Title: Diversity and evidence gaps among potential win–win solutions for conservation and human infectious disease control

Running Title: Win–wins for conservation and infectious disease control

Authors: Skylar R. Hopkins*[1,2], Kevin D. Lafferty[3], Chelsea L. Wood[4], Sarah H. Olson[5], Julia C. Buck[6], Giulio A. De Leo[7,8], Kathryn J. Fiorella[9], Johanna L. Fornberg[10], Andres Garchitorena[11,12], Isabel J. Jones[7], Armand M. Kuris[10], Laura H. Kwong[8,20], Christopher LeBoa[13,20], Ariel E. Leon[14*], Andrea J. Lund[15], Andrew J. MacDonald[16,17], Daniel C. G. Metz[18], Nicole Nova[16], Alison J. Peel[19], Justin V. Remais[20], Tara E. Stewart Merrill[21], Maya Wilson[14], Matthew H. Bonds[22], Andrew P. Dobson[23], David Lopez Carr[24], Meghan E. Howard[16], Lisa Mandle[8], Susanne H. Sokolow[8]

Affiliations:
[1]Skylar R. Hopkins, Ph.D., Department of Applied Ecology, North Carolina State University, Raleigh, NC 27695, USA
[2]National Center for Ecological Analysis and Synthesis, Santa Barbara, CA 93101, USA
[3]Kevin D. Lafferty, Ph.D., Full Professor Equivalent, Western Ecological Research Center, U.S. Geological Survey at Marine Science Institute, University of California, Santa Barbara, CA 93106, USA
[4]Chelsea L. Wood, Ph.D., School of Aquatic and Fishery Sciences, University of Washington, Seattle, WA 98195, USA
[5]Sarah H. Olson, Ph.D., Wildlife Conservation Society, Health Program, Bronx, NY 10460, USA
[6]Julia C. Buck, Ph.D., Department of Biology and Marine Biology, University of North Carolina Wilmington, Wilmington, NC 28403, USA
[7]Giulio A. De Leo, Ph.D., Full Professor; Isabel J. Jones, Ph.D., Hopkins Marine Station, Stanford University, Pacific Grove, CA 93950, USA
[8]Susanna H. Sokolow, D.V.M.; Laura H. Kwong, Ph.D.; Lisa Mandle, Ph.D.; Woods Institute for the Environment, Stanford University, Stanford, CA 94305, USA
[9]Kathryn J. Fiorella, Ph.D., Department of Population Medicine and Diagnostic Sciences and Master of Public Health Program, Cornell University, Ithaca, NY 14853, USA
[10]Armand M. Kuris, Ph.D., Full Professor; Johanna L. Fornberg, Ph.D., Department of Ecology, Evolution, and Marine Biology, University of California, Santa Barbara, CA 93106, USA
[11]Andres Garchitorena, Ph.D., MIVEGEC, Université Montpellier, Centre National de la Recherche Scientifique, Institut de Recherche pour le Développment, Montpellier 34090, France
[12]NGO PIVOT, Ranomafana, Infanadiana, Fianarantsoa 312, Madagascar
[13]Christopher LeBoa, Department of Epidemiology, Stanford University, Stanford, CA 94305, USA
[14]Ariel E. Leon, Ph.D.; Maya Wilson, Ph.D., Department of Biological Sciences, Virginia Tech, Blacksburg, VA 24061, USA *AEL's current address is U.S. Geological Survey, National Wildlife Health Center, Madison, Wisconsin, USA
[15]Andrea J. Lund, Ph.D., Department of Environmental and Occupational Health, University of Colorado School of Public Health, Aurora, CO, USA
[16]Nicola Nova, M.S.; Meghan Howard, M.S., Department of Biology, Stanford University, Stanford, CA 94305, USA
[17]Andrew MacDonald, Ph.D., Bren School of Environmental Science and Management, University of California, Santa Barbara, CA 93106, USA
[18]Daniel C.G. Metz, M.S., Scripps Institution of Oceanography, University of California, San Diego, CA 92093, USA
[19]Alison J. Peel, Ph.D., Centre for Planetary Health and Food Security, Griffith University, Nathan, Queensland 4111, Australia

[20]Justin V. Remais, Ph.D., Full Professor, Division of Environmental Health Sciences, University of California, Berkeley, Berkeley, CA 94720, USA
[21]Tara E. Stewart Merrill, Ph.D., Coastal and Marine Laboratory, Florida State University, St. Teresa, FL 32358, USA
[22]Mathew J. Bonds, Ph.D., epartment of Global Health and Social Medicine, Harvard Medical School, Boston, MA 02115, USA
[23]Andrew P. Dobson, Ph.D., Full Professor, Ecology and Evolutionary Biology, Princeton University, Princeton, NJ 08544, USA
[24]David Lopez Carr, Ph.D., Full Professor, Department of Geography, University of California, Santa Barbara, CA 93106, USA

*Corresponding author: 2076594172, skylar_hopkins@ncsu.edu

Summary:
As sustainable development practitioners have worked to “ensure healthy lives and promote well-being for all” and “conserve life on land and below water,” what progress has been made with win–win interventions that reduce human infectious disease burdens while advancing conservation goals? Using a systematic literature review, we identified 46 such proposed solutions, which we then investigated individually using targeted literature reviews. The proposed solutions addressed diverse conservation threats and human infectious diseases, and thus the proposed interventions varied in scale, costs, and impacts. Some potential solutions had medium- to high-quality evidence for prior success in achieving their proposed impacts in one or both sectors. However, there were notable evidence gaps within and among solutions, highlighting opportunities for further research and adaptive implementation. Stakeholders seeking win–win interventions can explore this review and an online database to find and tailor a relevant solution or to brainstorm new solutions entirely.

Keywords: biodiversity, disease ecology, ecosystem health, epidemiology, intervention, One Health, nature-based solutions, public health, restoration

Main Text:

Introduction

Ecosystem degradation can exacerbate infectious diseases that have long plagued humankind or cause novel pathogens to spill over from animals to humans.[1–6] By targeting connections between human infectious disease and the natural world, interventions might both “ensure healthy lives and promote well-being for all” and “conserve life on land and below water”—two Sustainable Development Goals (SDGs).[7–17] For example, putting tick collars on free-ranging dogs might reduce transmission of ticks and tick-borne disease from dogs to people and wildlife.[18] Indeed, sustainable development practitioners around the world are urgently seeking safe and effective cross-sector interventions that might prevent the next pandemic.[19]

Of course, no single win–win intervention will work in all contexts or solve all problems within complex socio-ecological systems.[20] Interventions that improve some outcomes for human health and ecosystems might even cause collateral impacts in other sectors, creating complex trade-offs among SDGs.[16,21,22] Tasked with choosing an optimal intervention for any given problem and socio-ecological context, practitioners need to know which intervention options exist and how to compare them. Or, in the event that no existing intervention is suitable, practitioners will need to know how to identify and evaluate new intervention options.

Unfortunately, the information needed to identify, implement, and evaluate win–win interventions that prevent or control human infectious diseases tends to be limited, inconsistent, and/or unconsolidated.[23] For instance, among conservation intervention studies that reported human well-being benefits, fewer than 2% considered health-specific outcomes, and only a subset of those considered emerging or endemic infectious diseases.[24,25] Furthermore, existing studies are scattered across siloed disciplines that use different research methodologies, measure different outcomes, and publish in different journals. Navigating this dispersed evidence landscape would be prohibitively time-consuming for practitioners interested in implementing win–win interventions.

To facilitate timely, evidence-based decision-making, we review existing evidence regarding win–win solutions that aim to simultaneously reduce human infectious disease burdens and advance conservation goals. Because there are growing policy initiatives for enacting "nature-based solutions",[8] we use the terms "intervention" and "solution" interchangeably throughout. First, we provide a "menu" of 46 such proposed solutions ranging from local to international scales and their individual information summaries. Stakeholders can explore these examples to find and tailor potential solutions to meet their needs, or to brainstorm new solutions entirely. We then synthesize information across the 46 solutions to describe some general criteria that stakeholders can use to identify and evaluate potentially viable solutions that achieve their specific goals within their resource constraints. Finally, we highlight evidence gaps within and among solutions that could be important targets for future research and implementation.

Search Strategy and Selection Criteria:

To find and synthesize evidence among proposed solutions, we used a subject-wide evidence synthesis, a two-phase approach for identifying and assessing a broad suite of interventions supported by heterogeneous evidence (Fig. 1).[26,27] In the first phase, we performed a systematic literature review of peer-reviewed papers and book chapters, which we used to identify solutions that have been proposed to simultaneously reduce human infectious disease burdens and advance conservation goals (see below; appendix p 2-4). In the second phase, we performed targeted rapid reviews[28] of the peer-reviewed and gray literature for each proposed solution, iteratively revising evidence summaries for each (see below; appendix p 4-5). Finally, we used these evidence summaries to categorize information for each solution, making it easier to synthesize and compare among solutions.

To create a list of proposed win–win solutions (Phase 1), we systematically reviewed publications in Thomson Reuters Web of Science™ (http://thomsonreuters.com) and NCBI Pubmed® (https://pubmed.ncbi.nlm.nih.gov) on 14 March 2018 (N=12,270 papers), including records published any time prior. We performed the search using 167 English search terms regarding conservation, ecology, infectious disease, and human populations (adapted from McKinnon et al.[25]; see appendix p 2-4 and 14 and Fig. S1 for PRISMA diagram). We identified 617 papers containing hypothesized or measured outcomes for both conservation and human infectious diseases—excluding papers that lacked proposed outcomes for one or both sectors—by using a combination of researcher classification and machine learning to sort records by relevance[29]. During subsequent full-text analysis, we removed any records that did not suggest at least one proposed win–win solution (e.g., papers about trade-offs where environmental degradation improves health). We then used full-text analysis of the final list of 383 records to group records pertaining to the same win–win solutions into collective case studies (appendix p 4). This resulted in a list of 46 unique proposed solutions (Fig. 2).

Each solution was then individually reviewed by one or two investigators (Phase 2: targeted rapid reviews), where keyword searches were used to find additional peer-reviewed publications on Web of Science™ and online searches were used to find gray literature. These rapid reviews were not systematic because they did not examine all published literature—a task that would not be possible for 46 interventions. Instead, investigators specifically sought publications with information relevant to 20 information categories, determined *a priori,* and summarized all information in a standard format (appendix p 4-5). A single lead investigator reviewed all collective case study summaries to ensure consistency, and then each summary was reviewed by an external expert (appendix p 5). Based on feedback from external experts, investigators iteratively searched for more information and revised the collective case study summary until the investigator and lead investigator deemed the review complete. The 46 summaries are available in an open access database: https://ecohealthsolutions.stanford.edu/research/win-win-solutions-people-and-nature

After finishing the collective case study summary, each investigator used a list of qualitative variables defined *a priori* to categorize information in a consistent way that could be compared across case studies. These variables included geographical location, conservation threat, infectious disease threat, mechanism or "lever" type, evidence for conservation and human infectious disease outcomes, and 11 criteria that we identified as indicative of viable solutions: *Harmless*, *Contained*, *Consistent*, *Feasible*, *Acceptable*, *Impactful*, *Effective*, *Affordable*, *Scalable*, *Sustainable*, and *Cost-Effective* (see definitions in appendix p 7-8). The investigators' designations were confirmed by the lead investigator and 1-2 other investigators to ensure consistency. Any discrepancies between how different people categorized information was discussed until consensus was reached. After information from all proposed solutions had been categorized, we synthesized information across the 46 solutions to describe their diversity and evidence gaps (Figs. 2-6).

Potential solutions were widespread and diverse:

The 46 potential solutions addressed diverse threats, collectively covering all continents (except Antarctica), most major pathogen groups (except fungi), and most conservation threat classes defined by the International Union for the Conservation of Nature (except "geological events" and "other"; Fig. 4).[30] Most solutions addressed multiple threats for health and conservation (e.g., multiple pathogen species, multiple IUCN threat classes). The 46 potential solutions also covered many intervention types and targets, ranging from vaccinating vampire bats against rabies in Peru[31] to establishing sustainable harvesting programs for medicinal plant species in Tanzania.[32] Potential solutions were diverse because the problems that they addressed were diverse.

Most solutions addressed pathogens with environmentally mediated transmission, such as vector-borne diseases and zoonotic diseases transmitted from animals to people (Fig. 4A), mirroring the strong focus on these diseases in the One Health, Planetary Health, and EcoHealth fields.[9,33,34] For example, the World Health Organization (WHO) and other international organizations support expanding training for integrated pest and vector management globally, because these management techniques might reduce total pesticide use while controlling both crop pests and disease vectors such as mosquitoes. Environmentally mediated diseases like these have probably been the easiest entry points for cross-sector solutions due to their obvious underlying links between human health and ecosystems.

Only a few potential solutions addressed diseases without environmentally mediated transmission, like HIV/AIDS and pneumonia. For example, people in poor health due to HIV/AIDS or other diseases are more likely to use easier and more destructive fishing practices in communities near Lake Victoria, so HIV/AIDS treatment and prevention programs might support both human health and aquatic conservation.[35] Focusing on these understudied links between ecosystems and directly transmitted and chronic human diseases might yield additional solutions for advancing conservation and health.

In addition to addressing diverse health threats, the potential solutions also addressed all IUCN conservation threats related to anthropogenic activities (Fig. 4C). Solutions related to land use change—agriculture & aquaculture (n=29) and urbanization & development (n=22)—were most common, probably because land use change is a leading driver of biodiversity declines[36] and disease spillover.[6,33,37,38] In contrast, only a few solutions addressed transportation corridors, energy and mining, and climate change, and never as the primary threat (Fig. 4C).

We did not include a collective case study where climate change was the primary conservation threat and global emissions reduction was the solution (appendix p 3-4), because the many health and conservation outcomes that could be achieved by global emissions reduction[9,10] have yet to be measured. Climate change is expected to become a more urgent threat over time,[7] so there is a clear need for actionable, targeted solutions related to climate change.

The conservation and health threats targeted by the potential solutions spanned all geographical scales, from sub-national or national extents to regions (multiple countries within a continent) to multiple continents (Fig. 4A). For example, vaccinating prairie dogs to reduce plague risk for endangered black-footed ferrets and humans applies sub-nationally to the Western United States,[39] whereas forest conservation to reduce human malaria might be relevant to multiple countries in Latin America, Africa, and Asia.[40,41] The potential solutions included targets in low- and middle-income countries, where there are high burdens of environmentally mediated human infectious diseases, and targets in high-income countries, where infectious disease burdens are lower and research effort is higher (Fig. 4A). Ultimately, one or more potential solutions probably exist for all countries, but the set of relevant solutions that apply to any given country could be expanded by future efforts to scale or translate existing solutions to new locations.

There were 27 potential solutions that involved implementing classic conservation interventions that have health benefits ("conservation levers for health"; Fig. 3), which are sometimes called "nature-based solutions" or "ecological levers for health".[8,42,43] One particularly common conservation intervention type was species management, such as controlling or eradicating invasive honeysuckle to reduce negative impacts on native vertebrates and reduce vector populations associated with honeysuckle,[44] and reintroducing native prawns extirpated by dams to help control the snails that transmit human schistosomiasis.[45] Another common conservation intervention type was land or water management or protection, such as conserving or restoring wetlands to restore biodiversity while also reducing waterborne diarrheal diseases.[46] Together, these 27 potential solutions are the most comprehensive list to date of conservation solutions that might specifically reduce human infectious diseases, an important subsector within the global focus on conservation solutions that improve general human well-being.[8,9,33,42]

Six potential solutions involved classic public health interventions that have conservation benefits ("health levers for conservation"; Fig. 3). For example, health system strengthening or family planning and reproductive health programs—including Population, Health, and Environment (PHE) programs in many countries[47]—have reduced illegal logging and deforestation,[48,49] improved coral and mangrove conditions in marine environments,[50] and improved community participation in or approval of conservation initiatives.[51] There were also several solutions that used insect vector control to reduce vector-borne disease risk for both people and wildlife.[52,53] These health interventions were often supported by limited evidence, either because there were not enough resources dedicated to monitoring and evaluation, or because interventions implemented by the health sector did not quantify ecosystem or conservation outcomes. Therefore, we expect that more health interventions that advance conservation goals might be imagined through increased collaboration between conservation and health organizations.

Finally, 13 potential solutions acted through interventions that were neither specific to public health nor conservation, but which affected both sectors ("levers for health and conservation"; Fig. 3). Many of these were policies regarding the food–energy–water nexus,[54] such as regulating protozoan pollution,[55] reducing antibiotic use in aquaculture,[56] reducing nutrient pollution and eutrophication associated with agriculture,[57] and implementing ballast water treatment protocols to prevent invasive pathogens and wildlife from moving among ports.[58] There were also outreach, education, or livelihood interventions, such as teaching people how to live safely with bats that might be virus reservoirs;[59] protecting tree sap collection pots from bat contamination using bamboo skirts;[60,61] and replacing wood-burning stoves with cleaner cookstoves to reduce deforestation and smoke-related pneumonia.[62] However, livelihood-focused interventions were relatively rare, so future efforts might discover more interventions that primarily target poverty and inequalities (SDGs 1 and 10) and that have downstream benefits for health and conservation (SDGs 1, 14, and 15).

The diversity among potential solutions is promising, because "there is no one-size-fits-all approach for One Health implementation."[33] The 46 examples described here cover many context-specific health and conservation threats, so stakeholders might be able to adapt one of these to meet their needs. Where none of the 46 potential solutions described here are relevant, stakeholders could design new solutions to meet their specific goals within their resource constraints. To determine whether any given solution will be viable for a given context, stakeholders can evaluate the 11 viability criteria described below: *Harmless*, *Contained*, *Consistent*, *Feasible*, *Acceptable*, *Impactful*, *Effective*, *Affordable*, *Scalable*, *Sustainable*, and *Cost-Effective* (Fig. 5, also see appendix p 7-8).

Identifying and minimizing trade-offs:

To evaluate potential trade-offs caused by a given intervention, we suggest considering three viability criteria (Figs. 2, 5): *Harmless* solutions are not expected to harm non-target aspects of human well-being for some people while attempting to help other people; *Contained* solutions are not expected to have negative, collateral impacts on non-human targets, or else potential collateral impacts could be avoided or fully mitigated; and *Consistent* solutions are expected to have only positive outcomes for their intended conservation and human infectious disease control targets in predictable contexts (i.e., no known negative outcomes). Two investigators used these definitions and available evidence to determine whether each potential solution met, failed, or was data-deficient for the three criteria (also see appendix p 6-7). Data limitations often made it difficult to decide whether a solution involved substantial trade-offs, but existing evidence demonstrated that 19 solutions could be *Harmless*, *Contained*, and *Consistent* under some contexts (Figs. 1 and 5).

Context-dependency was common among the 46 potential solutions. For example, introducing invasive predators that consume larval mosquitoes to control malaria has often negatively impacted ecosystems (e.g., violating the *Contained* criterion),[63] but in at least some contexts (e.g., native predators), mosquito predators are expected to have only positive outcomes for ecosystems (meeting the *Contained* criterion). However, for other solutions, we could not identify a mediating context. For example, correlational studies suggest that forest cover and host biodiversity impact competent host abundance in ways that can reduce human Lyme disease risk in North America (the "dilution effect").[64] Yet in this complex system, forest cover or host biodiversity have also been associated with unexpected amplification of Lyme disease risk[65], and thus it is unclear how forest conservation or restoration interventions would impact human health (i.e., this solution violates the *Consistent* criterion). Future research or innovation might identify specific, predictable scales and circumstances where this solution does no harm, but at present, it risks causing unpredictable harm to some people in some contexts.

Like most solutions, those that address pathogen spillover from wildlife to humans had data gaps regarding trade-offs. For example, wildlife trade is a conservation threat and a pathway for spillover from wildlife.[66–69] However, in several African countries, past bans on all wildlife hunting and consumption sometimes created food insecurity, illegal markets, and distrust in health authorities.[21,70–72] Bans developed in response to the recent COVID-19 pandemic might be similarly problematic.[73,74] This evidence demonstrates that wildlife trade bans can cause harm when they affect subsistence hunting and consumption. But wildlife trade bans or restrictions might be safe and feasible in other specific contexts. For example, many existing national and international wildlife pet trade restrictions aim to conserve wildlife (e.g., the Convention on International Trade in Endangered Species; https://cites.org), and there is increasing (but not universal) public support for bans or restrictions on "luxury" commercial wildlife trade in Asia due to the recent coronavirus outbreaks.[75] If successful, restrictions and bans that target the multi-billion-dollar commercial wildlife trade could prevent multi-trillion-dollar pandemics.[16,76] However, it is still unclear whether and when these policies can be successful, including whether they will favor illegal markets or erode support for conservation. Efforts to identify contexts where negative impacts are mediated, conservation is advanced, and spillover risks are reduced are urgently needed.

Achieving Socially Acceptable and Feasible solutions:

Two criteria can be used to determine whether solutions are immediately achievable (Fig. 5): *Feasible* solutions could be successfully implemented now, given existing technology and sufficient resources, and *Socially Acceptable* solutions are supported by the stakeholders who are affected by the intervention or could be made acceptable to the stakeholders. For example, the livestock medication diclofenac was implicated in dramatic vulture population declines in India, which might have allowed free-ranging dog populations and human rabies risk to increase.[77] Therefore, diclofenac was banned in India and surrounding nations, an intervention that was achievable because acceptable, alternative veterinary drugs that could replace diclofenac and that were not toxic to vultures already existed.[77] As this example illustrates, some of the 46 potential solutions have already been successfully implemented on national or multinational scales.

However, most potential solutions were data deficient for feasibility or social acceptability. For example, two potential solutions involve broadly "rewilding" North America with top carnivores to control infectious diseases in wild herbivores and possibly humans.[78] These potential solutions face opposition from some stakeholders (e.g., ranchers, hunters), and it is unclear whether rewilding can be made socially acceptable in places where the intervention would most impact disease transmission (or whether rewilding would lead to net reductions in disease risk). Indeed, solutions that involved changing peoples' lifestyles and cultures were often data deficient for *Acceptability*. This highlights a clear need for future human-dimensions and implementation research to evaluate cross-sector solution viability, as outlined by the Organisation for Economic Cooperation and Development (OECD).[79]

Impactful and Effective solutions achieve stakeholders' goals:
Whether a given solution meets stakeholders' goals can be evaluated using two criteria: *Impactful* solutions have the potential to meet stakeholders' quantitative goals (i.e., effect magnitude, clinical relevance), and *Effective* solutions can successfully achieve the desired outcomes. For example, building nest boxes to increase local predatory bird populations is proposed to control the rodent species that are reservoirs for hantaviruses.[80] This is an ecological lever for health,[42] but there is no evidence that nesting sites are limited in this example, so the intervention may only re-distribute non-threatened wildlife populations in ways that benefit humans, creating little value for stakeholders with strong conservation priorities (i.e., this solution might not be *Impactful* for conservation). There is also limited evidence that this solution can successfully reduce human disease burdens (i.e., this solution might not be *Effective* for human health). We did not quantify how *Impactful* each potential solution was, because there was no common system available to rank impacts given the diverse methods and metrics used across the relevant literature. However, we did qualitatively assess how *Effective* each solution was, as evidenced by prior success in achieving proposed goals (Fig. 6, appendix p 5-7).

We categorized existing evidence quality for each potential solution using a modified Bridge Collaborative rubric[81] with three categories: evidence types and diversity, evidence consistency, and evidence applicability (appendix p 5-7 and 15, Table S1). We then combined these three categories into one composite score for overall evidence quality for health outcomes and one score for conservation outcomes (Figs. 2 and 6): "no evidence" indicated that cases were supported only by hypotheses and anecdotes; "low evidence quality" indicated that there were limited supporting studies with moderate to major evidence gaps, unexplained inconsistency, or limited applicability; "medium evidence quality" indicated that there were several lines of evidence that were mostly consistent and applicable, where inconsistency could be explained; and "high evidence quality" indicated diverse evidence types, usually including an intervention study, that yielded consistent and applicable results and left little to no uncertainty regarding the outcome. The resulting composite evidence quality scores highlight which solutions have had demonstrable success for health and conservation outcomes and which still have evidence gaps.

There were seven solutions that already had medium to high evidence quality for both conservation and human health success and were thus *Effective* (Fig. 6). For example, vaccinating dogs and wild carnivores to reduce rabies transmission among dogs, wildlife, and people was supported by high evidence quality for both outcomes, including successful intervention programs.[82,83] Most solutions had higher evidence quality regarding *Effectiveness* for conservation than for health. For example, it is well established that controlling invasive rats, brushtail possums, and cats can conserve endemic species,[84–86] especially on islands. There are also studies linking invasive species control and human infectious disease burdens,[87,88] but the evidence types and diversity are more limited. Similarly, though forest restoration and conservation have well-established benefits to ecosystem structure and function,[89,90] and several correlational studies link upstream forest cover to reduced childhood diarrhea risk downstream,[91] there are no intervention studies linking forests to childhood diarrhea. Though evidence for these solutions could still be improved, these examples show that *Effective* cross-sector solutions do exist.

There were 17 potential solutions that had low overall evidence quality due to low evidence diversity, low evidence applicability, and/or evidence inconsistency that was difficult to explain for one or both outcomes. For example, a few observational studies (limited evidence diversity) quantified high leopard predation rates on free-ranging domestic dogs, an important disease reservoir for rabies near Mumbai.[92] Leopard conservation might reduce dog rabies and thus human rabies risk, but predation or culling of dogs could also counterintuitively increase rabies in dog reservoir populations (potentially not *Consistent*).[93] In another example, regulating drawdown rates for water reservoirs created by dams might restore aquatic communities and reduce larval mosquito survival and thus human malaria risk near dams.[94] However, the existing evidence did not come from countries with high malaria burdens (low applicability). In still another example, integrating wild grazing animals on land parcels used for grazing cattle, which are frequently treated for ticks, might increase forage availability for wildlife and reduce tick abundance on land parcels.[95] Tick abundance on land parcels might in turn affect human disease risk, but tick-borne disease incidence in humans has never been measured for this solution (low applicability). As these examples illustrate, many promising solutions had some supporting evidence, but most solutions had notable data gaps (Fig. 5).

Optimal solutions achieve goals within resource constraints:

In addition to goals (*Impactful* and *Effective*), stakeholders also have resource constraints. Resources determine which solutions can be implemented at the necessary scales and intensities to achieve their desired outcomes (*Affordable, Scalable,* and *Sustainable*) and how big the impact will be for a given resource budget (*Cost-Effective*). Different stakeholders might evaluate these last four criteria differently, because different stakeholders have different goals, priorities, and resources.

We note that resource costs and *Affordability* are distinct: cost is the resource price tag, whereas *Affordability* is the ability to pay. For human infectious diseases, public health intervention *Cost-Effectiveness* is usually quantified in disability adjusted life years (DALYs) averted per dollar, but DALYs and cost were rarely reported for the 46 potential solutions reviewed here. This highlights an important area for future research, because for most stakeholders, and perhaps especially those interested in human health outcomes, *Cost-Effectiveness* and *Affordability* will be the most important considerations when choosing a solution.

For some of the proposed solutions, the potential conservation and health *Impacts* would likely be too small for most stakeholders to justify the cost. For example, invasive python control in the Everglades reduces predation pressures on native vertebrates and might reduce human exposure to the vector-borne Everglades virus.[96] However, python eradication is costly and has not been achieved using existing resources, and maintaining continuous python control efforts at current intensities might not be feasible indefinitely (potentially not *Sustainable*). From a public health perspective, a cheaper and more direct public health or medical intervention might be preferred to python control. However, local stakeholders in the Everglades might value the small human health co-benefits from python control, even if their main goal is a potentially large conservation *Impact*. As this example illustrates, sometimes a small *Impact* in one sector (health or conservation) can be valued because it accompanies a large *Impact* in another sector, or because it fully addresses a small local problem.

It is often difficult to quantify the net value associated with all positive *Impacts* in all sectors for a given intervention. However, identifying these potential *Impacts* explicitly can help stakeholders to compare among multi-sector interventions.[16,21,22] Ultimately, for any given cross-sector problem, collaborations among stakeholders, economists, social scientists, and implementation scientists might be needed to determine which solution is optimal.

Evidence-based management under uncertainty:
Data-limited solutions that appear safe and feasible could be ideal for immediate research and adaptive implementation. However, strict adaptive implementation requires that multiple interventions are implemented simultaneously and compared, where approaches are subsequently modified according to what works best.[97] This approach is often infeasible in conservation and public health programs,[97] and it might be even more difficult for multi-sector solutions, leaving many data gaps unaddressed. When adaptive implementation is not possible, there might be other ways to fill in data gaps via safe implementation, such as by comparing across different programs that all monitor, evaluate, and share their outcomes. For example, multiple programs are improving hygiene or health care for people who work or recreate in great ape conservation areas, which could increase human health and reduce pathogen spillover from humans to apes.[98] Comparing outcomes across these programs might provide new insights for the IUCN's "Best Practice Guidelines for Health Monitoring and Disease Control in Great Ape Populations".[99] As evidence accumulates for this and other solutions, uncertainty will decline. Data gaps will still likely remain prominent in the near future, but action despite uncertainty will already be familiar for most public health and conservation practitioners.[9,10]

Conclusions:
The growing Planetary Health field emphasizes the links between human well-being and ecosystem integrity, but there has been limited guidance for how to leverage these relationships to implement viable win–win solutions that specifically reduce human infectious disease burdens. Here, we identified 46 such potential win–win solutions. We found that proposed solutions address diverse, context-dependent, and dynamic threats with cross-sector interventions that are equally diverse. Many proposed solutions had the potential to be safe and feasible under some predictable contexts, and some were supported by medium- to high-quality evidence of success. Some had the potential for large human health and/or conservation *Impacts*, such as forest conservation projects and health system strengthening initiatives. Others had relatively minor *Impacts* but might still be highly valued by local stakeholders. Synergies like these might be pivotal for achieving the soon-to-be revised Sustainable Development Goals.[16,21,22,100]

Though promising, all proposed solutions had some evidence gaps, and collectively, they did not cover all possible health and conservation threats. Evidence regarding conservation and health *Impacts* and intervention *Cost-Effectiveness* and *Affordability* were especially scarce, highlighting priorities for future research. At present, these data gaps within and among solutions complicate decision-making. More evidence will accumulate if stakeholders invest in research, adaptive implementation, and monitoring and evaluation for existing approaches. New solutions will also be imagined, filling in existing gaps among solutions or addressing new problems as they arise.

As new solutions and evidence accumulate, the viability criteria described here can be used to compare and update the evidence database for potential solutions, differentiating the solutions that do not work from those that successfully and cost-effectively advance health and conservation.

Acknowledgments: We thank the many researchers and practitioners who provided friendly reviews of the 46 evidence summaries. This research was conducted by the Ecological Levers for Health working group supported by the Science for Nature and People Partnership (SNAPP), a collaboration of The Nature Conservancy, the Wildlife Conservation Society, and the National Center for Ecological Analysis and Synthesis (NCEAS) at the University of California, Santa Barbara. KDL was supported by the U.S. Geological Survey Ecosystems Mission Area. CLW was supported by a Sloan Research Fellowship from the Alfred P. Sloan Foundation, an award from the National Science Foundation Division of Geosciences Biological Oceanography Program (OCE-1829509), and a University of Washington (UW) Innovation Award from the UW Innovation Imperative. AJM was supported by a National Science Foundation Postdoctoral Research Fellowship in Biology (#1611767) and by the National Science Foundation and the Fogarty International Center (DEB-2011147). NN was supported by the Bing Fellowship in Honor of Paul Ehrlich and the Stanford Data Science Scholars program. TSM is a Simons Foundation fellow of the Life Sciences Research Foundation. AJP was supported by a Queensland Government Accelerate Postdoctoral Research Fellowship and the DARPA PREEMPT program Cooperative Agreement # D18AC00031. AJL was supported by a James and Nancy Kelso Fellowship through the Stanford Interdisciplinary Graduate Fellowship (SIGF) program at Stanford University. IJJ was supported by a National Science Foundation Graduate Research Fellowship (#1656518). GADL and SHS were partially supported by the National Science Foundation (ICER-2024383 and DEB-2011179) and by the Bill & Melinda Gates Foundation (#OPP1114050). Any use of trade, product, or firm names in this publication is for descriptive purposes only and does not imply endorsement by the U.S. Government. Role of the funding sources: no funders played roles in the design, execution, or publication of this study.

Author contributions: CLW, IJJ, KDL, SRH, and SHS conceived the idea and designed the study; AJP, AJL, AJM, APD, CLW, IJJ, KDL, MEH, NN, SHO, SRH, and SHS designed the methods; AJP, AJL, AG, AJM, AEL, AMK, CLW, CL, DCGM, GADL, IJJ, JF, JCB, JVR, KJF, KDL, LHK, MC, MW, MEH, NN, SHO, SRH, SHS, TESM contributed case studies and/or performed experiments; SRH conducted formal data analysis; AJP, AJL, AJM, CLW, IJJ, KJF, NN, SHO, SRH, and SHS curated the data; all contributors contributed to writing and revision of the manuscript; AJP, AJL, AJM, CLW, CL, IJJ, JCB, KDL, LHK, NN, SHO, SRH, and SHS drafted figures and/or directed data visualization; KDL, SRH, and SHS provided oversight and leadership for the study; SRH and SHS managed and coordinated research planning and execution; DLC, KDL, and SHS acquired financial support for the project.

Conflict of Interest Statement: The authors declared no conflicts of interest.

Data Sharing Statement: The 46 evidence summaries are publicly available in a searchable database that can be accessed at this link: https://ecohealthsolutions.stanford.edu/research/win-win-solutions-people-and-nature

References:

1. Karesh, W. B. *et al.* Ecology of zoonoses: natural and unnatural histories. *The Lancet* **380**, 1936–1945 (2012).
2. Taylor, L. H., Latham, S. M. & Woolhouse, M. E. Risk factors for human disease emergence. *Philos. Trans. R. Soc. Lond., B, Biol. Sci.* **356**, 983–989 (2001).
3. White, R. J. & Razgour, O. Emerging zoonotic diseases originating in mammals: a systematic review of effects of anthropogenic land-use change. *Mammal Review* (2020) doi:10.1111/mam.12201.
4. Jones, K. E. *et al.* Global trends in emerging infectious diseases. *Nature* **451**, 990–993 (2008).
5. Jones, B. A. *et al.* Zoonosis emergence linked to agricultural intensification and environmental change. *PNAS* **110**, 8399–8404 (2013).
6. Faust, C. L. *et al.* Pathogen spillover during land conversion. *Ecol Lett* **21**, 471–483 (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*. https://ipbes.net/news/ipbes-global-assessment-summary-policymakers-pdf (2019).
8. Cohen-Shacham, E., Walters, G., Janzen, C. & Maginnis, S. *Nature-based Solutions to address global societal challenges*. (2016).
9. Whitmee, S. *et al.* Safeguarding human health in the Anthropocene epoch: report of The Rockefeller Foundation–Lancet Commission on planetary health. *The Lancet* **386**, 1973–2028 (2015).
10. U.N. Environment. *Global Environment Outlook 6*. http://www.unenvironment.org/resources/global-environment-outlook-6 (2019).
11. Berthe, F. C. J. *et al. Operational framework for strengthening human, animal and environmental public health systems at their interface*. 1–152 http://documents.worldbank.org/curated/en/703711517234402168/Operational-framework-for-strengthening-human-animal-and-environmental-public-health-systems-at-their-interface (2018).
12. United Nations. *Transforming our world: the 2030 Agenda for Sustainable Development*. (2015).
13. Dye, C. Expanded health systems for sustainable development. *Science* **359**, 1337–1339 (2018).
14. Naidoo, R. & Fisher, B. Reset Sustainable Development Goals for a pandemic world. *Nature* **583**, 198–201 (2020).

15. World Health Organization. *WHO Manifesto for a healthy recovery from COVID-19*. https://www.who.int/news-room/feature-stories/detail/who-manifesto-for-a-healthy-recovery-from-covid-19 (2020).

16. IPBES. *Workshop Report on Biodiversity and Pandemics of the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES)*. https://zenodo.org/record/4158500#.X6Faz5NKjPg (2020) doi:10.5281/zenodo.4158500.

17. Roche, B. *et al.* Was the COVID-19 pandemic avoidable? A call for a "solution-oriented" approach in pathogen evolutionary ecology to prevent future outbreaks. *Ecology Letters* **23**, 1557–1560 (2020).

18. Drexler, N. *et al.* Community-based control of the brown dog tick in a region with high rates of Rocky Mountain spotted fever, 2012-2013. *PLoS ONE* **9**, e112368 (2014).

19. Roche, B. *et al.* Water-borne transmission drives avian influenza dynamics in wild birds: The case of the 2005-2006 epidemics in the Camargue area. *Infection, Genetics and Evolution* **9**, 800–805 (2009).

20. Ostrom, E. A diagnostic approach for going beyond panaceas. *PNAS* **104**, 15181–15187 (2007).

21. Pooley, S., Fa, J. E. & Nasi, R. No conservation silver lining to Ebola. *Conserv Biol* **29**, 965–967 (2015).

22. Hopkins, S. R. *et al.* How to identify win–win interventions that benefit human health and conservation. *Nature Sustainability* 1–7 (2020) doi:10.1038/s41893-020-00640-z.

23. Kilpatrick, A. M., Salkeld, D. J., Titcomb, G. & Hahn, M. B. Conservation of biodiversity as a strategy for improving human health and well-being. *Philos Trans R Soc Lond B Biol Sci* **372**, (2017).

24. McKinnon, M. C., Cheng, S. H., Garside, R., Masuda, Y. J. & Miller, D. C. Sustainability: Map the evidence. *Nature News* **528**, 185 (2015).

25. McKinnon, M. C. *et al.* What are the effects of nature conservation on human well-being? A systematic map of empirical evidence from developing countries. *Environmental Evidence* **5**, 8 (2016).

26. Shackelford, G. E. *et al.* Evidence Synthesis as the Basis for Decision Analysis: A Method of Selecting the Best Agricultural Practices for Multiple Ecosystem Services. *Front. Sustain. Food Syst.* **3**, (2019).

27. Sutherland, W. J. & Wordley, C. F. R. A fresh approach to evidence synthesis. *Nature* **558**, 364–366 (2018).

28. Grant, M. J. & Booth, A. A typology of reviews: an analysis of 14 review types and associated methodologies. *Health Info Libr J* **26**, 91–108 (2009).

29. Cheng, S. H. *et al.* Using machine learning to advance synthesis and use of conservation and environmental evidence. *Conservation Biology* **32**, 762–764 (2018).

30. IUCN. *Threats Classification Scheme (Version 3.2)*. https://www.iucnredlist.org/resources/threat-classification-scheme (2018).

31. Streicker, D. G. *et al.* Ecological and anthropogenic drivers of rabies exposure in vampire bats: implications for transmission and control. *Proc. R. Soc. B* **279**, 3384–3392 (2012).

32. Syampungani, S., Chirwa, P. W., Akinnifesi, F. K., Sileshi, G. & Ajayi, O. C. The miombo woodlands at the cross roads: Potential threats, sustainable livelihoods, policy gaps and challenges. *Natural Resources Forum* **33**, 150–159 (2009).

33. Berthe, F. C. J. *et al. One health: operational framework for strengthening human, animal, and environmental public health systems at their interface*. 1–152 http://documents.worldbank.org/curated/en/961101524657708673/One-health-operational-framework-for-strengthening-human-animal-and-environmental-public-health-systems-at-their-interface (2018).

34. Zinsstag, J., Schelling, E., Waltner-Toews, D. & Tanner, M. From "one medicine" to "one health" and systemic approaches to health and well-being. *Prev Vet Med* **101**, 148–156 (2011).

35. Fiorella, K. J. *et al.* Human health alters the sustainability of fishing practices in East Africa. *Proc Natl Acad Sci U S A* **114**, 4171–4176 (2017).

36. Maxwell, S. L., Fuller, R. A., Brooks, T. M. & Watson, J. E. M. Biodiversity: The ravages of guns, nets and bulldozers. *Nature News* **536**, 143 (2016).

37. Plowright, R. K. *et al.* Pathways to zoonotic spillover. *Nature Reviews Microbiology* **15**, 502–510 (2017).

38. Loh, E. H. *et al.* Targeting Transmission Pathways for Emerging Zoonotic Disease Surveillance and Control. *Vector Borne Zoonotic Dis* **15**, 432–437 (2015).

39. Abbott, R. C., Osorio, J. E., Bunck, C. M. & Rocke, T. E. Sylvatic Plague Vaccine: A New Tool for Conservation of Threatened and Endangered Species? *EcoHealth* **9**, 243–250 (2012).

40. Guerra, C. A., Snow, R. W. & Hay, S. I. A global assessment of closed forests, deforestation and malaria risk. *Ann Trop Med Parasitol* **100**, 189–204 (2006).

41. Tucker Lima, J. M., Vittor, A., Rifai, S. & Valle, D. Does deforestation promote or inhibit malaria transmission in the Amazon? A systematic literature review and critical appraisal of current evidence. *Philos Trans R Soc Lond B Biol Sci* **372**, (2017).

42. Sokolow, S. H. *et al.* Ecological interventions to prevent and manage zoonotic pathogen spillover. *Philosophical Transactions of the Royal Society B: Biological Sciences* **374**, 20180342 (2019).

43. Seddon, N. *et al.* Getting the message right on nature-based solutions to climate change. *Global Change Biology* **n/a**,.

44. Allan, B. F. *et al.* Invasive honeysuckle eradication reduces tick-borne disease risk by altering host dynamics. *PNAS* **107**, 18523–18527 (2010).

45. Sokolow, S. H. *et al.* Reduced transmission of human schistosomiasis after restoration of a native river prawn that preys on the snail intermediate host. *PNAS* **112**, 9650–9655 (2015).

46. De Martis, G., Mulas, B., Malavasi, V. & Marignani, M. Can Artificial Ecosystems Enhance Local Biodiversity? The Case of a Constructed Wetland in a Mediterranean Urban Context. *Environ Manage* **57**, 1088–1097 (2016).

47. Yavinsky, R., Lamere, C., Patterson, K. & Bremner, J. *The Impact of Population, Health, and Environment Projects*. 46 (2015).

48. Webb, K. Planetary health in the tropics: how community health-care doubles as a conservation tool. *The Lancet Global Health* **6**, S28 (2018).

49. Jones, I. J. *et al.* Improving rural health care reduces illegal logging and conserves carbon in a tropical forest. *PNAS* **117**, 28515–28524 (2020).

50. D'agnes, L., D'agnes, H., Schwartz, J. B., Amarillo, M. L. & Castro, J. Integrated management of coastal resources and human health yields added value: a comparative study in Palawan (Philippines). *Environmental Conservation* **37**, 398–409 (2010).

51. Harris, A., Mohan, V., Flanagan, M. & Hill, R. Integrating family planning service provision into community-based marine conservation. *Oryx* **46**, 179–186 (2012).

52. Carney, R. M., Husted, S., Jean, C., Glaser, C. A. & Kramer, V. L. Efficacy of Aerial Spraying of Mosquito Adulticide in Reducing Incidence of West Nile Virus, California, 2005 - Volume 14, Number 5—May 2008 -

Emerging Infectious Diseases journal - CDC. *Emerging Infectious Diseases* (2008) doi:10.3201/eid1405.071347.

53. Wheeler, S. S. *et al.* Differential Impact of West Nile Virus on California Birds. *cond* **111**, 1–20 (2009).
54. D'Odorico, P. *et al.* The Global Food-Energy-Water Nexus. *Reviews of Geophysics* **56**, 456–531 (2018).
55. Fayer, R., Dubey, J. P. & Lindsay, D. S. Zoonotic protozoa: from land to sea. *Trends in Parasitology* **20**, 531–536 (2004).
56. Cabello, F. C. *et al.* Antimicrobial use in aquaculture re-examined: its relevance to antimicrobial resistance and to animal and human health. *Environ. Microbiol.* **15**, 1917–1942 (2013).
57. Galloway, J. N. *et al.* Transformation of the Nitrogen Cycle: Recent Trends, Questions, and Potential Solutions. *Science* **320**, 889–892 (2008).
58. Hess-Erga, O.-K., Moreno-Andrés, J., Enger, Ø. & Vadstein, O. Microorganisms in ballast water: Disinfection, community dynamics, and implications for management. *Science of The Total Environment* **657**, 704–716 (2019).
59. Lu, H., McComas, K. A., Buttke, D. E., Roh, S. & Wild, M. A. A One Health Message about Bats Increases Intentions to Follow Public Health Guidance on Bat Rabies. *PLOS ONE* **11**, e0156205 (2016).
60. Khan, S. U. *et al.* A randomized controlled trial of interventions to impede date palm sap contamination by bats to prevent nipah virus transmission in Bangladesh. *PLoS ONE* **7**, e42689 (2012).
61. Nahar, N. *et al.* A Controlled Trial to Reduce the Risk of Human Nipah Virus Exposure in Bangladesh. *EcoHealth* **14**, 501–517 (2017).
62. Dherani, M. *et al.* Indoor air pollution from unprocessed solid fuel use and pneumonia risk in children aged under five years: a systematic review and meta-analysis. *Bull World Health Organ* **86**, 390–398 (2008).
63. Azevedo-Santos, V. M., Vitule, J. R. S., Pelicice, F. M., García-Berthou, E. & Simberloff, D. Nonnative Fish to Control Aedes Mosquitoes: A Controversial, Harmful Tool. *BioScience* **67**, 84–90 (2017).
64. Keesing, F., Holt, R. D. & Ostfeld, R. S. Effects of species diversity on disease risk. *Ecol. Lett.* **9**, 485–498 (2006).
65. Salkeld, D. J., Padgett, K. A. & Jones, J. H. A meta-analysis suggesting that the relationship between biodiversity and risk of zoonotic pathogen transmission is idiosyncratic. *Ecol. Lett.* **16**, 679–686 (2013).

66. Masuzawa, T. *et al.* Leptospirosis in Squirrels Imported from United States to Japan. *Emerg Infect Dis* **12**, 1153–1155 (2006).
67. Smith, K. M. *et al.* Summarizing US Wildlife Trade with an Eye Toward Assessing the Risk of Infectious Disease Introduction. *EcoHealth* **14**, 29–39 (2017).
68. Martel, A. *et al.* Recent introduction of a chytrid fungus endangers Western Palearctic salamanders. *Science* **346**, 630–631 (2014).
69. Dirzo, R. *et al.* Defaunation in the Anthropocene. *Science* **345**, 401–406 (2014).
70. Bonwitt, J. *et al.* Unintended consequences of the 'bushmeat ban' in West Africa during the 2013–2016 Ebola virus disease epidemic. *Social Science & Medicine* **200**, 166–173 (2018).
71. Golden, C. D., Fernald, L. C. H., Brashares, J. S., Rasolofoniaina, B. J. R. & Kremen, C. Benefits of wildlife consumption to child nutrition in a biodiversity hotspot. *PNAS* **108**, 19653–19656 (2011).
72. Brashares, J. S. *et al.* Bushmeat hunting, wildlife declines, and fish supply in West Africa. *Science* **306**, 1180–1183 (2004).
73. Eskew, E. A. & Carlson, C. J. Overselling wildlife trade bans will not bolster conservation or pandemic preparedness. *The Lancet Planetary Health* **4**, e215–e216 (2020).
74. Seytre, B. Erroneous Communication Messages on COVID-19 in Africa. *The American Journal of Tropical Medicine and Hygiene* (2020) doi:10.4269/ajtmh.20-0540.
75. Zhang, L. & Yin, F. Wildlife consumption and conservation awareness in China: a long way to go. *Biodivers Conserv* **23**, 2371–2381 (2014).
76. Walzer, C. COVID-19 and the Curse of Piecemeal Perspectives. *Front. Vet. Sci.* **7**, (2020).
77. Markandya, A. *et al.* Counting the cost of vulture decline--An appraisal of the human health and other benefits of vultures in India. *Ecological Economics* **67**, 194–204 (2008).
78. Martin, J.-L., Chamaillé-Jammes, S. & Waller, D. M. Deer, wolves, and people: costs, benefits and challenges of living together. *Biological Reviews* **95**, 782–801 (2020).
79. OECD. *Addressing societal challenges using transdisciplinary research*. 80 https://www.oecd-ilibrary.org/science-and-technology/addressing-societal-challenges-using-transdisciplinary-research_0ca0ca45-en (2020).

80. Muñoz-Pedreros, A., Gil, C., Yáñez, J. & Rau, J. R. Raptor habitat management and its implication on the biological control of the Hantavirus. *Eur J Wildl Res* **56**, 703–715 (2010).

81. Tallis, H. *et al.* Aligning evidence generation and use across health, development, and environment. *Current Opinion in Environmental Sustainability* **39**, 81–93 (2019).

82. Cleaveland, S., Kaare, M., Tiringa, P., Mlengeya, T. & Barrat, J. A dog rabies vaccination campaign in rural Africa: impact on the incidence of dog rabies and human dog-bite injuries. *Vaccine* **21**, 1965–1973 (2003).

83. Randall, D. A. *et al.* An integrated disease management strategy for the control of rabies in Ethiopian wolves. *Biological Conservation* **131**, 151–162 (2006).

84. Keitt, B. S. & Tershy, B. R. Cat eradication significantly decreases shearwater mortality. *Animal Conservation* **6**, 307–308 (2003).

85. Pender, R. J., Shiels, A. B., Bialic-Murphy, L. & Mosher, S. M. Large-scale rodent control reduces pre- and post-dispersal seed predation of the endangered Hawaiian lobeliad, Cyanea superba subsp. superba (Campanulaceae). *Biol Invasions* **15**, 213–223 (2013).

86. Tait, P., Saunders, C., Nugent, G. & Rutherford, P. Valuing conservation benefits of disease control in wildlife: A choice experiment approach to bovine tuberculosis management in New Zealand's native forests. *Journal of Environmental Management* **189**, 142–149 (2017).

87. de Wit, L. A. *et al.* Potential public health benefits from cat eradications on islands. *PLoS Negl Trop Dis* **13**, (2019).

88. Barnett, S. A. Rat control in a plague outbreak in Malta. *J Hyg (Lond)* **46**, 10-18.2 (1948).

89. Daigneault, A. J., Eppink, F. V. & Lee, W. G. A national riparian restoration programme in New Zealand: Is it value for money? *Journal of Environmental Management* **187**, 166–177 (2017).

90. Chazdon, R. L. Beyond Deforestation: Restoring Forests and Ecosystem Services on Degraded Lands. *Science* **320**, 1458–1460 (2008).

91. Herrera, D. *et al.* Upstream watershed condition predicts rural children's health across 35 developing countries. *Nature Communications* **8**, 811 (2017).

92. Braczkowski, A. R. *et al.* Leopards provide public health benefits in Mumbai, India. *Frontiers in Ecology and the Environment* **16**, 176–182 (2018).

93. Morters, M. K. *et al.* Evidence-based control of canine rabies: a critical review of population density reduction. *J Anim Ecol* **82**, 6–14 (2013).

94. Kibret, S., Wilson, G. G., Ryder, D., Tekie, H. & Petros, B. Can water-level management reduce malaria mosquito abundance around large dams in sub-Saharan Africa? *PLoS ONE* **13**, e0196064 (2018).

95. Kiernan, J. D., Moyle, P. B. & Crain, P. K. Restoring native fish assemblages to a regulated California stream using the natural flow regime concept. *Ecological Applications* **22**, 1472–1482 (2012).

96. Hoyer, I. J. *et al.* Mammal decline, linked to invasive Burmese python, shifts host use of vector mosquito towards reservoir hosts of a zoonotic disease. *Biol. Lett.* **13**, (2017).

97. Westgate, M. J., Likens, G. E. & Lindenmayer, D. B. Adaptive management of biological systems: A review. *Biological Conservation* **158**, 128–139 (2013).

98. The Mountain Gorilla Veterinary Project 2002 Employee Health Group. Risk of Disease Transmission between Conservation Personnel and the Mountain Gorillas: Results from an Employee Health Program in Rwanda. *EcoHealth* **1**, 351–361 (2004).

99. Gilardi, K. V. K. *et al. Best practice guidelines for health monitoring and disease control in great ape populations*. (IUCN SSC Primate Specialist Group, 2015).

100. Nature. Time to revise the Sustainable Development Goals. *Nature* **583**, 331–332 (2020).

101. WHO. *Global Health Estimates 2016: Disease burden by Cause, Age, Sex, by Country and by Region, 2000-2016*. (2018).

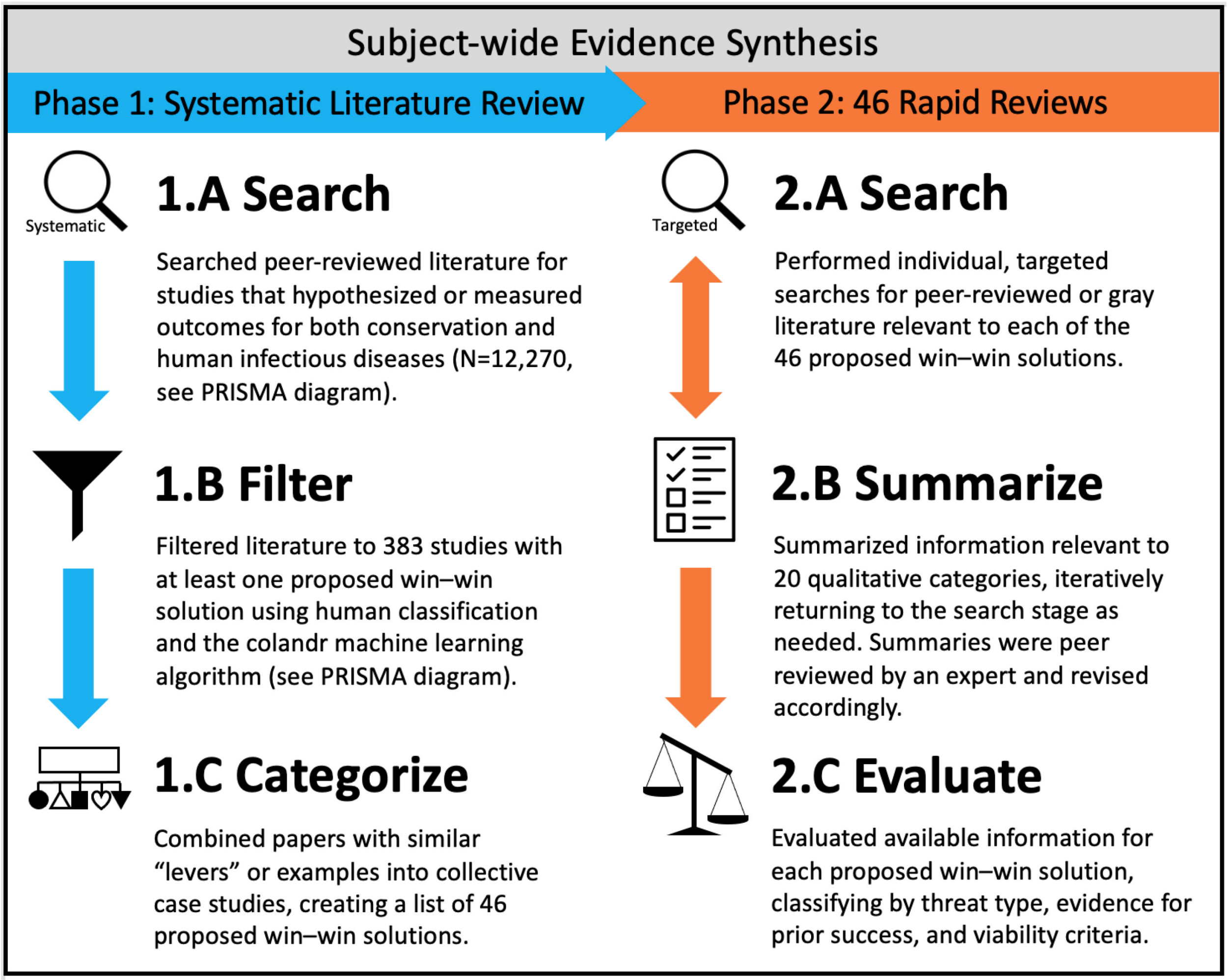

Fig. 1. To find, evaluate, and synthesize evidence from win–win solutions proposed to both reduce human infectious disease burdens and advance conservation goals, we used a subject-wide evidence synthesis. This method first uses a systematic literature review to identify a landscape of possible interventions and then each intervention is explored using an individual, targeted rapid review.[27] Phase 1 involved 10 researchers and Phase 2 involved 25 case study investigators and 44 external expert reviewers.

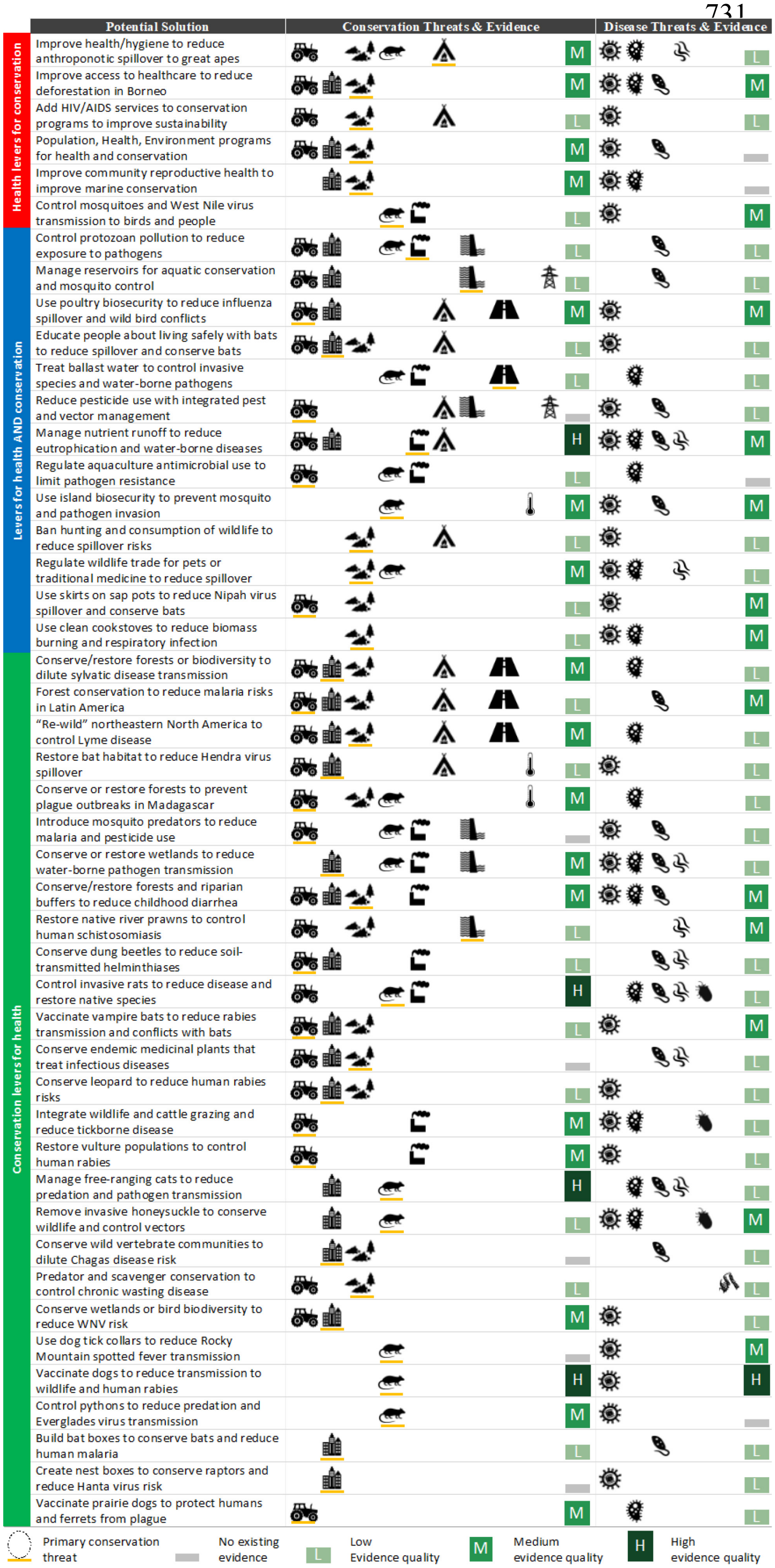

Fig 2. A menu of 46 potential solutions for advancing conservation goals and controlling human infectious diseases. For icon definitions, see Fig. 4.

Fig. 3. Six lose–lose scenarios that could be improved with win–win solutions that reduce human infectious disease burdens and advance conservation goals**.** *Health systems* that provide affordable healthcare in Indonesian Borneo reduce human disease burdens and illegal logging undertaken to pay for health care. *Vector control* is a public health intervention that might also benefit biodiversity, as in the case of North American birds susceptible to West Nile virus. *Law and policy* interventions that ban importation of non-native wildlife reservoirs (e.g., pouch rats) prevent spillover to humans and native wildlife. *Education and outreach* empower people to live safely with bats, reducing zoonotic spillover risk to people (e.g., Nipah virus) and potentially reducing human–bat conflicts. *Species management*, like vaccinating or sterilizing free-ranging domestic dog populations, reduces rabies transmission from dogs to humans and African carnivores. *Ecosystem management* interventions, like restoring wetland vegetation, reduce the survival of human and wildlife pathogens in the environment while restoring wildlife habitat. This figure was commissioned from artist Hiram Henriquez, and all photographs were either used under

creative commons licenses or purchased with commercial licenses (i.e., iStockphoto). Photographs of bamboo skirts were used with permission from Fernando Garcia and Nazmun Nahar.

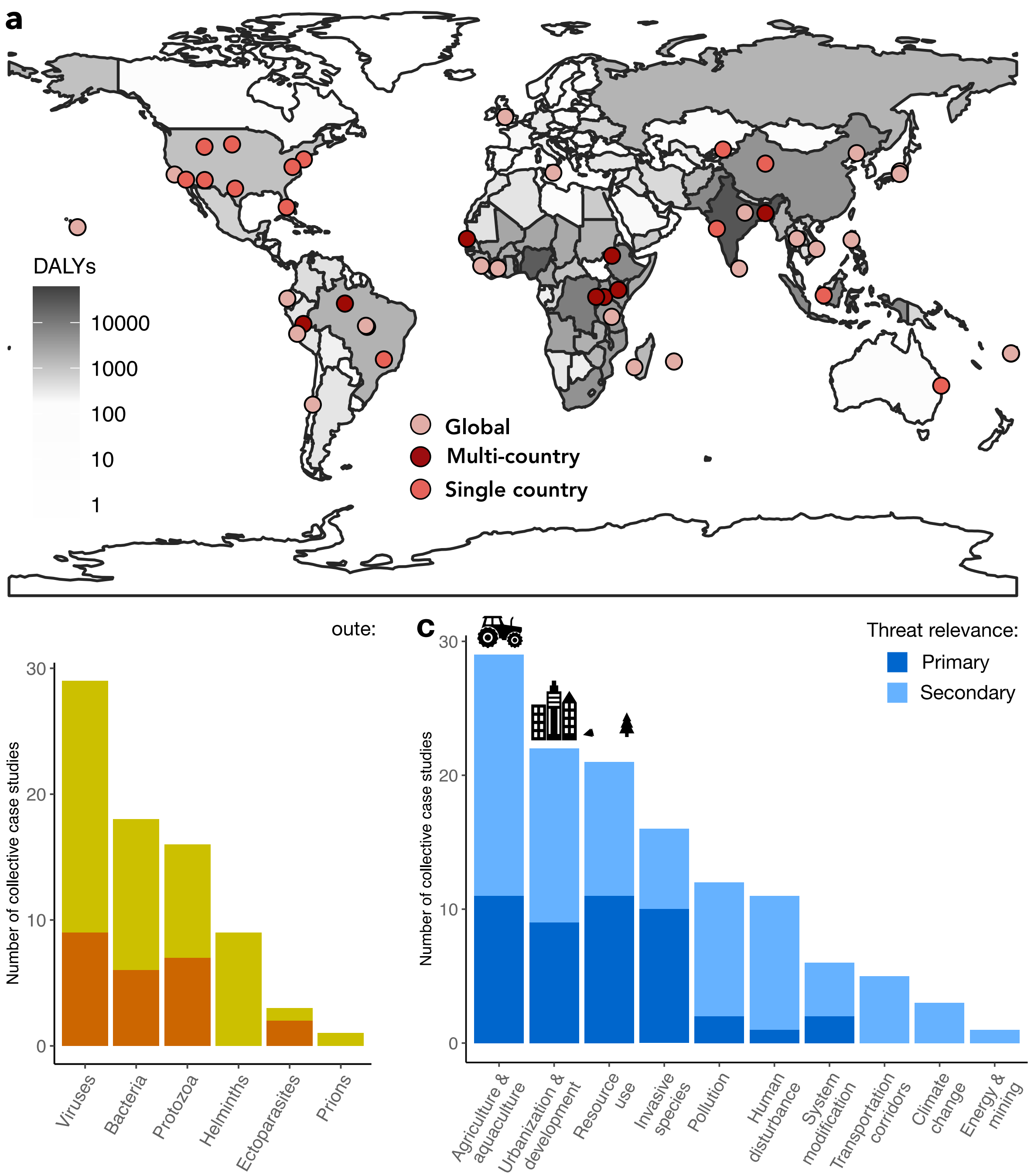

Fig. 4. Solutions are widespread and diverse. (A) The solutions covered all continents (except Antarctica), including countries with both high and low burdens of infectious diseases, as measured by total disability adjusted life years (DALYs) and reported by the World Health Organization for 2016.[101] (B) The solutions also covered most major pathogen taxa (except fungi) and transmission modes, where vector-borne transmission was the most common primary transmission mode across solutions. (C) Seven IUCN threat classes were considered the primary conservation threat addressed by at least one solution. In contrast, Transportation, Climate Change, and Energy and Mining were only ever secondary conservation threats addressed by any solution.

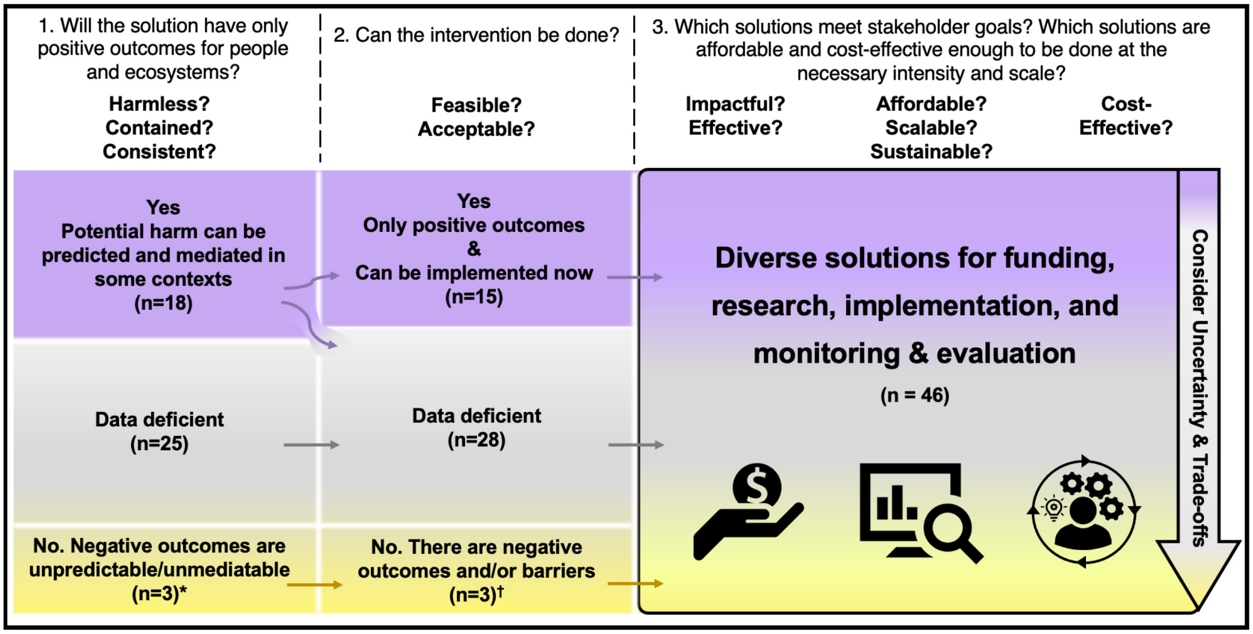

Fig. 5. Viable solutions can be identified and evaluated by 11 criteria. We evaluated five criteria to determine whether solutions were demonstrably *Harmless*, *Contained*, *Consistent*, *Feasible*, and *Acceptable* in some predictable contexts given evidence available now, or whether they were data deficient for those criteria. Stakeholders can evaluate six other criteria based on their priorities and resource constraints (*Impactful*, *Effective*, *Affordable*, *Scalable*, *Sustainable*, and *Cost-Effective*). *Three potential solutions had evidence for trade-offs that were at present unmitigable or unpredictable and were thus categorized as not *Harmless* (n=2) and/or not *Consistent* (n=2). All solutions were categorized as *Contained* or data deficient for the *Contained* criterion (not *Contained*: n=0). †No potential solutions had evidence for unmediatable barriers to implementation: not *Feasible* (n=0), not *Acceptable* (n=0).

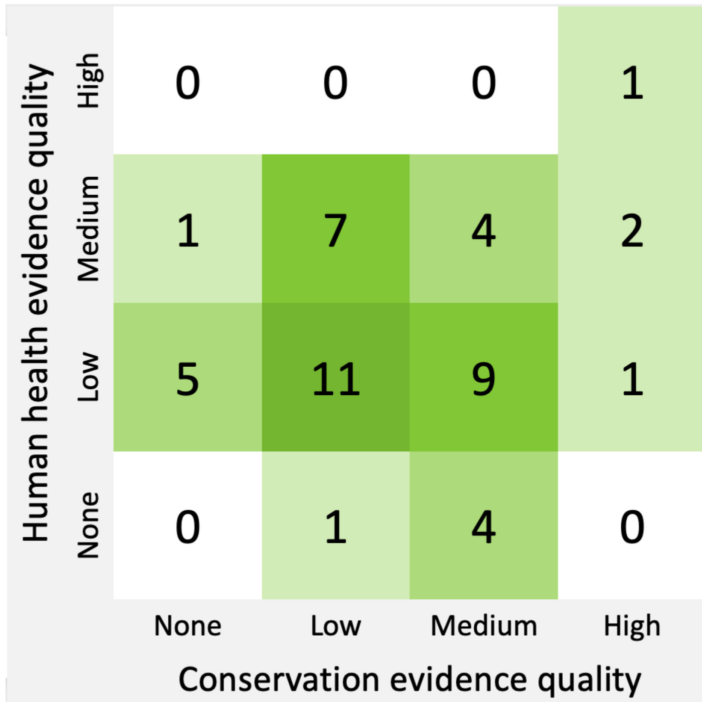

Fig. 6. Most solutions had evidence gaps. Each cell contains the number of solutions that had a given composite evidence quality score from rubrics based on evidence diversity, consistency, and applicability (None = hypotheses and anecdotes; Low = some supporting studies with moderate to major gaps, inconsistency, or limited applicability; Medium = several lines of evidence that are mostly consistent and applicable; and High = diverse, consistent, and highly applicable evidence leaves little to no uncertainty regarding the outcome). The green color scale is used to emphasize that most solutions were supported by low or medium evidence for conservation and/or health outcomes.