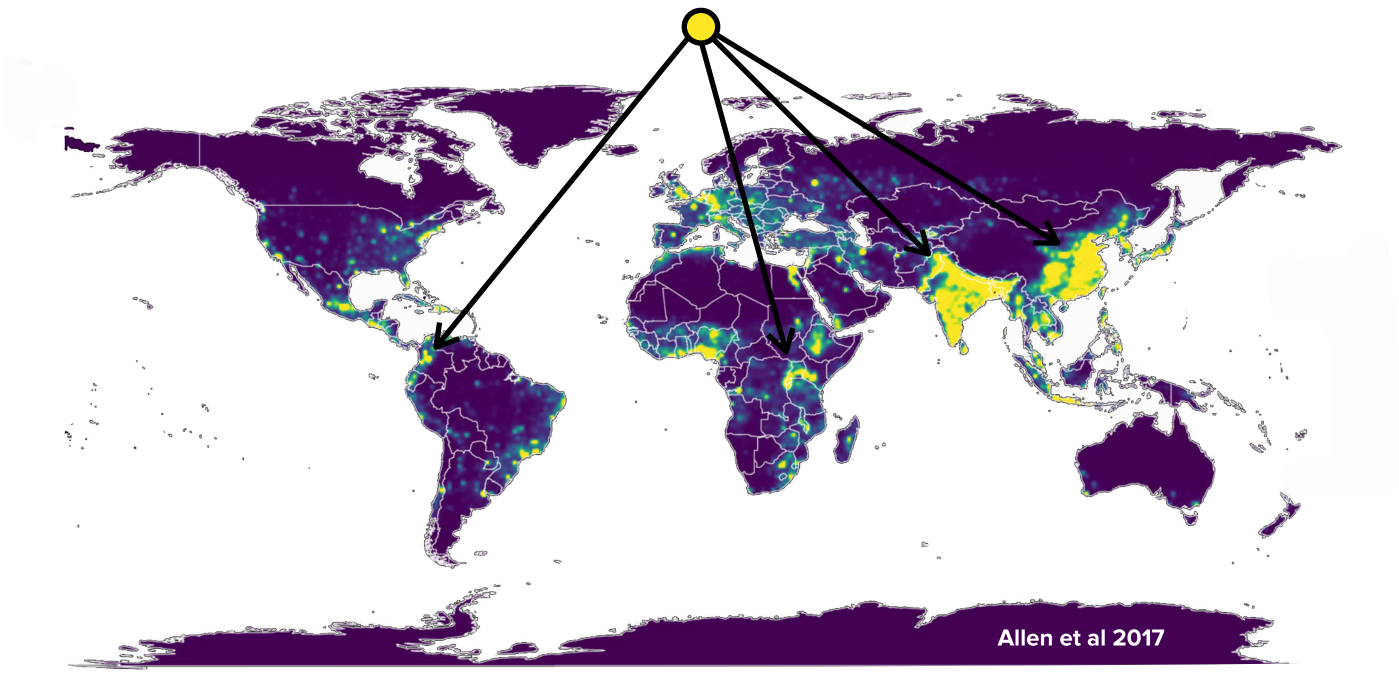


Figure 4. **Emerging Infectious Disease hotspots.** EID hotspots in the tropics are the cause of global pandemics. The Amazon is a forest area at high risk of moving towards EID hotspot status.

The future spillover model projects disease emergence from the present to 2050 under different policy scenarios using a spatial model of pan-tropical land use change (Busch & Engelmann 2017) coupled to a virus spillover mathematical model (modified from Faust 2018). The land cover model was calibrated based on the observed relationship from 2001-2012 between forest-cover loss (Hansen et al. 2013) and driver variables such as distance to cities and agricultural potential. The spillover model simulates virus transmission in forested landscapes on a 0.05 °grid (~5.5 km at the Equator) across the Amazon.

Lessons for the Amazon

Without enforced policies to stop deforestation, substantial land use change is likely across the Amazon (**Figure 5**). Under the model's weak policy scenario, a large fraction of areas that now have the highest forest cover will be deforested - more than 40% by 2050.

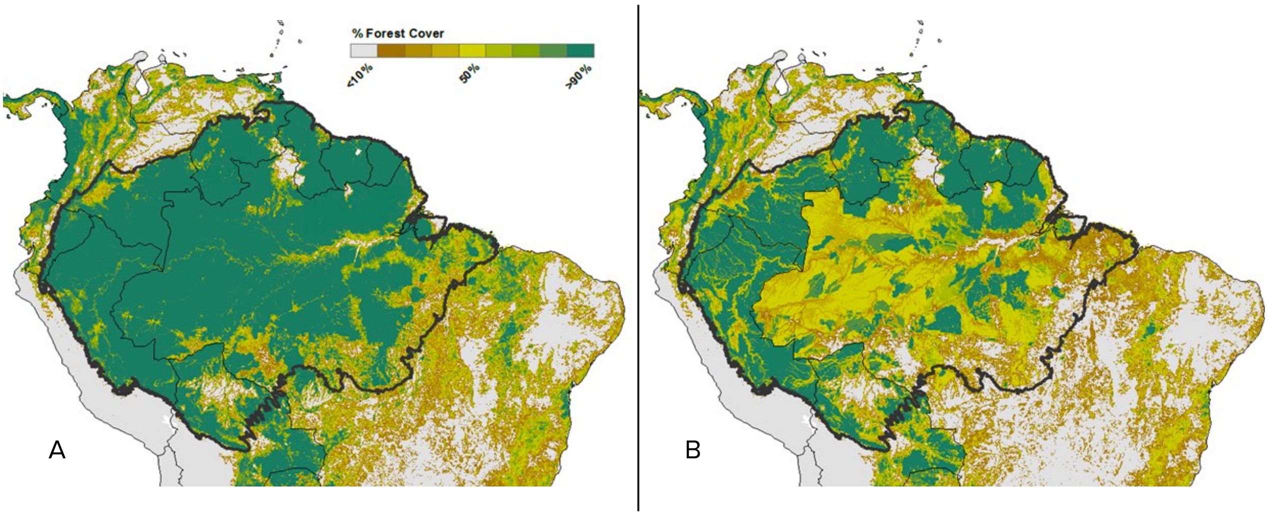


Figure 5. **Projected deforestation present to 2050**. Model forest cover for present (A - left panel) and 2050 (B - right panel). Model study area shown with a dark line. Spillover is expected to increase with loss of forest cover and increasing forest edge.

Our model shows that areas that are already deforested now (less than 40% of original forest cover remaining) are predicted to have a larger number of per capita spillover events on average than less deforested areas (**Figure 6**). In all cases, future deforestation will increase the number of per capita spillover events. But areas that are relatively pristine today, and are kept that way through low deforestation rates, will have a low number of spillover events on average. Notice that as deforestation increases, spillover peaks and then decreases as contact rates between wildlife and humans also decreases because most of the native habitat has disappeared. Spillover never declines to zero, however, meaning that there is always a chance for a spillover event to occur. The decline in spillover past the peak occurs at deforestation levels that would destroy climate services of the Amazon important to the region and the world. Taxa that carry pandemic-causing viruses become more prevalent at these high deforestation levels, an effect that is not represented in this model.

DEFORESTATION

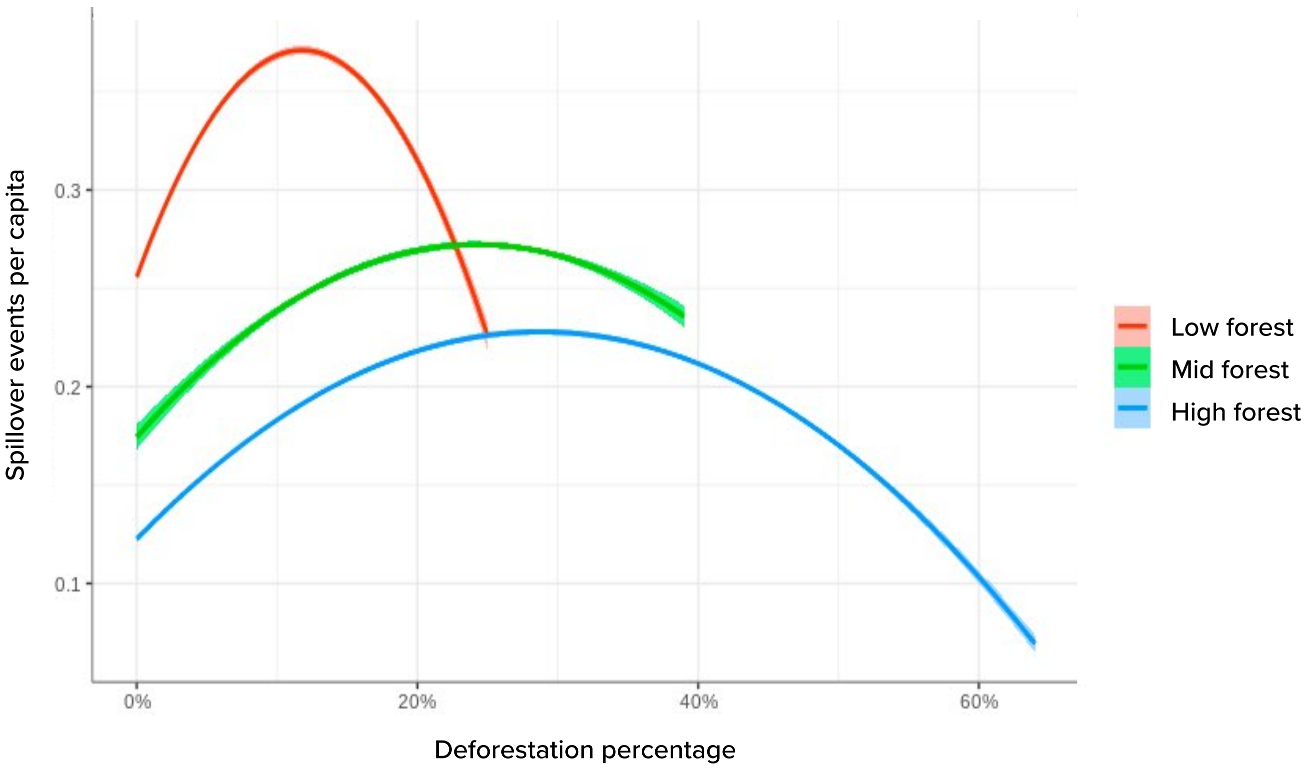


Figure 6. **Low deforestation means low spillover**. Areas with low, medium and high tree cover in 2020 (Low: below 40%, Mid: 40-60% and High: > 60%) all show low deforestation maintaining low spillover by 2050. While the three forest cover classes show different trajectories in average per capita number of spillover events in response to deforestation, all show many fewer spillover events in low deforestation than in moderate deforestation.

It is clear that most of the areas already deforested will have high numbers of per capita spillover events on average (**Figure 7**), and in some, the number of spillover events will sharply increase with modest further deforestation. Similarly, relatively intact areas, which are little deforested by 2050, have low numbers of per capita spillover events.

The model's results provide some valuable lessons for the Amazon that may pave the way for important policies. First, our analysis highlights the importance of protecting pristine areas from deforestation, otherwise the number of per capita spillover events will increase nonlinearly. Second, even a small amount of deforestation can have large impacts on spillover, especially if the deforested areas were pristine. The rate at which deforestation occurs affects mean per capita spillover events, but saturates after 20% deforestation between now and 2050.

While deforestation in the Brazilian Amazon has been on the rise since 2012, the trend has intensified in the last two years (Ferrante and Fearnside 2019). This sharp increase is associated with poor implementation of environmental laws coupled with a more recent dismantling of environmental enforcement agencies (Ferrante and Fearnside 2019, Vale et al. 2021). Intense land encroachment by miners, loggers and land grabbers is threatening the lives and livelihoods of traditional and indigenous peoples, who are increasingly exposed to violence and to COVID-19 (Ferrante and Fearnside 2020).

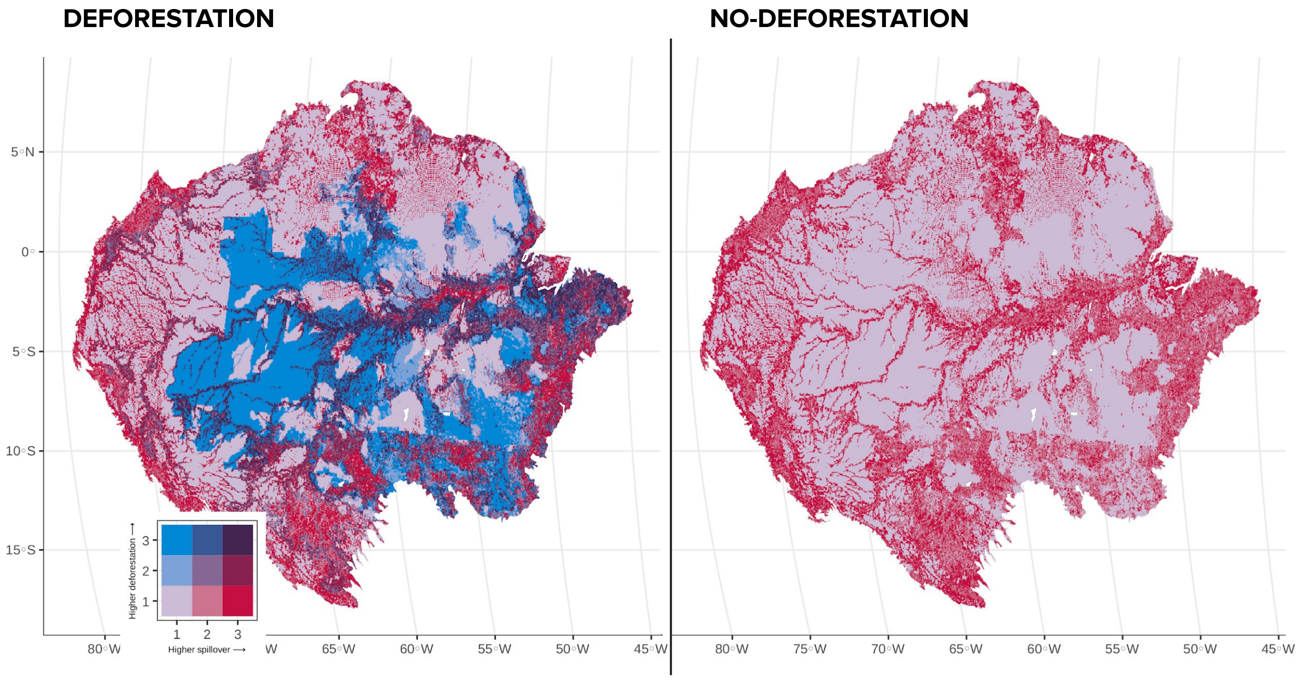


Figure 7. **Map of the Amazon (white line) and projected mean number of spillover events per capita and change in cover between 2020 and 2050 (deforestation)**. Areas that presently have a high cover of trees (> 60%) and will experience low deforestation will have low levels of spillover (< 0.12, lower left corner cell in the inset color code) and should be protected from deforestation. Areas of high spillover and high deforestation cluster around population centers and should be prioritized for land use planning and community health support. Many areas in the Amazon are already deforested and will have a high level of spillover (> 0.3) even if they suffer little additional deforestation (< 40%) up to 2050 (lower right corner cell in the inset color code panel).These areas should be considered in restoration programs such as the Brazilian Native Vegetation Recovery Plan (PLANAVEG).

Policy Recommendations

Our modeling of virus spillover in the Amazon suggests that policies that reduce deforestation, especially in high forest cover areas, are the best lever for limiting spillover potential. Here we present our top policy recommendations in order of likely impact on pandemic prevention, but they are all important for avoiding increased spillover of globally dangerous viruses in the region:

- **End illegal incursions into the Amazon forest.** Across the Amazon, COVID-19 has provided cover for illegal and illicit activities in high forest cover areas, intensifying patterns underway before the pandemic hit (Kroner et. al. 2021, Vale et al. 2021). These actions change land use in ways that may become permanent and lead to growing human populations within high forest areas, creating perfect conditions for spillover. It is urgent that these incursions be reversed, particularly in protected areas that harbor exactly the type of high forest cover most associated with low spillover.
- **Strengthen legal protections and enforcement to reduce deforestation.** In Brazil, resuming the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm) or putting in place a similar cross-cutting coordination policy to reduce illegal deforestation would be the most effective way to prevent future pandemics. Weakened law enforcement and monitoring have caused increasing deforestation rates so resuming the prior approach of central policy coordination by the Executive Office's Chief of Staff should be considered. Once in place, strong leadership and convening power help avoid policy incoherence and promote better communication and synergy among the many sectoral and regional policies in the Brazilian Amazon. Policies for bioeconomy and

sustainable use of standing forest can help foster sustainable development models across the region. Additional long-term positive impacts can be achieved by: 1) speeding up the implementation of the Native Vegetation Protection Law, especially by streamlining the analysis and validation of farms registries in the Rural Environmental Register (CAR) of the Brazilian Forest Service, 2) integrating the state deforestation licenses databases into an unique database (the SINAFLOR/Ibama) in order to determine the illegality of deforestation events detected by remote sensing monitoring (e.g. PRODES, DETER and Mapbiomas), and 3) strengthening programs to reduce uncertainty of land tenure and to properly allocate the 49.8 million hectares under federal and regional government responsibility.

- **Establish strong coordinated, cross-cutting deforestation control policies among Amazon countries.** These include the Leticia Pact and also actions to foster sustainable development and tools such as those of the fourth phase of Brazilian PPCDam (2016-2020) and exploring the land use policy mix concept (Strassburg et al. 2017). Policies should be tailored to the political and social contexts of each individual Amazonian country, and supported by the Inter-American Development Bank and other international donor agencies.
- **Strengthen indigenous land rights.** Indigenous lands are essential to maintain high forest cover in the Amazon. They have proved less vulnerable to invasion than some protected areas (Nepstad et al. 2006, Adeney et al 2009), reinforcing both the national and local importance of indigenous management. Unfortunately, indigenous communities have been particularly hard hit by COVID-19 (Ferrante & Fearnside 2020). Governmental recognition of indigenous land rights and promotion of a culture of respect through national and subnational government policy and action should be maintained and strengthened.
- **Improve health, sanitation and development practices in high population areas.** High population, low forest cover areas in the Amazon have very high spillover risk, often on par with international Emerging Infectious Disease (EID) hotspots, and require improved health and sanitation practices to ameliorate the high likelihood of human-wildlife contact. A package of community-based measures based on the principles of the One Health concept combines community health clinics, improved forest management (including wildlife trade suppression) and healthier on-farm practices to reduce wildlife-domestic animal-human viral transmission pathways. In these areas, planned development to avoid haphazard interweaving of forest fragments and human settlements can help reduce the risk of spillover. These efforts are more costly per capita and per hectare than reducing deforestation and may require national government or international funding mechanisms (see below). Forest restoration may be required and will eventually reduce spillover risk.
- **Discourage wildlife trade.** Wildlife trade maximizes human-wildlife contact and needs to be reduced to control spillover risk (Dobson et al. 2020). Needed measures include proper funding of existing wildlife trade laws and mandates as well as improved monitoring and creative policy and legislative solutions to discourage trade in wildlife. Education campaigns help raise awareness of the link between wildlife trade and pandemics.
- **Support risk reduction efforts through interlocking programs.** All of the above efforts benefit from being embedded in a system of interlocking national and subnational programs that can be strengthened and modified to reduce pandemic risk. Relevant programs include subnational government programs and multi-stakeholder initiatives such as Brazilian

Paraì State Amazonas Now Plan (PEAA-PA), the Governors' Climate and Forests Task Force, the Brazilian Coalition on Climate, Forest and Agriculture and community-based timber and non-timber production value-chain enhancement.

- **Commit adequate funding.** Protected Areas systems in all basin countries must have actionable management plans and adequate funding in order to reduce deforestation across the Amazon, so a high priority for pandemic prevention is strengthening the implementation of programs such as Herencia Colombia and Patrimonio Natural del Perú, and the Amazonian Protected Area Program (ARPA), with its goal to protect 60 million hectares.

Costs and Finance

The costs of reducing deforestation are far less than the costs of dealing with pandemics (Dobson et al. 2020). **Figure 8** illustrates current global investment in pandemic prevention (using 2020 budget allocations as an example) and costs (late 2020 pandemic costs) compared with the costs and benefits of a strategy emphasizing annual investment in prevention and early detection. Before COVID-19, investment (upper light red circles) favored disease control, including testing ("containment') and hospital preparedness ("mitigation"). The result of this investment strategy is large-scale loss of life, stress on healthcare systems and workers, catastrophic health care costs in the billions and economic losses amounting to tens of trillions of dollars (upper large pink circles).

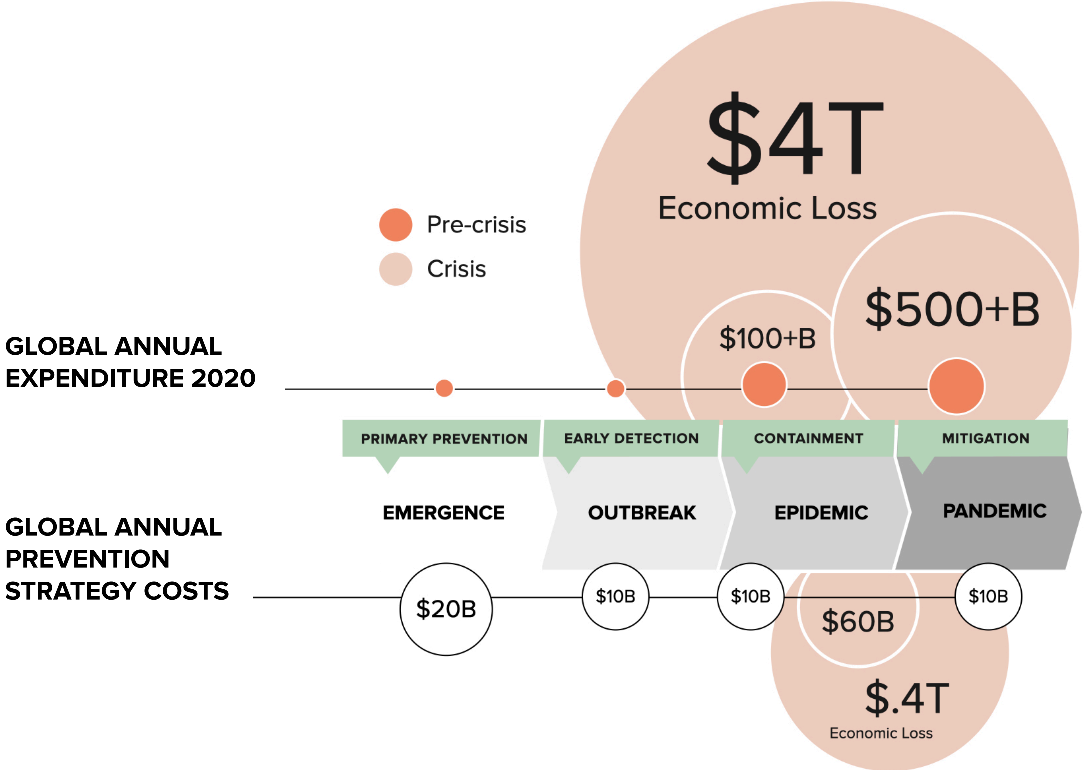


Figure 8. **Global investment strategy for pandemic prevention.** Current annual pre-COVID 19 investments, upper light red circles. Prevention strategy annual investment, lower white circles. The prevention strategy represents a major investment in primary prevention, including reduced deforestation and community-forest-farm health, resulting in major reduction in loss of life, health care cost savings, and avoidance of economic damage (difference between upper and lower pink circles).

A wiser investment strategy emphasizes prevention at the sources - in global EID hotspots through community-forest-farm health improvement and through minimizing deforestation to maintain high forest cover to minimize human-wildlife interaction in high forest areas like the Amazon. Global annual investment in a prevention strategy (Fig. 8, lower white circles) results in much lower loss of life, health care costs and economic damages (lower pink circles). While not all pandemics can be prevented, prevention of a significant fraction pays large returns in avoiding social disruption, loss of life and damage to national economies.

Effective actions to prevent, monitor and fight deforestation when it was under control cost the Brazilian government US$1 billion per year, which represents only 0.1% of Brazil's total federal budget (Cunha et al. 2016). And a substantial part of these funds came from abroad through the Amazon Fund, including a US$1 billion commitment from Norway (Nepstad et al. 2009, but see Karagiannopoulos 2019). This investment is a small fraction of the one-year US$94.5 billion allocation to Brazil's COVID-19 emergency fund. The PPCDam model achieves reductions in deforestation at lower cost than carbon pricing approaches (Busch & Engelmann 2017) and is applicable to other forested regions of the Tropics where the capacity to rapidly improve governance is high (DeFries et al. 2013).

Because damages are global, but prevention costs are centered in tropical areas like the Amazon, a global cooperative solution is needed. Tropical forest countries can implement policies that reduce deforestation, and improve community-forest-farm health in areas at high risk of spillover. G7 countries can contribute funds that make these programs possible, particularly in remote, underserved areas. **The Brazilian Amazon deforestation policy at its most effective provides a model for how these programs can be nationally-driven with international support. All of the countries of the world need to cooperate to fund and take action to reduce the risk of another global pandemic. The Amazon may provide the example for the world to follow.**

References

Adeney, J.M., Christensen, N.L. and Pimm, S.L. (2009). Reserves Protect against Deforestation Fires in the Amazon. *PLoS ONE* 4: e5014. DOI:10.1371/journal.pone.0005014

Allen, T., Murray, K.A., Zambrana-Torrelio, C., Morse, S.S., Rondinini, C., Di Marco, M., Breit, N., Olival, K.J. and Daszak (2017). Global hotspots and correlates of emerging zoonotic diseases. *Nature Communications*, 8: 1-10. DOI: 10.1038/s41467-017-00923-8

Azevedo-Ramos, C.A., Moutinho, P., Arruda, V.L.D.S., Stabile, M.C., Alencar, A., Castro, I. and Ribeiro, J.P., 2020. Lawless land in no man's land: The undesignated public forests in the Brazilian Amazon. *Land Use Policy*, 99: 104863. DOI:10.1016/j.landusepol.2020.104863

Arima, E. Y., Barreto, P., Araújo, E. and Soares-Filho, B. (2014). Public policies can reduce tropical deforestation: Lessons and challenges from Brazil. *Land Use Policy*, 41: 465-473. doi:10.1016/j.landusepol.2014.06.026

Assunção, J., Gandour, C. and Rocha, R. (2015). Deforestation slowdown in the Brazilian Amazon: prices or policies? *Environment and Development Economics*, 20: 697-722. DOI:10.1017/s1355770x15000078

Busch, J. and Engelmann, J. (2017). Cost effectiveness of reducing emissions from tropical deforestation, 2016-2050. *Environmental Research Letters*, 13: 015001.

Castro, M.C., Baeza, A., Codeço, C.T., Cucunubá, Z.M., Dal'Asta AP, De Leo, G.A., Dobson, A.P., Carrasco-Escobar, G., Lana, R.M., Lowe, R., Monteiro, A.M.V., Pascual, M. and Santos-Vega, M. (2019). Development, environmental degradation, and disease spread in the Brazilian Amazon. *PLoS Biol*, 17: e3000526. DOI:10.1371/journal.pbio.3000526

Chaves, L.S.M., Conn, J.E., López, R.V.M. and Sallum, M.A.M. (2018). Abundance of impacted forest patches less than 5km^2 is a key driver of the incidence of malaria in Amazonian Brazil. *Scientific Reports*, 8: 7077. DOI:10.1038/s41598-018-25344-5

Cunha, F.A.F.S., Börner, J., Wunder, S., Cosenza, C.A.N. and Lucena, A.F.P (2016). The implementation costs of forest conservation policies in Brazil. *Ecological Economics*, 130: 209-220. DOI:10.1016/j.ecolecon.2016.07.007

Dave, R., Saint-Laurent, C., Murray, L., Daldegan, G.A., Brouwer, R., de Mattos Scaramuzza, C.A., Raes, L., Simonit, S., Catapan, M., Contreras, G.G. and Ndoli, A., 2018. *Second Bonn challenge progress report*. Application of the Barometer in 2018. DOI:10.2305/IUCN.CH.2019.06.en

DeFries, R., Herold, M., Verchot, L., Macedo, M.N. and Shimabukuro, Y. (2013) Export-oriented deforestation in Mato Grosso: harbinger or exception for other tropical forests? *Philosophical Transactions of the Royal Society B*, 368: 20120173. DOI:10.1098/rstb.2012.0173

Dobson, A. P., Pimm, S. L., Hannah, L., Kaufman, L., Ahumada, J. A., Ando, A. W., Bernstein, A., Busch, J., Daszak, P., Engelmann, J., Kinnaird, M.F., Li, B.V., Loch-Temzelides, T., Lovejoy, T., Nowak, K., Roehrdanz, P.R. and Vale, M. M. (2020). Ecology and economics for pandemic prevention. *Science*, 369: 379-381. DOI: 10.1126/science.abc3189

Ellwanger, J. H., Kulmann-Leal, B., Kaminski, V.L., Valverde-Villegas, J., Veiga, A.B.G., Spilki, F.R., Fearnside, P.M., Caesar, L., Giatti, L.L., Wallau, G.L., Almeida, S.E.M., Borba, M.R., Hora, V.P. and Chies, J.A.B. (2020). Beyond diversity loss and climate change: Impacts of Amazon deforestation on infectious diseases and public health. *Anais da Academia Brasileira de Ciências*, 92: e20191375. DOI:10.1590/0001-3765202020191375

Faust, C.L., McCallum, H.I., Bloomfield, L.S., Gottdenker, N.L., Gillespie, T.R., Torney, C.J., Dobson, A.P. and Plowright, R.K. (2018). Pathogen spillover during land conversion. *Ecology Letters*, 21: 471-483. DOI:10.1111/ele.12904

Ferrante, L., and Fearnside, P.M. (2019). Brazil's new president and 'ruralists' threaten Amazonia's environment, traditional peoples and the global climate. *Environmental Conservation*, 46: 261-263. DOI:10.1017/S0376892919000213

Ferrante, L. and Fearnside, P.M. (2020). Protect indigenous peoples from COVID-19. *Science*, 368: 251. DOI:10.1126/science.abc0073.

Friedman, J.H. (2001). Greedy Function Approximation: A Gradient Boosting Machine. *Annals of Statistics*, 29:1189-1232.

Gibb, R., Redding, D.W., Chin, K.Q., Donnelly, C.A., Blackburn, T.M., Newbold, T. and Jones, K.E. (2020). Zoonotic host diversity increases in human-dominated ecosystems. *Nature*, 584: 398-402. DOI:10.1038/s41586-020-2562-8

Kroner, R.E.G., Qin, S., Cook, C.N., Krithivasan, R., Pack, S.M., Bonilla, O.D., Cort-Kansinally, K.A., Coutinho, B., Feng, M., Garcia, M.I.M. and He, Y., 2019. The uncertain future of protected lands and waters. *Science*, 364: 881-886. DOI:10.1126/science.aau5525

Han, B.A., Kramer, A.M. and Drake, J.M. (2016). Global patterns of zoonotic disease in mammals. *Trends in Parasitology*, 32: 565-577. DOI:10.1016/j.pt.2016.04.007

Hansen, M. C., Potapov, P. V., Moore, R., Hancher, M., Turubanova, S. A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini,L., Justice,C.O., and Townshend, J.R.G. (2013). High-resolution global maps of 21st-century forest cover change. *Science*, 342: 850-853. DOI:10.1126/science.1244693

IBGE (Instituto Brasileiro de Geografia e Estatística). PIB Municipal - Produto interno bruto a preços correntes Frequência: Anual de 2002 até 2015 Unidade: R$ (mil), a preços do ano 2000. Extracted from: http://www.ipeadata.gov.br/Default.aspx

IPBES (Intergovernmental Platform on Biodiversity and Ecosystem Services) (2020). *Workshop Report on Biodiversity and Pandemics of the Intergovernmental Platform on Biodiversity and Ecosystem Services*. Daszak, P., das Neves, C., Amuasi, J., Hayman, D., Kuiken, T., Roche, B., Zambrana-Torrelio, C., Buss, P., Dundarova, H., Feferholtz, Y., Foldvari, G., Igbinosa, E., Junglen, S., Liu, Q., Suzan, G., Uhart, M., Wannous, C., Woolaston, K., Mosig Reidl, P., O'Brien, K., Pascual, U., Stoett, P., Li, H. and Ngo, H.T. (Eds). Bonn, Germany: IPBES Secretariat. DOI:10.5281/zenodo.4147318

Johnson, C.K., Hitchens, P.L., Pandit, P.S., Rushmore, J., Evans, T.S., Young, C.C. and Doyle, M.M. (2020). Global shifts in mammalian population trends reveal key predictors of virus spillover risk. *Proceedings of the Royal Society B*, 287: 20192736. DOI:10.1098/ rspb.2019.2736

Karagiannopoulos, L. (2019). Norway stops Amazon fund contribution in dispute with Brazil. Reuters (Environment), Aug 15, 2019. Available at: https://www.reuters.com/article/us-brazil-environment-norway-idUSKCN1V52C9

Kessler, M.K., Becker, D.J., Peel, A.J., Justice, N.V., Lunn, T., Crowley, D.E., Jones, D.N., Eby, P., Sánchez, C.A. and Plowright, R.K. (2018). Changing resource landscapes and spillover of henipaviruses. *Annals of the New York Academy of Sciences*, 1429: 78-99. DOI: 10.1111/nyas.13910

Leendertz, S.A.J., Gogarten, J.F., Düx, A., Calvignac-Spencer, S. and Leendertz, F.H. (2016). Assessing the evidence supporting fruit bats as the primary reservoirs for Ebola viruses. *EcoHealth*, 13: 18-25. DOI:10.1007/s10393-015-1053-0

Loh, E.H., Zambrana-Torrelio, C., Olival, K.J., Bogich, T.L., Johnson, C.K., Mazet, J.A., Karesh, W. and Daszak, P. (2015). Targeting transmission pathways for emerging zoonotic disease surveillance and control. *Vector-Borne and Zoonotic Diseases*, 15: 432-437. DOI:10.1089/ vbz.2013.1563

Looi, L.M. and Chua, K.B. (2007). Lessons from the Nipah virus outbreak in Malaysia. *Malaysian Journal of Pathology*, 29(2): 63-67.

MacDonald, A. J. and Mordecai, E. A. (2019). Amazon deforestation drives malaria transmission, and malaria burden reduces forest clearing. *Proceedings of the National Academy of Sciences*, 116: 22212-22218. DOI:10.1073/pnas.1905315116

Mollentze, N. and Streicker, D.G. (2020). Viral zoonotic risk is homogenous among taxonomic orders of mammalian and avian reservoir hosts. *Proceedings of the National Academy of Sciences*, 117: 9423-9430. DOI:10.1073/pnas.1919176117

Nepstad, D., Schwartzman, S., Bamberger, B., Santilli, M., Ray, D., Schlesinger, P., Lefebvre, P., Alencar, A., Prinz, E., Fiske, G. and Rolla, A. (2006). Inhibition of Amazon deforestation and fire by parks and indigenous lands. *Conservation Biology*, 20: 65-73. DOI:10.1111/j.1523-1739.2006.00351.x

Nepstad, D., McGrath, D., Stickler, C., Alencar, A., Azevedo, A., Swette, B., Bezerra, T., DiGiano, M., Shimada, J., Motta, R.S., Armijo, E., Castello, L., Brando, P., Hansen, M.C., McGrath-Horn, M., Carvalho, O. and Hess, L. (2014). Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains. *Science*, 344: 1118-23. DOI:10.1126/science.1248525

Nepstad, D., Soares, B. S., Merry F., Lima, A., Moutinho, P., Carter, J., Bowman, M., Cattaneo, A., Rodrigues, H., Schwartzman, S., McGrath, D. G., Stickler, C. M., Lubowski, R., Piris-Cabezas, P., Rivero, S., Alencar, A., Almeida, O. and Stella, O. (2009). The end of deforestation in the Brazilian Amazon. *Science*, 326: 5958. DOI:10.1126/science.1182108

Olival, K.J., Hosseini, P.R. Zambrana-Torrelio, C., Ross, N., Bogich, T.L. and Daszak, P. (2017). Host and viral traits predict zoonotic spillover from mammals. *Nature*, 546: 646-650. DOI: 10.1038/nature22975

Olivero, J., Fa, J.E., Real, R., Márquez, A.L., Farfán, M.A., Vargas, J.M., Gaveau, D., Salim, M.A., Park, D., Suter, J. and King, S. (2017). Recent loss of closed forests is associated with Ebola virus disease outbreaks. *Scientific Reports*, 7: 1-9. DOI:10.1038/s41598-017-14727-9

Platto, S., Zhou, J., Yanqing, W., Huo, W. and Carafoli, E. (2021). Biodiversity loss and COVID-19 pandemic: The role of bats in the origin and the spreading of the disease. *Biochemical and Biophysical Research Communications*, 538: 2-13. DOI: 10.1016/j.bbrc.2020.10.028

Plowright, R.K., Eby, P., Hudson, P.J., Smith, I.L., Westcott, D., Bryden, W.L., Middleton, D., Reid, P.A., McFarlane, R.A., Martin, G. and Tabor, G.M. (2015). Ecological dynamics of emerging bat virus spillover. *Proceedings of the Royal Society B*, 282: 20142124. DOI:10.1098/rspb.2014.2124

Rivers, M. (2021). Manaus is collapsing again. Is a new coronavirus variant to blame? CNN,January 28, 2021. Available at: https://edition.cnn.com/2021/01/27/americas/manaus-brazil-covid-19-new-variant-intl/index.html

Rulli, M.C., Santini, M., Hayman, D.T. and D'Odorico, P. (2017). The nexus between forest fragmentation in Africa and Ebola virus disease outbreaks. *Scientific Reports*, 7: 41613. DOI:10.1038/srep41613

Seltmann, A., Czirják, G. Á., Courtiol, A., Bernard, H., Struebig, M. J. and Voigt, C. C. (2017). Habitat disturbance results in chronic stress and impaired health status in forest-dwelling paleotropical bats. *Conservation Physiology*, *5*: bcox020. DOI:10.1093/conphys/cox020.

Soares-Filho, B., Rajão, R., Macedo, M., Carneiro, A., Costa, W., Coe, M., Rodrigues, H. and Alencar, A. 2014. Cracking Brazil's Forest Code. *Science*, 344: 363–364. DOI:10.1126/science.1246663

Strassburg, B.B., Brooks, T., Feltran-Barbieri, R., Iribarrem, A., Crouzeilles, R., Loyola, R., Latawiec, A.E., Oliveira Filho, F.J., Scaramuzza, C.A.D.M., Scarano, F.R. and Soares-Filho, B. (2017). Moment of truth for the Cerrado hotspot. *Nature Ecology & Evolution* 1: 1-3. DOI:10.1038/s41559-017-0099

Vale, M. M., Berenguer, E., Menezes, M. A., Castro, E. B. V., Siqueira, L. P. and Rita, C. Q. P. (2021). The COVID-19 pandemic as an opportunity to weaken environmental protection in Brazil. *Biological Conservation*, 108994. DOI:10.1016/j.biocon.2021.108994

Vasconcelos, P. F. C. and Calisher, C. H. (2016). Emergence of Human Arboviral Diseases in the Americas, 2000–2016. *Vector-Borne and Zoonotic Diseases*, 16: 295-301. DOI:10.1089/vbz.2016.1952

Vasconcelos, P.F.C., Rosa, A.P. A.T, Rodrigues, S.G., Rosa, E.S.T, Dégallier, N. and Rosa, J.F.T. (2001). Inadequate management of natural ecosystem in the Brazilian Amazon region results in the emergence and reemergence of arboviruses. *Cadernos de Saúde Pública*, 17 (Supp): 155-164. DOI:10.1590/S0102-311X2001000700025

Vittor, A. Y., Gilman, R. H., Tielsch, J., Glass, G., Shields, T. I. M., Lozano, W. S., ... and Patz, J. A. (2006). The effect of deforestation on the human-biting rate of *Anopheles darlingi*, the primary vector of falciparum malaria in the Peruvian Amazon. *American Journal of Tropical Medicine and Hygiene*, 74: 3-11. DOI:10.4269/ajtmh.2006.74.3

Woolhouse, M. and Antia, R. (2008). Emergence of new infectious diseases. In: S.C. Stearns, and J.K. Koella, (Eds) Evolution in Health and Disease, 2nd ed. Oxford: Oxford University Press. pp. 215-228.

Woolhouse, M.E. and Gowtage-Sequeria, S. (2005). Host range and emerging and reemerging pathogens. *Emerging Infectious Diseases*, 11: 1842-1847. DOI:10.1098/rstb.2011.0354

Zhou, H., Chen, X., Hu, T., Li, J., Song, H., Liu, Y., Wang, P., Liu, D., Yang, J., Holmes, E.C., Hughes, A.C., Bi, Y. and Shi, W. (2020). A novel bat coronavirus closely related to SARS-CoV2 contains natural insertions at the S1/S2 cleavage site of the spike protein. *Current Biology*, 30: 2196-2203. DOI:10.1016/j.cub.2020.05.023