OPINION

We need biosphere stewardship that protects carbon sinks and builds resilience

Johan Rockström[a,b,1], Tim Beringer[a], David Hole[c], Bronson Griscom[c], Michael B. Mascia[c], Carl Folke[b,d], and Felix Creutzig[e,f]

Earth's biosphere, its extraordinary and complex web of species and ecosystems on land and in the oceans, drives the life-sustaining cycles of water and other materials that enable all life on Earth to thrive. The biosphere is also a principal driver of immense negative feedback loops in the Earth system that stabilize atmospheric CO_2 concentrations and thereby global climate—including carbon sequestration by vegetation, soils, and the oceans. As such, Earth's ecosystems have played a central role in keeping our planet's climate system unusually stable throughout the last 11,700 years (i.e., the inter-glacial Holocene). During this epoch, global mean temperatures have oscillated only about 1 °C around the pre-industrial average, providing the unique conditions that allowed human civilizations to flourish. Today, ocean and land ecosystems remove around 50% of anthropogenic CO_2 emissions from the atmosphere each year (1), an extraordinary biophysical feat, given that these emissions have risen from approximately 4 gigatonnes of carbon (GtC) per year in 1960 to around 11 GtC per year today. Put another way, half our "climate debt" is removed, for free, by the biosphere every year—a vast subsidy to the world economy.

Safeguarding the biosphere from further degradation or collapse is an existential challenge for humanity. There are important steps we can take to contain the damage. Image credit: Shutterstock/Kritskiy-ua.

The recent Working Group 1 report of the sixth assessment of the Intergovernmental Panel on Climate Change (IPCC) confirmed this major nature contribution to climate stability, estimating the cumulative carbon sequestration by land and oceans to be 56% of all human-caused emissions between 1850 and 2019 (2). All major global climate models whose simulations give us hope of meeting the target of the Paris Climate Agreement—to keep warming well below 2 °C—take the continued provision of this gigantic biosphere endowment for granted, merely concluding, as in the recent IPCC report, that the efficiency of nature's carbon sink may reduce slightly for high emission pathways. This means that the ability of intact nature to continue to sequester carbon is already factored into the climate models and thus in the estimate of the remaining carbon budget to hold to the Paris climate target. Yet this fundamental assumption relies on terrestrial and marine ecosystems remaining sufficiently intact and resilient to human pressures, even as climate change progresses (3). It is therefore concerning that the IPCC now concludes that Earth's temperature is slightly more sensitive to rising CO_2 concentrations than previously thought (4)—meaning our remaining carbon budget to achieve the Paris target may have effectively shrunk. If we were able to more accurately simulate feedbacks in the global carbon cycle, such as tipping points in forest ecosystems (5) and abrupt permafrost thaw (6), the

[a]Potsdam Institute for Climate Impact Research, 14473 Potsdam, Germany; [b]Stockholm Resilience Centre, Stockholm University, SE 106 91 Stockholm, Sweden; [c]Conservation International, Arlington, VA 22202; [d]Beijer Institute, Royal Swedish Academy of Sciences, SE-104 05 Stockholm, Sweden; [e]Mercator Research Institute on Global Commons and Climate Change, 10829 Berlin, Germany; and [f]Sustainability Economics of Human Settlements, Technische Universität Berlin, 10623 Berlin, Germany

The authors declare no competing interest. D.H. and M.B.M. were supported by a grant from Gordon and Betty Moore to Conservation International. B.G. was supported by the Lui-Walton Innovators Fellowship program.

Any opinions, findings, conclusions, or recommendations expressed in this work are those of the authors and have not been endorsed by the National Academy of Sciences.

[1]To whom correspondence may be addressed. Email: johan.rockstrom@pik-potsdam.de.

This article contains supporting information online at https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.2115218118/-/DCSupplemental.
Published September 15, 2021.

estimated remaining budget could disappear altogether. Hence, safeguarding the biosphere from further degradation or collapse is an existential challenge for humanity.

A Crucial Role

Today, major carbon sinks exist in remaining intact tropical, temperate, and boreal forests, absorbing around 0.7, 0.7, and 0.5 GtC per year, respectively (Fig. 1*A*). Forests regrowing after past disturbances take up another 1.3 GtC per year. Grasslands and rangelands sequester about 0.6 GtC per year; peatlands 0.1 GtC per year; and mangroves, seagrasses, and marshes around 0.2 GtC per year. Total net ocean uptake is around 2.5 GtC per year. In total, ecosystems on land store almost four times the current atmospheric CO_2 content of 880 GtC. Of this amount, humanity has contributed around 255 GtC by burning fossil fuels and changing land use since 1850 (1).

Are we at risk of losing the biosphere carbon sinks and thereby the safe operating space for humanity provided by nature? The latest evidence is not encouraging. The land carbon sink has shown increasing interannual variability since the 1950s, indicating rising instability in the land–atmosphere carbon exchange (*SI Appendix*, Fig. 1). More than 75% of the land surface has been altered by humans, removing 50% of vegetation biomass, whereas less than 5% of the oceans remain free from our interference (7). Yet to date, the world's relatively intact ecosystems and forested areas have not only proved remarkably resilient to climate change but have also increased the overall land carbon sink in response to elevated CO_2 levels—most notably the northern hemisphere forests (8).

We may, however, be approaching a tipping point. Human activities driving deforestation and degradation have already turned the Brazilian Amazon into a carbon source (9), and other tropical biomes may be moving toward a similar fate, compounded by the effects of higher temperatures and increased frequency of droughts on tree growth and mortality (10). Global warming also increases risks of wildfires in temperate and boreal forests, which could flip Northern hemisphere ecosystems from sink to source in coming decades (11). This has led to rising concerns that human activities risk triggering biosphere feedbacks that could set the planet on a trajectory away from Holocene conditions toward a much warmer state, with potentially catastrophic effects for societies and ecosystems (12, 13).

What if ecosystems on land had already lost their capacity to remove and store CO_2? Using the reduced complexity climate model MAGICC6 ("Model for the Assessment of Greenhouse Gas Induced Climate Change Version 6"), we examined changes in global mean temperature up till now and in the future under the RCP2.6 emission scenario—the only emission pathway that aligns with the Paris agreement—but assumed that ecosystems on land had stopped absorbing CO_2 from 1900 onwards. In such a world, global temperatures would have risen much faster (Fig. 1*C*, red line). In fact, we would have already crossed the 1.5 °C threshold, demonstrating that terrestrial ecosystems have reduced warming by at least 0.4 °C since 1900. Furthermore, if ecosystems on land cease to be a net carbon sink, this would lead to a dramatically higher rate of global warming compared with the standard RCP2.6 climate simulation that assumes intact land (and ocean) carbon sinks during the 21st century (Fig. 1*C*, blue line). By 2100, global mean temperature would be moving decisively toward 3 °C warming, even if the rapid decarbonization actions assumed in the RCP2.6 scenario pathway were fully implemented—and this is without even *considering* that rising temperatures would begin to release the vast biosphere carbon stocks themselves.

We have reached a new risk landscape. For the first time in human history, we face a planetary emergency. Not only have human pressures on Earth reached dangerously high levels, but we see signs that humanity may no longer be able to count on the capacity of the biosphere to continue dampening greenhouse gas emissions and hold onto its carbon stocks. The question therefore is how can we safeguard and enhance the ecological functions in the living biosphere that regulate its carbon sinks to have a chance of maintaining a stable and manageable planet that can equitably support humanity?

Toward Biosphere Stewardship

Avoiding a climate catastrophe requires at least three global transformations, unprecedented in both magnitude and speed: a transformation of the energy system that cuts emissions by half each decade to reach net-zero by 2050; a transformation of the agriculture and forestry sectors from greenhouse gas sources to sinks within 30 years; and a transformation of our relationship with nature to one that conserves, restores, and enhances its benefits for people and planet. Each must begin immediately and occur simultaneously to have a chance of achieving the Paris climate target, as well as broader global sustainability targets embedded in the United Nations Sustainable Development Goals and the Convention on Biological Diversity. To be clear: Maintaining and enhancing carbon sinks in the biosphere is a prerequisite to hold global warming well below 2 °C—and vice-versa. The more global warming exceeds 1.5 °C, the more likely we are to experience major impacts on ecosystems, triggering feedbacks that will accelerate warming and further harm people.

We argue that biosphere stewardship—the pursuit of social-ecological sustainability, from local to global scale, that ensures the health and resilience of Earth's life support systems—is an indispensable guiding principle and building block for the successful implementation of these transformations (14). In operational terms, biosphere stewardship implies a fundamental shift in governance from reducing human pressures only, to managing nature actively to promote multigenerational human wellbeing. This suggests that critical biomes should be recognized as global commons in service of humanity (15) and managed in ways that connect local authority, nation state integrity and culture, with collective governance by the world community (16). Indeed, the combination of

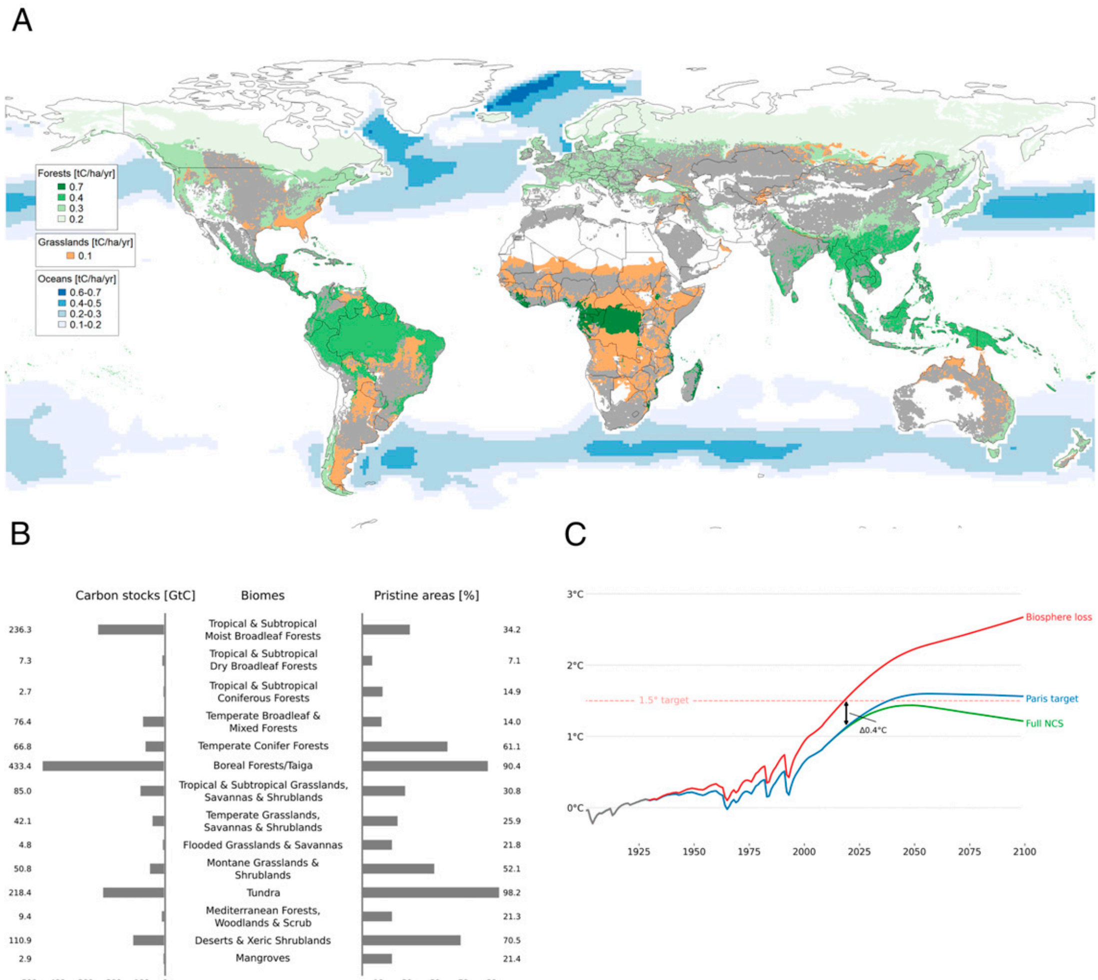

Fig. 1. (*A*) Carbon sinks in major biomes (*SI Appendix*, Table 1). Grey areas indicate regions dominated by agriculture. (*B*) Carbon stocks in vegetation and soils in major biomes and the share of each biome remaining intact today (*SI Appendix*, Table 1). (*C*) Global average temperature changes relative to pre-industrial levels under RCP2.6, where the pathway meeting the "Paris target" is the standard RCP2.6 simulation. "Biosphere loss" shows global temperature change without land carbon sinks from 1900. The Δ0.4 °C arrow shows the estimated dampening effect up until today from land-based ecosystems. "Full NCS" assumes large-scale restoration of land-based natural carbon sinks in forests, grasslands, peatlands, and wetlands, as well as avoided future ecosystem degradation, amounting to total emission reductions of 4.6 GtC per year after 2030 (*SI Appendix*, Methods for details).

local and indigenous knowledge with international technical and financial support is vital for enabling effective stewardship (17).

Strategic Considerations

First, evidence is rapidly growing that a wide range of land management practices that conserve, restore, or sustainably manage natural ecosystems and working lands, collectively termed Natural Climate Solutions (NCS), constitute a vital toolbox for practical biosphere stewardship that could deliver a third of global CO_2 emission reductions needed by 2030 (18). Turning again to the MAGICC6 model, we estimate that full implementation of NCS, in conjunction with the broader Paris-compatible decarbonization across all sectors embedded in RCP2.6, would limit warming by an additional 0.3 °C by the end of the century (green line in Fig. 1*C*). To deliver on the full potential of NCS, however, a roadmap is needed that specifies the stewardship actions—connecting key actors to strategies and places—to catalyze an exponential decline in CO_2 emissions through 2050 (19, 20). The roadmap's long-term goals are already clear: 1) rapidly safeguard irrecoverable carbon stocks in vulnerable terrestrial and coastal ecosystems [i.e., stocks that, if lost, cannot be recovered by 2050 (21)]; 2) achieve a net carbon absorbing land use sector; and 3) restore and regenerate degraded native ecosystems as carbon sinks. The latter goal requires resilience-building strategies, including disturbance management, in contrast to restoring carbon sinks through single species and simplified ecosystem that are vulnerable to climate shocks like fires or droughts.

Second, we must translate the overall framing of biosphere stewardship into actionable paths for *all* sectors and actors in society. Governments must establish and deliver on targets for NCS within their nationally determined contributions (NDCs) to the

Paris Climate Agreement—a huge current gap.[*] Similarly, cities and businesses should adopt and deliver on the growing momentum to set science-based targets for a safe operating space for critical Earth system functions (including biosphere carbon sinks), such as those being developed through the Science-Based Targets Network (SBTN). Local communities, faith-based organizations, and civil society groups all have vital roles in conserving, restoring, and better managing the biosphere, none more so than Indigenous peoples, just 5% of the global population, but stewarding more than 25% of the Earth's land surface (22).

Third, we need to implement policies and financial mechanisms tailored to catalyze action at scale. These include governments and businesses adopting full costing of environmental externalities and natural capital accounting, along with regulations to underpin fit-for-purpose sustainability principles to guide financial and investment decisions. Such efforts are rapidly gaining traction with key financial actors, including the Task Force on Climate-Related Financial Disclosures (TFCD)[†] and incipient sister Task Force on Nature-Related Financial Disclosures (TNFD).[‡] Current direct subsidies to the fossil fuel industry totaled US$320 billion in 2019,[§] with a cost to society exceeding US$5 trillion annually when their social and environmental externalities are included.[||] These subsidies must be replaced by policy measures guiding sustainable investments, such as a global price on carbon aligned with the latest estimates of the social cost of carbon of more than 100 US$ per ton of CO_2. Strategically designed carbon pricing offers a pathway toward mutually reinforcing climate mitigation and biosphere stewardship (23); a tropical carbon tax, as low as US$15 per ton of CO_2 (24), could support the finance required to avoid most tropical deforestation, estimated at 141 billion US$ per year (18).

Alongside top-down actions such as carbon pricing, biosphere stewardship necessitates deep partnership with local actors. Combining international finance streams with local pay-outs for protecting land carbon sinks, for example, via payments for ecosystems services (PES), holds promise in reducing deforstation (25). Prioritizing local and indigenous communities in forest landscape restoration, and affording people tenure rights to manage their lands, aligns global biosphere stewardship with local stewardship and environmental justice (26).

Scaling and Accelerating

The moment for such transformative actions is now, with recent economic, social, and technological developments opening an historic window of opportunity for driving sustainable change. Social movements, many youth-led and focused on climate justice and equity, have helped transform global public opinion in the past few years, with almost two-thirds of respondents of the largest global survey to date now citing climate change as an "emergency" that demands action.[#] Governments are being forced to respond—in April 2021, a lawsuit brought by the "Fridays for Future" movement ordered the German government to significantly tighten its climate protection law because it was judged as violating the constitution by delaying action, thereby placing too large a share of the mitigation burden and climate risks on future generations.[**] The speed of social change is mirrored in the pace of technological innovations creating the foundation for necessary shifts in consumer behavior; for example, in the United States sales of plant-based foods grew almost two-and-a-half times faster than total food sales between 2018 and 2020.[††]

Finally, out of the world's COVID-19 nightmare comes an unprecedented opportunity: As of August 2021, the world's 50 largest economies had announced $19.74 trillion in spending in response to the pandemic, including $3.38 trillion (some 17%) for long-term economic recovery.[‡‡] Although biosphere stewardship is a prerequisite to avoid a climate disaster, it is also a vital tool to prevent the next pandemic given the increasing risk of zoonotic virus spillovers resulting from unsustainable human exploitation of wildlife habitats and irresponsible management of wildlife and domestic animals in a hyper-connected, globalized world (27). Aligning this immense stimulus with biosphere stewardship principles would provide the financial muscle to drive the transformations we identify above—a once-in-a-generation opportunity to catalyze resilient post-COVID revitalization that accelerates integrated action toward a manageable climate future.

We see elements of such strategies emerging, with countries like Denmark, Germany, France, and South Korea leading on "green" recovery. Most countries, however, risk missing this golden opportunity; of the $3.38 trillion of proposed longer-term recovery investments, only 15% is currently "green", and even that is primarily focused on cutting greenhouse gas emissions or air pollution, with just 3% directed toward stewardship of nature. It is vital, therefore, that the world uses the UN Climate Change Conference and the UN Biodiversity Conference at the end of this year to rebuild momentum toward truly "building back better."

Time is not on our side. Within this decade we must bend the global curves of greenhouse gases emissions *and* of biodiversity loss. And let us not fool ourselves. Biosphere stewardship for Earth resilience puts stringent boundaries on "net-zero" targets for climate that have already been adopted by more than 100 countries to date. The "net" in net-zero targets for climate, therefore, must not result in delayed action to rapidly drive down fossil fuel emissions. Carbon markets, increasingly

* https://wwfint.awsassets.panda.org/downloads/wwf_ndc_food_final_low_res.pdf

† https://www.fsb-tcfd.org/

‡ https://tnfd.info/

§ https://www.iea.org/topics/energy-subsidies

|| https://www.imf.org/-/media/Files/Publications/WP/2019/WPIEA2019089.ashx

https://www.undp.org/publications/peoples-climate-vote

** https://www.bundesverfassungsgericht.de/SharedDocs/Pressemitteilungen/EN/2021/bvg21-031.html

†† https://gfi.org/marketresearch/

‡‡ https://recovery.smithschool.ox.ac.uk/tracking/

relied on to efficiently finance climate solutions, must follow strict science-based standards, such that net-zero targets are genuinely achieved.

In policy terms, an integrated climate–nature agenda is gaining momentum. A consensus is emerging that if climate science translates to net-zero emissions by 2050, then ecological science translates to net-zero loss of biodiversity and ecological functions from 2020 onwards. Setting the reference point for halting nature loss to 2020 is a reflection of the exceptional risks taken by humanity in the current phase of global mass extinction of species. From this point onwards, loss of biodiversity must be halted, as fast as possible (recognizing that a certain level of continued loss cannot be avoided) and reaching net-positive (in relation to 2020) by 2030, through the combined efforts of halting loss and investing in restoration and regeneration of ecosystems.[§§]

Whether the world can make good on the many promises of a resilient recovery after the coronavirus crisis remains to be seen. Successfully doing so may well determine whether we have a chance of keeping the planet in a stable state able to provide adequate life support for coming generations on Earth. Biosphere stewardship is essential for this endeavor.

[§§] Global Goal for Nature - working paper May 2021. https://www.naturepositive.org

1 P. Friedlingstein *et al.*, Global carbon budget 2020. *Earth Syst. Sci. Data* **12**, 3269–3340 (2020).

2 IPCC, *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, V. Masson-Delmotte, *et al.*, Eds. (Cambridge University Press, 2021).

3 B. J. Cardinale *et al.*, Biodiversity loss and its impact on humanity. *Nature* **486**, 59–67 (2012).

4 S. Sherwood, *et al.*, An assessment of Earth's climate sensitivity using multiple lines of evidence. *Rev. Geophys.* **58**, e2019RG000678 (2020).

5 P. D. L. Ritchie, J. J. Clarke, P. M. Cox, C. Huntingford, Overshooting tipping point thresholds in a changing climate. *Nature* **592**, 517–523 (2021).

6 IPCC, *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*, V. Masson-Delmotte, *et al.*, Eds. (World Meteorological Organization, 2018).

7 IPBES, *Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*, S. Díaz, *et al.*, Eds. (IPBES Secretariat, 2019).

8 P. Ciais *et al.*, Five decades of northern land carbon uptake revealed by the interhemispheric CO_2 gradient. *Nature* **568**, 221–225 (2019).

9 Y. Qin, *et al.*, Carbon loss from forest degradation exceeds that from deforestation in the Brazilian Amazon. *Nat. Clim. Change*, **11**, 442–448 (2021).

10 W. Hubau *et al.*, Asynchronous carbon sink saturation in African and Amazonian tropical forests. *Nature* **579**, 80–87 (2020).

11 X. J. Walker *et al.*, Increasing wildfires threaten historic carbon sink of boreal forest soils. *Nature* **572**, 520–523 (2019).

12 W. Steffen *et al.*, Trajectories of the Earth System in the Anthropocene. *Proc. Natl. Acad. Sci. U.S.A.* **115**, 8252–8259 (2018).

13 T. Westerhold *et al.*, An astronomically dated record of Earth's climate and its predictability over the last 66 million years. *Science* **369**, 1383–1387 (2020).

14 C. Folke *et al.*, Our future in the Anthropocene biosphere. *Ambio* **50**, 834–869 (2021).

15 F. Creutzig, Govern land as a global commons. *Nature* **546**, 28–29 (2017).

16 P. Dasgupta, *The Economics of Biodiversity: The Dasgupta Review* (HM Treasury, London, 2021).

17 S. Díaz *et al.*, Assessing nature's contributions to people. *Science* **359**, 270–272 (2018).

18 B. W. Griscom *et al.*, Natural climate solutions. *Proc. Natl. Acad. Sci. U.S.A.* **114**, 11645–11650 (2017).

19 J. Falk *et al.*, *Exponential Climate Action Roadmap* (Future Earth, 2018).

20 M. Mills *et al.*, How conservation initiatives go to scale. *Nat. Sustain.* **2**, 935–940 (2019).

21 A. Goldstein *et al.*, Protecting irrecoverable carbon in Earth's ecosystems. *Nat. Clim. Chang.* **10**, 287–295 (2020).

22 S. T. Garnett *et al.*, A spatial overview of the global importance of Indigenous lands for conservation. *Nat. Sustain.* **1**, 369–374 (2018).

23 F. Creutzig, The mitigation trinity: Coordinating policies to escalate climate mitigation. *One Earth* **1**, 76–85 (2019).

24 E. B. Barbier, R. Lozano, C. M. Rodríguez, S. Troëng, Adopt a carbon tax to protect tropical forests. *Nature* **578**, 213–216 (2020).

25 S. Jayachandran *et al.*, Cash for carbon: A randomized trial of payments for ecosystem services to reduce deforestation. *Science* **357**, 267–273 (2017).

26 J. T. Erbaugh *et al.*, Global forest restoration and the importance of prioritizing local communities. *Nat. Ecol. Evol.* **4**, 1472–1476 (2020).

27 A. P. Dobson *et al.*, Ecology and economics for pandemic prevention. *Science* **369**, 379–381 (2020).