Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Ecosystem restoration is integral to humanity's recovery from COVID-19

Jake M Robinson, James Aronson, Christopher B Daniels, Neva Goodwin, Craig Liddicoat, Laura Orlando, David Phillips, Jessica Stanhope, Philip Weinstein, Adam T Cross, Martin F Breed

COVID-19 has devastated global communities and economies. The pandemic has exposed socioeconomic disparities and weaknesses in health systems worldwide. Long-term health effects and economic recovery are major concerns. Ecosystem restoration—ie, the repair of ecosystems that have been degraded—relates directly to tackling the health and socioeconomic burdens of COVID-19, because stable and resilient ecosystems are fundamental determinants of health and socioeconomic stability. Here, we use COVID-19 as a case study, showing how ecosystem restoration can reduce the risk of infection and adverse sequelae and have an integral role in humanity's recovery from COVID-19. The next decade will be crucial for humanity's recovery from COVID-19 and for ecosystem repair. Indeed, in the absence of effective, large-scale restoration, 95% of the Earth's land could be degraded by 2050. The UN Decade on Ecosystem Restoration (2021–30) declaration reflects the growing urgency and scale at which we should repair ecosystems. Importantly, ecosystem restoration could also help to combat the health and socioeconomic issues that are associated with COVID-19, yet it is poorly integrated into current responses to the disease. Ecosystem restoration can be a core public health intervention and assist in COVID-19 recovery if it is closely integrated with socioeconomic, health, and environmental policies.

Lancet Planet Health 2022; 6: e769–73

College of Science and Engineering, Flinders University, Bedford Park, SA, Australia (J M Robinson PhD, C Liddicoat PhD, M F Breed PhD); **Center for Conservation and Sustainable Development, Missouri Botanical Garden, St Louis, MO, USA** (J Aronson PhD); **Green Adelaide Landscape Board, Adelaide, SA, Australia** (Prof C B Daniels DSc); **Economics in Context Initiative** (N Goodwin PhD) **and School of Public Health** (L Orlando MPA), **Boston University, Boston, MA, USA; School of Public Health** (C Liddicoat, Prof P Weinstein FAFPHM) **and School of Allied Health Science and Practice** (J Stanhope PhD), **The University of Adelaide, Adelaide SA, Australia; Department of Medical Science and Public Health, Bournemouth University,**

COVID-19-related health issues

The effects of SARS-CoV-2 infection can vary from asymptomatic, to a predominantly respiratory illness, to short-term and long-term multisystem illness that is characterised by immune dysfunction with symptoms referable to multiple bodily systems (figure 1).[1–3] COVID-19 and associated sequelae can be fatal, and the global death toll associated with the infection is already over 6 million as of August, 2022.[4] The costs of COVID-19 to individuals and society also manifest because of loss of employment, loss of mobility, and response measures, such as physical distancing and lockdowns.[5,6] The likelihood of, and outcomes from, infection are also heavily skewed. Individuals living in poverty, in accommodation of a poor standard, with greater exposure to toxicants at home or work, and without access to open or green space are more likely to get infected and have an increased likelihood of mortality associated with COVID-19.[7–9] These individuals are also more likely to have pre-existing poor health with suboptimal resilience and immune functioning and, consequently, substantially poorer outcomes from COVID-19.[10]

Engaging with nature to improve health

In addition to the fundamental roles that ecosystems have in human health (eg, resource provision, nutrient cycling, and climate regulation), spending time engaging with nature is beneficial to both physical and mental health.[11–13] Several potential pathways link nature exposure and health (eg, biological, psychological, social, and physical activity). Growing evidence suggests that exposure to diverse environmental microbiota is important in immunoregulation, and green spaces can enhance physical activity and social interaction.[14,15]

Some of these pathways have direct implications for resilience against and recovery from COVID-19. For example, emerging evidence suggests that exposure to phytoncides (ie, plant volatile compounds) can enhance the activity of natural killer cells, a subset of lymphocytes that are important in the immune and endocrine systems.[16,17] A considerable body of evidence also indicates that people who live near and regularly engage with natural environments of high quality have better mental health than do people who live in nature-depleted urban areas.[9] Exposure to and engagement with nature are

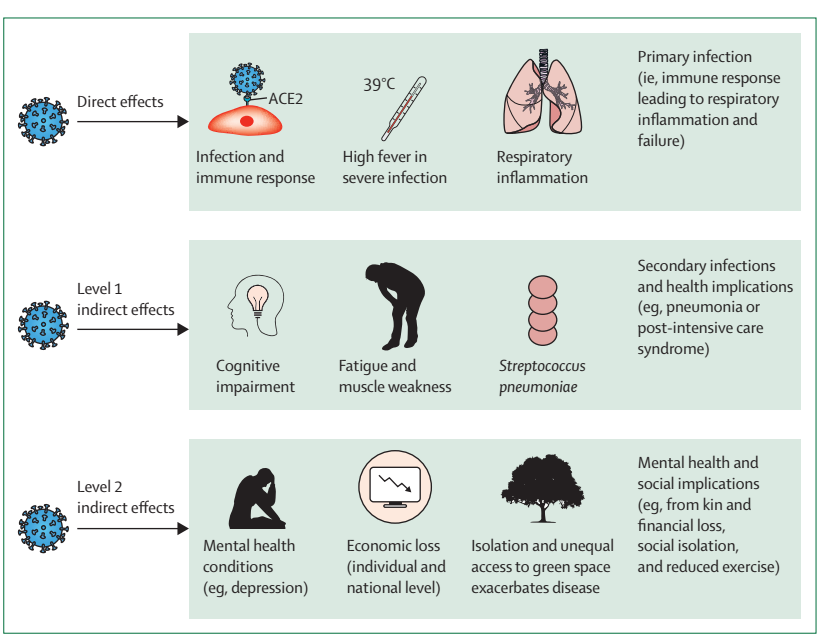

Figure 1: **Direct and indirect effects of COVID-19 on human health**
SARS-CoV-2 infection can directly cause inflammation and respiratory failure, and death in severe cases (ie, direct effects). Many cases of secondary infection have been recorded (level 1 indirect effects; eg, bacterial pneumonia, long COVID, and post-intensive care syndrome). Other indirect effects of COVID-19 include the exacerbation of mental health conditions attributed to social isolation, loss of kin and finances, and unequal access to health-promoting environments (level 2 indirect effects).

Poole, UK (D Phillips FFPH); **School of Molecular and Life Sciences, Curtin University, Bentley, WA, Australia** (A T Cross PhD)

Correspondence to: Dr Adam T Cross, School of Molecular and Life Sciences, Curtin University, Bentley, WA 6102, Australia
adam.cross@curtin.edu.au

or

Dr Martin F Breed, College of Science and Engineering, Flinders University, Bedford Park, SA 5042, Australia
martin.breed@flinders.edu.au

important in promoting mental health through emotional and cognitive connectedness and enhanced psychological restoration.[18] Importantly, metabolic and immune dysfunction and mental illness are considered risk factors for severe COVID-19[19] and are associated with an increased risk of infection and mortality.[20] Therefore, active engagement with the natural environment could potentially enhance resilience against and recovery from COVID-19.

Gut microbiota appears to have a direct role in regulating the magnitude of COVID-19 severity via the modulation of host immune responses[21,22] and is influenced by exposure to environmental microbiota.[23–25] Environmental microbiota exposures and immune training can enhance protection against infections and autoimmune responses[26] and, therefore, improve immune-mediated responses to the multifaceted effects of COVID-19. Moreover, a randomised controlled trial in mice showed an anxiety-reducing effect of trace amounts of soil-associated butyrate-producing bacteria, which was found particularly in biodiverse soils.[23]

Ecosystem restoration: a public health intervention

Ecosystem restoration is the repair of degraded ecosystems and can be considered a public health intervention. For example, the repair of damaged ecosystems enhances the provision of ecosystem services and can improve society's connection to nature by fostering a sense of environmental stewardship and providing increased opportunities to engage with biodiversity.[27] There are probably microbiota-derived health benefits associated with restoring biodiverse environments (figure 2A). These benefits might result from enhancing opportunities for interactions with immunoregulatory microbiota,[23–25] and provision of biogenic compounds, such as phytoncides, which can improve resilience to viral infections via immune priming. Furthermore, ecosystem restoration should also increase regulating ecosystem services, with relevance to COVID-19. For example, ecosystem restoration can contribute towards reducing air pollution,[28] exposure to which is a risk factor for increased COVID-19 mortality.[29,30] Finally, engaging with nature by participating in ecosystem restoration is a health-supporting activity, which is often described as reciprocal restoration.[31]

Restored habitats could provide stable populations of zoonotic reservoir hosts, and thereby reduce human–wildlife interactions and the likelihood of spillover events, whereas degradation and human encroachment increase the risk of spillover events (figure 2B).[32] The exploitation of ecosystems to supply resources and services to generally more urban and affluent communities might be leaving rural and poorer communities with higher multidimensional health risks. These risks can manifest not only via ecosystem degradation—which reduces ecosystems' capacity to produce quality nutrients, support

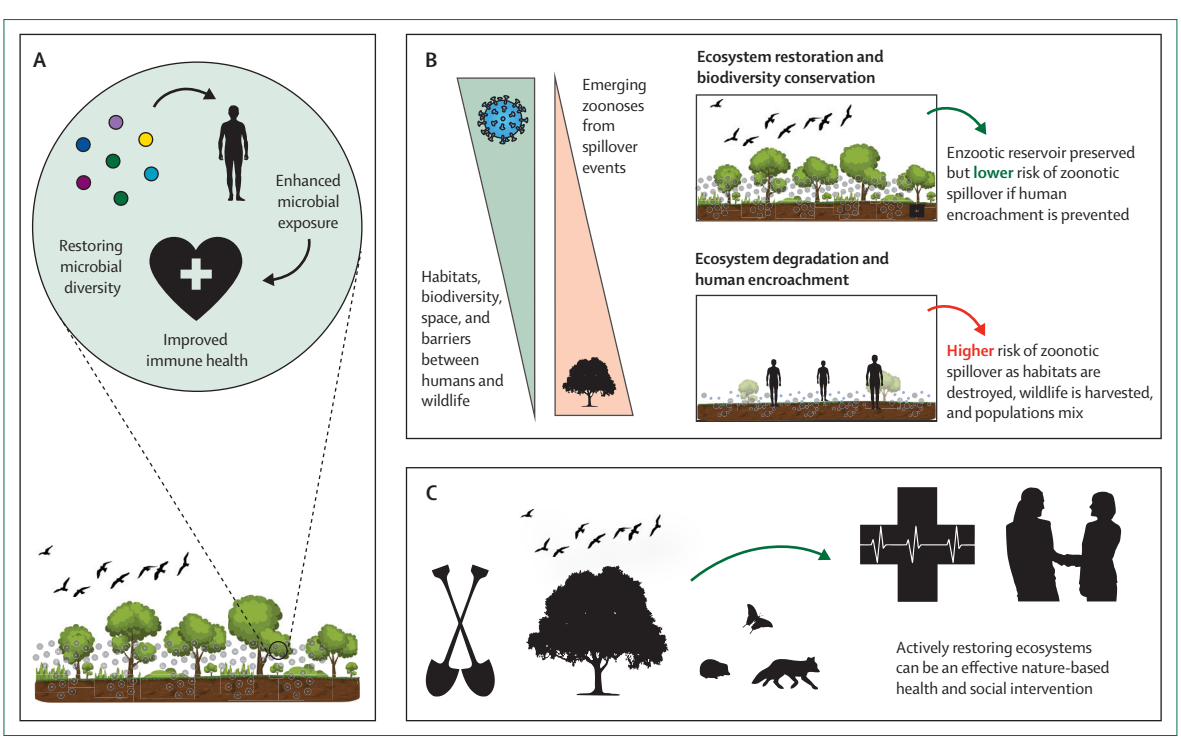

Figure 2: **Examples of the benefits of ecosystem restoration for human health**
(A) Restoring biodiverse environments might promote immune regulation through enhanced exposure to diverse microbiota. (B) Restoring nature can contribute to reducing the risk of zoonotic spillover via creating a habitat for stable populations of disease vectors. (C) Active engagement in ecosystem restoration can be implemented as a restoration-based health intervention—ie, reciprocal restoration—with important psychosocial and employment co-benefits.

livelihoods, and maintain resilience to climate change-related stress—but also by increasing exposure to emerging infectious diseases via their animal reservoirs.[32] Ecosystem degradation, along with the projected rise in global urbanisation, is likely to further increase hazardous interfaces for zoonotic pathogen exposure, thus increasing the likelihood of future disease spillover and potential pandemics.[32] Importantly, restoration should be done in the right context and the potential risks of restoration in some contexts should be recognised. For example, it is possible that restoration in urban settings could result in increased human–wildlife interactions by restoring the habitat of zoonotic hosts in these dense human settlements, leading to increased exposure to health risks.[33] As a result, a thorough cost–benefit analysis of the health-promoting versus harm-causing pathways is essential.[34]

Ecosystem restoration can also improve social equity in access to nature, the importance of which was shown during COVID-19 lockdowns, during which neighbourhood green and blue spaces had an important role in helping people to cope with the pandemic and the public health measures implemented to reduce transmission.[12,35,36] There is increasing interest in restoration-based health interventions, which are sometimes known as green prescriptions, for the health benefits of nature engagement.[27] These interventions can encourage education, exercise, and broad lifestyle changes that reduce COVID-19 risk factors, such as metabolic diseases (figure 2C).[37,38] Similar to evaluating how restoration could influence health-promoting versus harm-causing pathways, an assessment of restoration's potential to accentuate rather than attenuate social inequities is also needed. For example, work on green gentrification shows that, without appropriate safeguards, creating green spaces in urban areas can displace deprived populations in favour of more affluent ones.[39]

The issue of recovery from specific COVID-19 episodes (at the individual and societal levels) is also situated within the broader health and social variables discussed. From an ecosystem restoration perspective, what is needed for COVID-19 recovery is not different from what is needed to build and maintain good public health more broadly; indeed, human health is intimately dependent on the natural world.

Policy development for a healthier recovery

Improved policy developments that focus on ecosystem restoration are required to integrate health–biodiversity co-benefits in the implementation of nature-based solutions and assist in society's recovery from COVID-19 and adverse sequelae. These policy developments should include evidence-based tools to inform policy guidance and catalyse health-sector leadership and cross-sectoral policy via international and local policy processes. Examples of international policy processes of relevance include the Sustainable Development Goals, the World Health Assembly, and the Conferences of the Parties to the UN Framework Convention on Climate Change and the Convention on Biological Diversity.

Emphasising the importance of ecosystem restoration should be central to any long-term COVID-19 recovery programmes and to reducing the risk of future emerging infectious disease spillover events. Raising awareness among public health practitioners of the importance of ecosystem restoration, nature exposure, and engagement is crucial to this aim, as will be the integration of ecosystem restoration within existing public health programmes (eg, environmental health) to reduce the growing deficit in immunoregulation and to promote rehabilitation from long COVID and multisystem diseases. Indeed, if the only public health messaging and policy for pandemics, such as COVID-19, is around non-targeted cleanliness and staying at home, then the protective role of diverse environmental exposure diminishes. The potential deficit in immunoregulation is acknowledged by the portrayal of COVID-19 as a synergistic epidemic,[40] the aggregated effects of multiple concurrent (including non-communicable) diseases, which are often linked to poor immunoregulation. Public health policies should recognise this potential synergy and emphasise the importance of ecosystem restoration in facilitating access to positive environmental exposures. As previously noted, it is also important to thoroughly assess the potential of restoration projects to worsen health outcomes in some contexts, such as through increased contact with vector-borne diseases in urban areas.

Ecosystem restoration programmes also provide employment opportunities,[41] which could mitigate pandemic-associated job losses. Several socioecological problems could be addressed through policy changes that promote employment in ecosystem restoration, especially if such policy changes prioritise locations where ecosystem degradation affects marginalised or ill-treated communities. As the world develops strategies to recover from COVID-19 and further recognises the need for, and the great value of, ecosystem restoration, many more people will need to be trained to do this work. Struggling economies can be supported through the development of restoration economies and the provision of jobs.[41] These jobs could include environmental management, ecotherapy, tree planting crews, and plant nursery roles.

Inequities have become evident in the disease risk profiles of communities affected by COVID-19, and there are strong socioeconomic drivers for the degree to which particular community groups have been affected. People continue to be reliant on access to natural areas during lockdowns,[12,37] and marginalised communities in deprived areas tend not to have sufficient access to nature. However, the degree to which this luxury effect contributes to the disease and economic burden of COVID-19 is not quantified. COVID-19 has emphasised

and exacerbated pre-existing environmental inequalities, and interventions should aim to counter these inequalities. COVID-19 will probably have the greatest health and wellbeing effects in regions that already have high levels of poverty and heavily degraded environments, because these conditions are least conducive to favourable health and resilience. Ecosystem restoration should be integrated into social policy as a socioecological endeavour that recognises the potential to help to improve social equity, health, and resilience by improving ecosystem functioning.[27] The National Park City Foundation movement would help to enable such a pursuit. The movement encourages community-led action to embrace the importance of urban ecosystems for wildlife and people. For instance, in London, UK, and Adelaide, SA, Australia, community-led activities under the National Park City Foundation initiatives in these cities include establishing orchards, initiating nature-based health and wellbeing events, coordinating art and culture activities, establishing ecosystem restoration sites, and enhancing the network of community gardens across the cities.

For more on the **National Park City Foundation** see https://www.nationalparkcity.org

The Sustainable Development Goals encompass human and ecosystem health challenges, and ecosystem restoration is essential to both. The three most directly relevant Sustainable Development Goals include Goal 3: Good Health and Wellbeing, Goal 11: Sustainable Cities and Communities, and Goal 15: Life on Land. Nations recognise the importance of restoring nature and connecting people with the environment to improve health and wellbeing. For example, in the UK, the Department for Environment, Food and Rural Affairs published the *A Green Future: our 25 year plan to improve the environment* in 2018.[42] Key goals in this plan include ecosystem restoration and encouraging nature-based interventions that aim to facilitate behavioural changes to benefit health and wellbeing. The UN Decade on Ecosystem Restoration (2021–30) was launched on World Environment Day on June 5, 2021, and sets out to support governments, organisations, and communities to promote a global movement focusing on the restoration of degraded ecosystems. One of the key aims is to develop legislative and policy frameworks to incentivise restoration, which is done under the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Implementing these policy developments should be a global priority given that, in the absence of effective restoration, 95% of the planet's terrestrial ecosystems are projected to be degraded by 2050.[43]

For more on the **UN Decade on Ecosystem Restoration** see https://www.decadeonrestoration.org

Conclusion

In this Viewpoint, we have given three examples of links between ecosystem restoration and the reduction in risk of infection and adverse sequelae from COVID-19 (ie, enhancing immunoregulation via exposure to diverse microbial communities and biogenic compounds, restoring habitats and preventing human encroachment, and enhancing overall health and wellbeing through nature engagement and measures to improve social equity). If these and other public health interventions from ecosystem restoration are to be realised, then urgent policy action is required at all levels, from local government to intergovernmental platforms, to transform social, economic, and financial models towards a simultaneous healthy recovery of both ecosystems and humanity.

Contributors

JMR, JA, NG, CL, LO, PW, ATC, and MFB conceptualised the Viewpoint. JMR created the figures. MFB acquired the funding. All authors wrote the original draft and reviewed and edited the Viewpoint.

Declaration of interests

We declare no competing interests.

Acknowledgments

We thank Andrew Breed, Cristina Romanelli, and Chris Skelly for their helpful suggestions on an earlier draft of this manuscript. MFB received financial support from the Australian Research Council (LP190100051, LP190100484, and DP210101932).

References

1 Song CY, Xu J, He JQ, Lu YQ. Immune dysfunction following COVID-19, especially in severe patients. *Sci Rep* 2020; **10:** 15838.

2 Sadiq M, Aziz OA, Kazmi U, et al. Multisystem inflammatory syndrome associated with COVID-19 in children in Pakistan. *Lancet Child Adolesc Health* 2020; **4:** e36–37.

3 Sayampanathan AA, Heng CS, Pin PH, Pang J, Leong TY, Lee VJ. Infectivity of asymptomatic versus symptomatic COVID-19. *Lancet* 2021; **397:** 93–94.

4 Worldometers. COVID-19 coronavirus pandemic. https://www.worldometers.info/coronavirus (accessed July 12, 2021).

5 Bangash MN, Owen A, Alderman JE, Chotalia M, Patel JM, Parekh D. COVID-19 recovery: potential treatments for post-intensive care syndrome. *Lancet Respir Med* 2020; **8:** 1071–73.

6 Papadopoulou A, Efstathiou V, Yotsidi V, et al. Suicidal ideation during COVID-19 lockdown in Greece: prevalence in the community, risk and protective factors. *Psychiatry Res* 2021; **297:** 113713.

7 Mena GE, Martinez PP, Mahmud AS, Marquet PA, Buckee CO, Santillana M. Socioeconomic status determines COVID-19 incidence and related mortality in Santiago, Chile. *Science* 2021; **372:** 6545.

8 Mattos Dos Santos R. Isolation, social stress, low socioeconomic status and its relationship to immune response in COVID-19 pandemic context. *Brain Behav Immun Health* 2020; **7:** 100103.

9 Lu Y, Chen L, Liu X, et al. Green spaces mitigate racial disparity of health: a higher ratio of green spaces indicates a lower racial disparity in SARS-CoV-2 infection rates in the USA. *Environ Int* 2021; **152:** 106465.

10 Geary RS, Wheeler B, Lovell R, Jepson R, Hunter R, Rodgers S. A call to action: improving urban green spaces to reduce health inequalities exacerbated by COVID-19. *Prev Med* 2021; **145:** 106425.

11 Robinson JM, Brindley P, Cameron R, MacCarthy D, Jorgensen A. Nature's role in supporting health during the COVID-19 pandemic: a geospatial and socioecological study. *Int J Environ Res Public Health* 2021; **18:** 2227.

12 Bratman GN, Anderson CB, Berman MG, et al. Nature and mental health: an ecosystem service perspective. *Sci Adv* 2019; **5:** eaax0903.

13 Shanahan DF, Astell-Burt T, Barber EA, et al. Nature-based interventions for improving health and wellbeing: the purpose, the people and the outcomes. *Sports (Basel)* 2019; **7:** 141.

14 Aerts R, Honnay O, Van Nieuwenhuyse A. Biodiversity and human health: mechanisms and evidence of the positive health effects of diversity in nature and green spaces. *Br Med Bull* 2018; **127:** 5–22.

15 Marselle MR, Hartig T, Cox DTC, et al. Pathways linking biodiversity to human health: a conceptual framework. *Environ Int* 2021; **150:** 106420.

16 Li Q, Kobayashi M, Wakayama Y, et al. Effect of phytoncide from trees on human natural killer cell function. *Int J Immunopathol Pharmacol* 2009; **22:** 951–59.

17 Li Q. Effect of forest bathing trips on human immune function. *Environ Health Prev Med* 2010; **15:** 9–17.

18 Breed MF, Cross AT, Wallace K, et al. Ecosystem restoration: a public health intervention. *Ecohealth* 2021; **18:** 269–71.

19 Yeoh YK, Zuo T, Lui GC, et al. Gut microbiota composition reflects disease severity and dysfunctional immune responses in patients with COVID-19. *Gut* 2021; **70:** 698–706.

20 Wang Q, Xu R, Volkow ND. Increased risk of COVID-19 infection and mortality in people with mental disorders: analysis from electronic health records in the United States. *World Psychiatry* 2021; **20:** 124–30.

21 Moreira-Rosário A, Marques C, Pinheiro H, et al. Gut microbiota diversity and C-reactive protein are predictors of disease severity in COVID-19 patients. *Front Microbiol* 2021; **12:** 705020.

22 Roslund MI, Puhakka R, Grönroos M, et al. Biodiversity intervention enhances immune regulation and health-associated commensal microbiota among daycare children. *Sci Adv* 2020; **6:** eaba2578.

23 Liddicoat C, Sydnor H, Cando-Dumancela C, et al. Naturally-diverse airborne environmental microbial exposures modulate the gut microbiome and may provide anxiolytic benefits in mice. *Sci Total Environ* 2020; **701:** 134684.

24 Rook GA. Regulation of the immune system by biodiversity from the natural environment: an ecosystem service essential to health. *Proc Natl Acad Sci USA* 2013; **110:** 18360–67.

25 Roslund MI, Parajuli A, Hui N, et al. A placebo-controlled double-blinded test of the biodiversity hypothesis of immune-mediated diseases: environmental microbial diversity elicits changes in cytokines and increase in T regulatory cells in young children. *Ecotoxicol Environ Saf* 2022; **242:** 113900.

26 McCormick R. Does access to green space impact the mental well-being of children: a systematic review. *J Pediatr Nurs* 2017; **37:** 3–7.

27 Chen K, Wang M, Huang C, Kinney PL, Anastas PT. Air pollution reduction and mortality benefit during the COVID-19 outbreak in China. *Lancet Planet Health* 2020; **4:** e210–12.

28 Kimmerer R. Restoration and reciprocity: the contributions of traditional ecological knowledge. In: Egan D, Hjerpe EE, Abrams J, eds. Human dimensions of ecological restoration. Washington, DC: Island Press, 2011: 257–76.

29 Liang D, Shi L, Zhao J, et al. Urban air pollution may enhance COVID-19 case-fatality and mortality rates in the United States. *Innovation (Camb)* 2020; **1:** 100047.

30 Gopalakrishnan V, Ziv G, Hirabayashi S, Bakshi BR. Nature-based solutions can compete with technology for mitigating air emissions across the United States. *Environ Sci Technol* 2019; **53:** 13228–37.

31 Gibb R, Redding DW, Chin KQ, et al. Zoonotic host diversity increases in human-dominated ecosystems. *Nature* 2020; **584:** 398–402.

32 Brancalion PHS, Broadbent EN, de-Miguel S, et al. Emerging threats linking tropical deforestation and the COVID-19 pandemic. *Perspect Ecol Conserv* 2020; **18:** 243–46.

33 Plowright RK, Reaser JK, Locke H, et al. Land use-induced spillover: a call to action to safeguard environmental, animal, and human health. *Lancet Planet Health* 2021; **5:** e237–45.

34 Marselle MR, Lindley SJ, Cook PA, Bonn A. Biodiversity and health in the urban environment. *Curr Environ Health Rep* 2021; **8:** 146–56.

35 Berdejo-Espinola V, Suárez-Castro AF, Amano T, Fielding KS, Oh RRY, Fuller RA. Urban green space use during a time of stress: a case study during the COVID-19 pandemic in Brisbane, Australia. *People Nat* 2021; **3:** 597–609.

36 Venter ZS, Barton DN, Gundersen V, Figari H, Nowell M. Urban nature in a time of crisis: recreational use of green space increases during the COVID-19 outbreak in Oslo, Norway. *Environ Res Lett* 2020; **15:** 104075.

37 Robinson JM, Breed MF. Green prescriptions and their co-benefits: integrative strategies for public and environmental health. *Challenges* 2019; **10:** 9.

38 Lawton BA, Rose SB, Elley CR, Dowell AC, Fenton A, Moyes SA. Exercise on prescription for women aged 40–74 recruited through primary care: two year randomised controlled trial. *BMJ* 2008; **337:** a2509.

39 Jelks NO, Jennings V, Rigolon A. Green gentrification and health: a scoping review. *Int J Environ Res Public Health* 2021; **18:** 907.

40 Horton R. Offline: COVID-19 is not a pandemic. *Lancet* 2020; **396:** 874.

41 BenDor TK, Livengood A, Lester TW, Davis A, Yonavjak L. Defining and evaluating the ecological restoration economy. *Restor Ecol* 2015; 23: 209–19.

42 HM Government. A green future: our 25 year plan to improve the environment. March 22, 2018. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/693158/25-year-environment-plan.pdf (accessed April 2, 2021).

43 Yu Y, Zhai W, Martinez-Murillo JF, Pereira P. Loess plateau: form degradation to restoration. *Sci Total Envrion* 2020; 738: 140206.