PNAS PERSPECTIVE

Reimagining infrastructure for a biodiverse future

Charles B. van Rees[a,b,1], Darixa D. Hernández-Abrams[c], Matthew Shudtz[b], Roderick Lammers[d], James Byers[a], Brian P. Bledsoe[b,e], Matthew V. Bilskie[b,e], Jon Calabria[b,f], Matthew Chambers[b,e], Emily Dolatowski[b,f], Susana Ferreira[b,g], Laura Naslund[a], Donald R. Nelson[b,h], Nathan Nibbelink[b,i], Burton Suedel[c], Amanda Tritinger[c], C. Brock Woodson[b,e], S. Kyle McKay[c], and Seth J. Wenger[a,b]

Edited by Arun Agrawal, University of Michigan, Ann Arbor, MI; received January 11, 2023; accepted September 25, 2023

Civil infrastructure will be essential to face the interlinked existential threats of climate change and rising resource demands while ensuring a livable Anthropocene for all. However, conventional infrastructure planning largely neglects the contributions and maintenance of Earth's ecological life support systems, which provide irreplaceable services supporting human well-being. The stability and performance of these services depend on biodiversity, but conventional infrastructure practices, narrowly focused on controlling natural capital, have inadvertently degraded biodiversity while perpetuating social inequities. Here, we envision a new infrastructure paradigm wherein biodiversity and ecosystem services are a central objective of civil engineering. In particular, we reimagine infrastructure practice such that 1) ecosystem integrity and species conservation are explicit objectives from the outset of project planning; 2) infrastructure practices integrate biodiversity into diverse project portfolios along a spectrum from conventional to nature-based solutions and natural habitats; 3) ecosystem functions reinforce and enhance the performance and lifespan of infrastructure assets; and 4) civil engineering promotes environmental justice by counteracting legacies of social inequity in infrastructure development and nature conservation. This vision calls for a fundamental rethinking of the standards, practices, and mission of infrastructure development agencies and a broadening of scope for conservation science. We critically examine the legal and professional precedents for this paradigm shift, as well as the moral and economic imperatives for manifesting equitable infrastructure planning that mainstreams biodiversity and nature's benefits to people. Finally, we set an applied research agenda for supporting this vision and highlight financial, professional, and policy pathways for achieving it.

nature-based solutions | climate change | sustainable development | conservation | future cities

1. Background

Humanity must confront a multitude of interlinked environmental and socio-economic challenges to achieve a sustainable and equitable Anthropocene (1–4), the alternatives to which are unacceptable (5, 6). Urgent and coordinated action is needed to address rising resource demands, accelerating impacts of climate change, and the ongoing degradation of Earth's ecological life support systems. The latter of these challenges is driven by declines in global biodiversity. We define biodiversity as more than just the number or richness of species in an area, but the variety and relative abundance of species, habitats, ecological functions, and genes in the natural environment. Civil infrastructure—including roads and bridges, dams and reservoirs, water treatment, navigation, stormwater and flood management, and coastal defenses—lies at the intersection of contemporary global sustainability challenges. Infrastructure development and management are central to supporting a growing human population, improving well-being, and providing resilience to global change. Furthermore, infrastructure systems are considered essential to the attainment of nearly three-quarters of the Sustainable Development Goals (7). However, future infrastructure development decisions also have far-reaching and potentially negative implications for biodiversity and environmental sustainability.

The health and functioning of Earth's biosphere determine the provisioning of ecological services like oxygen generation, food and fuel production, and water purification and storage that ultimately sustain life (8). These and many other ecosystem services and the ecological functions that maintain them are carried out, supported, and stabilized by biodiversity. As species extinctions and population declines continue, the quality, delivery, and dependability of those services are therefore eroded, leading to growing risks for society. Continued degradation of our biosphere also increases the likelihood and severity of existential threats like pandemics from emergent zoonotic diseases, against which biodiverse ecosystems act as a buffer (9, 10). The reality of these threats has prompted calls for ambitious and decisive action to protect biodiversity, such as protecting 30% of Earth's land and ocean area by 2030 (the 30 × 30 initiative) (11).

Author affiliations: [a]River Basin Center, Odum School of Ecology, University of Georgia, Athens, GA 30602; [b]Institute for Resilient Infrastructure Systems, University of Georgia, Athens, GA 30602; [c]Environmental Laboratory, U.S. Army Corps of Engineers Engineer Research and Development Center, Vicksburg, MS 39180; [d]Department of Environmental Engineering, Central Michigan University, Mount Pleasant, MI 48858; [e]School of Environmental, Civil, Agricultural, and Mechanical Engineering, College of Engineering, University of Georgia, Athens, GA 30602; [f]College of Environment and Design, University of Georgia, Athens, GA 30602; [g]College of Agricultural Economics, Department of Agricultural and Applied Economics, University of Georgia, Athens, GA 30602; [h]Department of Anthropology, College of Arts and Sciences, University of Georgia, Athens, GA 30602; and [i]Warnell School of Forestry and Natural Resources, University of Georgia, Athens, GA 30602

Author contributions: C.B.v.R., D.D.H.-A., M.S., R.L., J.B., B.P.B., M.V.B., J.C., M.C., E.D., S.F., L.N., D.R.N., N.N., B.S., A.T., C.B.W., S.K.M., and S.J.W. designed research; C.B.v.R., D.D.H.-A., M.S., S.F., L.N., D.R.N., N.N., and B.S. performed research; and C.B.v.R., D.D.H.-A., M.S., R.L., J.B., B.P.B., E.D., S.F., L.N., D.R.N., N.N., B.S., A.T., S.K.M., and S.J.W. wrote the paper.

The authors declare no competing interest.

This article is a PNAS Direct Submission.

[1]To whom correspondence may be addressed. Email: charles.vanrees@uga.edu.

This article contains supporting information online at https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.2214334120/-/DCSupplemental.

Published November 6, 2023.

Although efforts to address biodiversity loss are growing, they remain inadequate and disproportionately burden marginalized populations throughout the globe, while insufficiently recognizing conservation solutions that support Indigenous land relations or are compatible with shared- or mixed-use landscapes (12).

The present decade is a pivotal moment for global infrastructure development, with massive investments in conventional infrastructure revitalization and expansion on the scale of tens of trillions of US dollars planned worldwide (13). Industrialized nations, faced with aging civil infrastructure in which many assets have exceeded their planned lifespan, are revitalizing and rethinking their infrastructure portfolios (14). By contrast, in industrializing nations, particularly in the global South, new infrastructure investments must meet the needs of growing populations that are increasingly adopting the resource-intensive lifestyles of wealthier countries (15). How we meet these infrastructure needs will have far-reaching consequences due to path dependency or "lock-in," whereby choices made in the present commit decision-makers to a given path for years into the future (16). Due to the scale and lifespan of planned investments, infrastructure development decisions in the present decade will likely determine our global social–ecological trajectory for the next century or more. To help ensure a just and sustainable trajectory over that lengthy time horizon, it will be necessary to conceptualize biodiversity and environmental justice as an integrated part of infrastructure (17, 18). In other words, there is an urgent need for a new paradigm to guide infrastructure development and ensure that the coming wave of infrastructure investments delivers a sustainable and equitable future for all (1, 6, 19, 20).

One critical aspect of the necessary infrastructure paradigm shift is making biodiversity and its essential ecosystem services a core objective of infrastructure planning and management (20, 21) to facilitate nature-positive outcomes in human-dominated and mixed-use landscapes (12) at ecologically significant scales. The groundwork for this shift has already been laid in countries like the United States. For example, the US Infrastructure Investment and Jobs Act (IIJA) mentions the terms "habitat connectivity," "habitat restoration," and "natural infrastructure" 18, 14, and 17 times, respectively, and more than $25 billion is slated for the implementation and development of Nature-based Solutions (NbS) (22). It is critical to seize opportunities like these to implement a new approach to infrastructure for people and nature. Such an approach must go beyond expanding the accounting of benefits and instead manifest a realignment of the mission of infrastructure agencies (20).

In this perspective, we put forward an interdisciplinary vision that redefines the relationship between ecosystems, biodiversity, and infrastructure to one of synergy rather than conflict or mitigation. We envision a strategic, nature-positive approach that maximizes the equitable delivery of ecosystem services to people while leveraging the larger scale of infrastructure projects to promote meaningful conservation impacts. We draw from civil and environmental engineering, ecology, landscape architecture and design, conservation science, social science, economics, and environmental law to frame this vision, critically assess its necessity, and outline approaches to achieve it. Although we focus our in-depth analysis on the policies, funding mechanisms, and agencies of the United States to provide actionable guidance, we emphasize the importance of and potential for realizing this vision at a global scale and across different local contexts. Accordingly, this perspective is intended to highlight context-specific pathways for the United States, while starting a broader dialogue on how nature-positive infrastructure development might manifest elsewhere.

2. Infrastructure and Biodiversity—The Historical Context

Historically, civil infrastructure development has been an essential economic engine but also a driver of ecological degradation and biodiversity loss at the global scale (23–25). For example, levees, dams, and culverts are considered key factors in the widespread loss of freshwater biodiversity (26–29). In the Coosa River system in Alabama, 36 mollusk species were driven extinct by impoundments and related impacts (30), representing the greatest modern extinction event in North America. In coastal systems, seawalls, jetties, and breakwaters fragment natural habitat structures, alter erosion patterns, and are a large driver of biodiversity loss worldwide (31, 32). For example, coastal armoring and infrastructure development in China have greatly reduced the extent of tidal mudflats, exacerbating declines in migratory shorebirds (33, 34).

Conventional infrastructure practices also disproportionately burden and impact marginalized people. The role of infrastructure development in the disintegration of communities and perpetuation of environmental injustices through relocation, resettlement, gentrification, and other processes is well-documented at the global scale (35–38). Infrastructure projects can further reduce the well-being for marginalized populations by removing access to key ecosystem services (39–41), ultimately resulting in underserved urban populations living in the areas with the lowest biodiversity (42). Many historical approaches to biodiversity conservation, particularly the expulsion of communities from protected areas, have similarly harmed marginalized local peoples (43, 44).

In recent decades, 20th-century paradigms have matured, with increasing attention to social–ecological systems and justice in conservation (45) and an expansion of infrastructure objectives to include other societal cobenefits and ecosystem services (20). Infrastructure development impacts on biodiversity are increasingly accounted for, and mitigation frameworks like no-net-loss are a common solution in practice, although their efficacy has been called into question (46, 47). The emerging field of NbS, which involves deliberately harnessing ecosystem services and ecological functions to deliver infrastructure outcomes, ostensibly provides another step forward, with greater integration of ecological and societal outcomes (20, 48). However, the evidence base for their value to biodiversity conservation and to promoting social justice is limited and in need of thorough assessment (18, 49).

3. A Vision for Civil Infrastructure and Biodiversity

Although the historical progression of infrastructure practices shows a trend of increasing appreciation for ecosystem functions and biodiversity as well as social equity, further advancement along this trajectory will be necessary to achieve a sustainable

Anthropocene. A new paradigm in civil infrastructure is needed that acknowledges and leverages the increasing overlap ecological conservation, landscape planning, and infrastructure development, and seizes opportunity for synergy between them (20). Here, we present a vision for infrastructure that includes biodiversity as an asset, rather than a constraint or a liability. We argue that such an approach is key to addressing the coupled challenges of climate change adaptation, rising infrastructure demand, and biodiversity loss. Furthermore, we suggest that due to the interdigitation of ecological and social outcomes in many systems, this vision may also provide important opportunities to help reverse historical injustices sustained by conventional approaches in both infrastructure development and biodiversity conservation.

Our vision is more than an analytical tool or framework; it is a call to fundamentally rethink infrastructure development as an environmentally regenerative practice that can be carried out in ways that are ecologically sustainable and environmentally just. This vision manifests four essential principles: 1) ecosystem integrity and species conservation are explicit objectives from the outset of project planning; 2) infrastructure design and management strategically integrate biodiversity into diverse project portfolios that draw from a spectrum of conventional approaches to NbS and natural habitats; 3) ecosystem functions reinforce and enhance the performance and lifespan of infrastructure projects; and 4) civil engineering promotes environmental justice by counteracting legacies of social inequity and disenfranchisement stemming from conventional practices in infrastructure development and nature conservation (Fig. 1).

The first principle is in parallel with widespread calls for "mainstreaming biodiversity" and "nature-positive" operations across climate, conservation, finance, and other sectors (20, 21, 50, 51) but necessarily builds upon the foundation of mitigation-based frameworks (52) in seeking to enhance biodiversity, rather than minimize losses. From a procedural point of view, this means including forms of ecological restoration among design goals early in the planning process rather than viewing species and their habitats as constraints (53). This principle also necessitates synergistic infrastructure solutions that simultaneously deliver a broad range of services and impart greater resilience to infrastructure in a changing operating environment while supporting native ecosystems. The Ecological Stakeholder Analog concept (53, 54), originally developed for water resources management, is one example of a way to include nature at the outset of the decision-making process, rather than as an afterthought. van Rees and Reed (53) advocated for its use in stormwater management on O'ahu, Hawai'i, where the strategic placement of drainage swales and retention ponds could be leveraged to simultaneously increase habitat connectivity for endangered waterbirds.

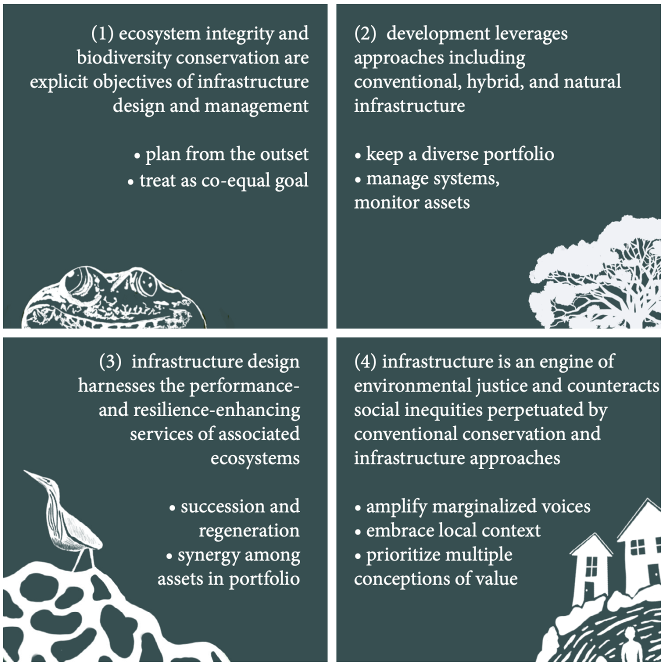

Fig. 1. A diagram of the four principles of nature-positive infrastructure development put forward in this perspective. In each case, key themes or practices to realizing that principle are highlighted beneath the principle itself.

The second principle necessitates that infrastructure development leverages approaches from conventional infrastructure, NbS, hybrid solutions, and intact natural systems (55, 56). This means that a gradient of natural, artificial, restored, and modified ecosystems and the functions they perform are necessary components of the 21st-century infrastructure toolbox (Fig. 2). We use the term NbS to refer to systems that utilize, rehabilitate, or mimic natural ecological processes, as well as ecological communities, ecosystems, and habitats that perform useful services for society, including civil infrastructure functions (48, 57). For instance, floodplain ecosystems, which improve water quality, lower peak flood heights, and provide important habitat, can be naturally existing or can be restored by removing flood barriers like levees (58). Importantly, biodiversity underpins the delivery of ecosystem services by NbS and natural infrastructure, necessitating its careful stewardship (59). Although many governments are calling for increased use of NbS worldwide, their implementation has not been explicitly tied to relevant and mission-critical biodiversity goals (18, 60).

Infrastructure approaches across the spectrum from artificial to natural can be leveraged to support biodiversity in different ways. For example, while the infrastructure services provided by wilderness areas and national forests are directly driven by biodiversity, necessitating its conservation and management, conventional infrastructure assets like dams may be intentionally operated in ways that support or reduce impacts on biodiversity (e.g., via environmental flows). Some infrastructure features like stormwater ponds might include biodiversity as an intended cobenefit, while others for which biodiversity benefits might be unintentional (e.g., seawalls as substrate for the larval settlement of sessile organisms or stream culverts as roost sites for bats) could be opportunistically modified to enhance biodiversity benefits (e.g., biofriendly concrete; Fig. 2).

In the context of this vision, we frame activities like monitoring, maintaining, and restoring ecosystems and the biodiversity that sustains them as a form of asset management (61, 62). These assets should be managed as systems of conventional and natural infrastructure features that work in concert, rather than in isolation, requiring coordination at the landscape scale (63). This thinking leads to the third key aspect of our vision, which centers around harnessing ecosystem services to enhance infrastructure functions and their resilient delivery under global change. In this context, the diverse

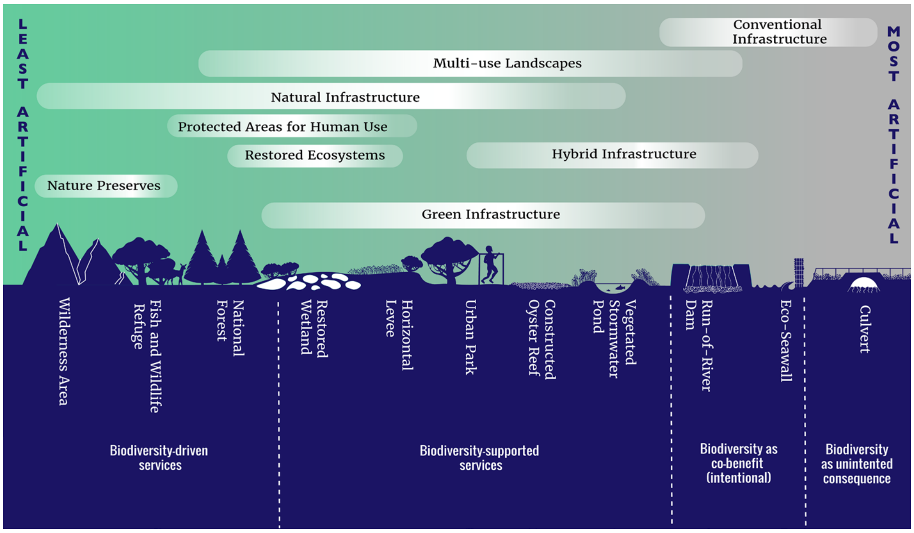

Fig. 2. The spectrum of infrastructure and land management practices can be strategically employed for biodiversity-positive infrastructure development. Examples of specific applications are found across the bottom (blue), while categorizations and commonly used terms are juxtaposed above.

portfolio of approaches necessitated by the second principle are viewed, managed, operated, and monitored as a single synergistic system for delivering myriad societal benefits. For example, protected and restored floodplains can reduce flood damage on adjacent infrastructure (56, 64), while mangroves, marshes, and coral reefs attenuate wave action and total water levels, complementing and enhancing other coastal protection (65, 66). Projects may benefit from the regenerative and self-reinforcing function of ecological succession over longer time scales, with ecological feedbacks that improve performance. For example, coastal vegetation communities mature over time after disturbance and stabilize barrier islands and marsh landscapes via soil accumulation and ecological succession (67). Embracing such feedbacks and synergies can help civil infrastructure transition from a paradigm of no-net-loss of biodiversity to one of net gain (68).

Finally, we argue that any new paradigm integrating civil infrastructure and biodiversity conservation must counteract their shared legacy of environmental injustice toward marginalized peoples. In other words, we consider it imperative that the coming wave of infrastructure investment be leveraged as an engine for promoting social equity. Accordingly, the distribution of benefits and costs stemming from infrastructure development and implementation under this paradigm must be equitable and cannot ignore or perpetuate historical injustices. Furthermore, infrastructure development under this paradigm must be viewed as an opportunity to deliberately counteract environmental inequities stemming from the economic development and biodiversity conservation practices of the past.

Recent research acknowledges the potential for NbS to combat societal inequity by providing more nuanced alternatives to the exclusionary practice of establishing protected areas (18, 49). Our paradigm broadens this approach to include other forms of conventional and green infrastructure, emphasizing the potential for promoting environmentally just outcomes where biodiversity enhancement becomes an infrastructure planning and management objective. For instance, by recognizing Indigenous land relations and species of cultural importance in the operation (via environmental flows; 69) or decommissioning of existing dams (70).

Ultimately, we see the realization of this vision as a fundamental change in the societal conception of infrastructure, spilling over into adjacent fields of land, water, and natural resources management. This will likely require a substantial expansion in the missions of existing infrastructure agencies in national governments and their stronger integration with other authorities responsible for other priorities like wildlife conservation, sustainable development, and health. We envision a global society in which major civil works are intentionally planned and designed to enhance biodiversity for economic, ecological, and ethical reasons and used as an instrument of environmental justice to counteract historic biases and inequities. Fully realized, this would mean including the biosphere as part of global infrastructure and working accordingly for its maintenance and continued function over long (multidecadal or greater) time scales.

4. The Basis and Need for a New Paradigm

Given the scale of this vision, it is worthwhile to consider the justifications and feasibility for achieving it, as the prospects of widespread adoption will depend substantially on precedent in existing policy and practice, as well as its ethical foundations. Below, we briefly summarize economic, legal, professional, and ethical considerations that may motivate a paradigm shift in civil infrastructure. Our narrative begins with the most widely recognized considerations and continues to less apparent ones, highlighting unrecognized precedence and the tacit moral foundation for this vision in prevailing concepts of environmental justice (Fig. 3).

4.1. Economic and Logistical Considerations. There is increasing evidence that projects embracing a natural capital approach can offer substantial cost savings over conventional solutions, especially when assessed over longer time scales (71). Compelling examples abound in contemporary literature. In the United States, watershed protection and green stormwater infrastructure provide US$ billions in cost savings for large cities (72, 73), while floodplain restorations in large river systems provide a cost-effective alternative to expensive levee repairs and provide substantial flood protection to agricultural and residential areas of the semi-arid West (58, 74, 75). NbS or Natural Infrastructure projects have the added economic advantage of reducing maintenance costs via ecological

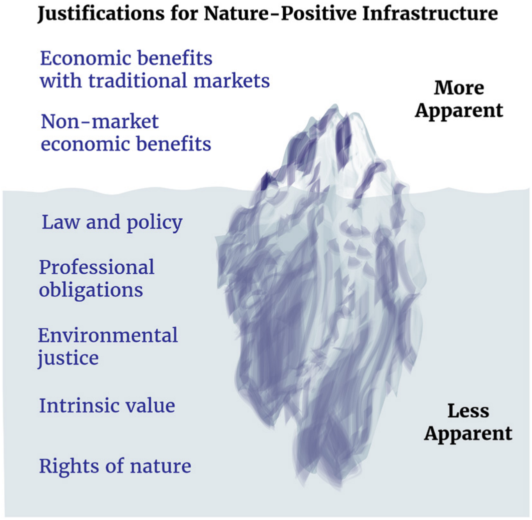

Fig. 3. An illustration of the many values and precedents that justify the inclusion of biodiversity in infrastructure management. While market and non-market economic benefits are increasingly recognized (above water), many other legitimate arguments remain largely neglected (below water).

self-repair and succession, while protecting and enhancing conventional infrastructure in the same system. This has been observed in floodplains (76) as well as coastal systems (65, 66, 77). These projects also deliver multiple ecosystem services, rather than the single functions of many traditional infrastructure projects, greatly expanding potential benefits (78, 79). However, it is also important to acknowledge the potential costs of widespread NbS implementation, both in property buyouts to provide sufficient space for restored or artificial ecosystems and in opportunity costs for areas that are protected or maintained for ecosystem services (80). These costs will require careful evaluation at local scales to ensure effective and equitable implementation.

Advances in economic valuation methods for nonmarketed ecosystem services may offer new avenues for integrating these multiple benefits into the cost–benefit decision-making (81–83). However, it is worth noting that integrating biodiversity per se into economic analyses is difficult; contemporary frameworks instead use an indirect, natural capital approach (71). All economic accounting systems face important challenges stemming from uncertainty in ecosystem dynamics and human preferences and may differ substantially among stakeholders and locales, posing a major obstacle to implementation (84, 85).

4.2. Precedent in Contemporary Law and Policy. The value of nature and the intent to protect it are strongly represented in US and international law, including the underlying theories and principles of said laws as well as enacted statements of purpose, procedural requirements, and substantive mandates (86) (*SI Appendix*, *Supporting Information* 2). Procedural mandates in US law (e.g., the National Environmental Policy Act (NEPA) and its state-level counterparts) also ensure that government agencies tasked with planning and permitting infrastructure projects consider the impacts of planned infrastructure on the environment, including cumulative effects. Other statutes have substantive mandates relevant to biodiversity protection and enhancement (23). Chief among them is the Endangered Species Act (ESA), which protects listed species' designated critical habitat and prohibits harmful impacts on individuals [16 U.S.C. § 1532(19)]. Although the species-centric structure of the ESA constrains its effectiveness in terms of broader ecosystem enhancement, there are success stories involving single-species protections that resulted in more extensive biodiversity improvements (87). Other legal mandates affecting infrastructure planning and design that specifically recognize biodiversity and the necessity for its protection are listed in *SI Appendix*, *Supporting Information* 3.

International law and policies outside of the United States also offer additional examples of thinking in line with a nature-positive infrastructure paradigm. The Rio Declaration on Environment and Development (88) recognized the key concept of sustainable development, and the Convention on Biological Diversity (89) encouraged parties to develop national strategies for the conservation and sustainable use of biodiversity. In countries like Bangladesh, Colombia, New Zealand, and Canada, some ecosystems or natural features have been awarded legal personhood (90), reinforcing the notion of including biodiversity in civil infrastructure decision-making.

4.3. Precedent from Professional Practice. The established codes of ethics and conduct of professional societies and licensing boards serve as important guideposts for defining what is and is not a professional responsibility in a field. Biodiversity outcomes appear directly and indirectly in such codes for many infrastructure-related disciplines. For instance, the National Society of Professional Engineers (NSPE)'s first "fundamental canon" centers on the "safety, health, and welfare of the public" (91). Global biodiversity directly affects human well-being and contributes materially to these central goals of the discipline. Many codes of ethics in the infrastructure community extend this directive and oblige professionals to "adhere to the principles of sustainable development," and "make every effort to enhance, respect, and restore the life-sustaining integrity of the landscape" (American Society of Landscape Architects) (92).

More broadly, many codes of professional practice and ethics emphasize obligations to public interests (not just clients), including environmental outcomes (93). Many professional organizations are modifying codes of ethics to match changing societal needs, revising them to emphasize emerging societal needs, and pushing professionals toward sustainable development. These professional practices pave the way for incorporating biodiversity goals in infrastructure development.

4.4. Moral and Equity Considerations. Biodiversity's intrinsic value (94) is an increasingly recognized consideration for its protection (95, 96), along with its contributions to people by supporting cultural diversity, food systems, language, and spirituality (97–99). It supports human health by reducing disease prevalence (100), improving mental well-being (101), and provisioning food, medicine, clean air, and water (102, 103). In supporting human well-being in such diverse ways, biodiversity and its protection can be considered well-aligned with the ultimate goals of infrastructure development. In many Indigenous ontologies, humans and nonhumans have multigenerational kinship which obligates reciprocity; by contrast, predominantly European, colonial, and neoliberal capitalist worldviews conceptualize people and nature as inherently separate (104, 105). A nature-positive infrastructure paradigm may provide both the opportunity to better honor Indigenous rights, sovereignty, and worldviews, but also a pathway for manifesting reciprocity and coequal support of human and nonhuman well-being in modern engineering practice (106). NbS in particular, perhaps the dominant toolset for achieving nature-positive infrastructure development, could potentially facilitate a transition away from the purely utilitarian valuation of nature to an ethos including relational value, a hallmark of many Indigenous ways of thinking (107). It is also worth acknowledging that stewardship of, and connection to, nature are not exclusively tenets of non-Western spirituality. For example, Pope Francis strongly communicated the necessity and collective responsibility of protecting biodiversity in his 2016 encyclical Laudato Si' (108).

The present capacity of people to experience biodiversity is inequitably distributed both intra- and inter-generationally (109), a situation for which current infrastructure practices are partly responsible (*Infrastructure and Biodiversity—The Historical Context*). Promoting nature-positive futures by integrating infrastructure development with biodiversity enhancement provides an opportunity to redirect implementation objectives to environmentally just outcomes, reducing inequities caused by development and conservation practices of the past (110).

5. Pathways and Strategies to Achieve the Vision

Realizing a shift to a nature-positive infrastructure paradigm at meaningful scales will be a massive undertaking, requiring policy, action, financial support, and interdisciplinary research from new knowledge to implementation frameworks. McKay et al. (20) briefly outlined four critical tasks that must be pursued to mainstream NbS for infrastructure development and increase coordination between civil engineering and conservation science. Here, we expand upon these directions and outline actions and priorities for manifesting nature-positive infrastructure development more broadly across policy, research, finance, and governance. We intend for this narrative to act as a starting point for much-needed conversations at local, national, and global scales. Due to the wide variety of legal contexts between nations, we focus on the United States for in-depth, actionable policy recommendations, but broaden our focus in other sections to frame recommendations around other topics for international application.

5.1. Institutional and Policy Actions. Strengthened social–ecological governance is required to avoid repeating historical failures in which infrastructure-related ecological degradation undermines human well-being among marginalized communities (111), perpetuating structural, political, and socioeconomic inequities (112, 113). Governance of infrastructure planning and development must include a justice and equity lens, acknowledging that social and behavioral engineering are implicated in infrastructure projects. Projects alter the way humans interact with the people and world around them and as much as they create possibilities, they also create constraints (114). Thus, it is critical that a justice and equity lens accounts not just for distribution of risks and benefits but also focuses on the representational and procedural aspects of equity. There are many ways that an individual project may cultivate equity in all aspects of planning, design, execution, and monitoring (115). However, unless there are high-level changes in policy and guidance that provide budget space, allow additional time, and define an increased scope to project planners, efforts are likely to be partial or detrimental to an equitable process. Such extensive changes to national policies must be tailored to the cultural, economic, and governance contexts of different regions and countries. Here, we highlight policy actions in a US context to provide a more in-depth analysis, with the intention that parallel actions are apparent for readers in other regions.

Numerous agencies in US federal and state governments have responsibilities for protecting nature and biodiversity, but there is no one entity with clear responsibility that can serve as a champion and leader. One potential solution would be to assign resources and authority around biodiversity conservation and management to a specific agency and thus move toward centralized responsibility. This would require statutory changes via an act of Congress, and the potential advantages and drawbacks of such an approach are worth careful consideration. Where new laws or policies are logistically prohibitive, executive action could initiate an interagency task force to better centralize efforts and to provide coordination around biodiversity enhancement.

As an alternative to the complex legislative and administrative undertaking that would be required to establish a centralized authority for biodiversity conservation and management, policymakers may consider narrower changes to existing statutory authorities that, individually and combined, would facilitate nature-positive infrastructure development. While Congress has not enacted many novel environmental statutes in recent decades, it has regularly updated infrastructure planning and development legislation, offering frequent entry points for nature-positive concepts and practices. Laws such as the Federal Surface Transportation Assistance Act, Water Resources Development Acts, and Clean Water Act define how certain infrastructure is planned, designed, and constructed. Congress could amend those laws with text that establishes enforceable mandates to promote biodiversity. To ensure that federal agencies are at least considering the impacts of their actions on biodiversity, Congress could also amend NEPA to clearly state the expectation that environmental assessments and environmental impact statements performed under NEPA must analyze direct, indirect, and cumulative impacts on biodiversity. Although such procedural analytical mandates do not ensure biodiversity-positive outcomes, they increase consideration and transparency.

Even without acts of Congress, there are opportunities for executive branch agencies to advance nature-positive infrastructure practices. The president, through executive orders, has the ability to promote broad policy objectives, research initiatives, and changes to administrative practices and interagency coordination. An executive order on biodiversity and infrastructure could promote the vision we have laid out in this article, but would require ongoing leadership and dedicated resources, which cannot be guaranteed across changing administrations. Individual agencies can also amend existing regulations to clarify expectations regarding promotion of biodiversity. The White House Council on Environmental Quality, for example, could amend its definition of environmental impacts to ensure that all NEPA analyses examine biodiversity impacts, as suggested above. The 2013 Principles, Requirements and Guidelines for Water and Land Related

Resources Implementation Studies (PR&G; 116) offer another administrative pathway. The PR&G require certain federal agencies to update their project evaluation policies to include the pursuit of "healthy and resilient ecosystems" as a guiding principle. The PR&G only apply to federal investments in water resources—e.g., US Army Corps of Engineers flood risk management projects—but the healthy and resilient ecosystem principle and others could be extended to apply to other types of infrastructure projects.

Substantial changes to existing evaluation and cost–benefit accounting procedures for infrastructure and development projects are necessary for making biodiversity an explicit, primary objective of infrastructure development. To include biodiversity in benefit–cost analysis, indicators of ecological health and conservation benefit will be necessary and must be accommodated in practice (*Financing a New Approach to Biodiversity and Infrastructure*). Ideally, this would involve quantifying and monetizing any changes in ecosystem services from implemented projects. The White House's Natural Capital Accounts initiative (117) may provide valuable conceptual tools for this effort, allowing for aspects of nature to be formally evaluated as natural assets and services.

5.2. Addressing Knowledge Gaps through Research and Professional Training. As a first step toward guiding global research to inform this paradigm, we suggest convening experts from engineering, landscape architecture, ecology, conservation biology, the social sciences, and other disciplines to set an applied research agenda for nature-positive infrastructure and NbS development. Such an agenda should emphasize 1) supporting evidence-based practice 2) closing knowledge gaps for widespread implementation of NbS and other nature-positive infrastructure, and 3) overcoming institutional inertia and operational challenges to facilitate implementation. Addressing these knowledge gaps will require strategic, applied research and knowledge synthesis of technical, biophysical, and social aspects of civil engineering practice. To use some US examples, joint meetings between groups like the American Society of Civil Engineers, the Society for Conservation Biology, and the American Anthropological Society, or special sessions in larger conferences like the American Geophysical Union or Ecological Society of America meetings would be a productive way to frame research priorities in multidisciplinary settings. Meetings could also provide training opportunities via workshops for current and future interdisciplinary professionals working in sustainable infrastructure projects.

A foundational knowledge gap for NbS in particular and nature-positive approaches in general is in facilitating widespread implementation and adoption at scale. Social sciences research, particularly identifying barriers to implementation and catalysts of societal change at disciplinary, political, and cultural levels will be particularly important. Also essential will be research on translating scientific knowledge into meaningful actions and identifying barriers and sources of inertia that constrain the development and implementation of nature-positive infrastructure at the project scale (63). Frameworks applying the practices of knowledge coproduction (118) to NbS would also be of great value in ensuring that development and management decisions are equitable and socially sustainable across locales of different historical, cultural, political, and ecological contexts. This is especially important as infrastructure projects begin to more explicitly consider biodiversity, given the close interdigitation of ecosystems and cultural value systems in many parts of the world (119). Such research will enable the necessary integration of expert- and target-driven (top–down) and community-driven (bottom–up) forces in generating infrastructure solutions that both follow a coordinated mission and are appropriate to local ecological and societal contexts.

An interdisciplinary research agenda should also collect, inventory, and synthesize evidence on the biodiversity benefits and impacts of different infrastructure projects to create guidelines, metrics, and tools for planning and implementation at different scales. This includes calling for new empirical research on a range of NbS across biomes and ecosystems, alongside meta-analyses of existing studies of conservation and infrastructure performance. Recent efforts to assess the evidence for the biodiversity benefits of NbS (18, 120) are a valuable start to this process. Specialized and strategic approaches to monitoring the interactions of ecosystems and Natural Infrastructure will be necessary to collect further empirical evidence of performance benefits. In this sense, every conservation, restoration, or infrastructure project can be treated as an experiment with specific research questions and opportunities for learning (121). Initiatives like the United Kingdom's nationwide biodiversity indicators (122) and the US National Nature Assessment (123) provide an excellent opportunity to develop an important evidence base for mainstreaming biodiversity in agency activities at the national scale.

The scientific and engineering communities must engage in the translation and distillation of existing and future knowledge on biodiversity and NbS to inform policy and practice. Quantitative or semiquantitative indices are urgently needed to facilitate the accounting of project effects (positive and negative) on biodiversity, and to compare management alternatives according to multiple criteria. The ability to monetize and compare the biodiversity benefits or costs of a given project depends on a functional framework providing units of accounting for biodiversity. While the recent Dasgupta Report (71) rightly suggests that biodiversity is practically unquantifiable, project planners nevertheless must balance biodiversity outcomes with other project costs and benefits. In the absence of a quantitative metric or metrics, biodiversity will either be valued at an arbitrary level or not at all. Even a flawed and limited metric may be more useful than excluding biodiversity from decision-making altogether, and the goal of any metric of biodiversity should be a functional basis in sound ecological and social science theory, not perfection. Formalizing such metrics will require the ecological and conservation communities to actively engage with environmental economists, engineers, and decision-makers. Pragmatic (even if imperfect) indices for assessing project performance around key biodiversity criteria will address major knowledge gaps for decision-making and implementation (*Institutional and Policy Actions*). Accordingly, the development of ecologically informed, transparent, and flexible frameworks for quantifying various facets of biodiversity in different social and ecological contexts should be a research priority at the global scale. The development of such frameworks should involve participation by governmental, academic, and private entities to ensure feasibility and legitimacy.

Training current and new generations of interdisciplinary professionals will be critical in implementing NbS and ensuring that the right infrastructure projects are done the right way, providing resilient services while enhancing biodiversity. Future civil engineers and conservation professionals must have a basic literacy in fields beyond their disciplinary expertise to facilitate the collaboration necessary for delivering on the promises of combined nature-infrastructure approaches. This will require more robust and flexible graduate programs for students in many related fields that promote collaboration and provide a common foundation of knowledge. Competitive grants for universities like the US NSF's Research Traineeship Program may be a useful model to proliferate. Providing training and upskilling opportunities for current practitioners in government and industry is also critical and could be accomplished via conference workshops, online training, and certificate programs.

5.3. Financing a New Approach to Biodiversity and Infrastructure. Realizing this ambitious vision for nature-positive infrastructure necessarily requires financial support at multiple levels. Increased awareness of how biodiversity loss puts economies, public health, and production at risk has led to calls for the private financial sector to engage in nature-positive finance (124). This involves allocating funds towards activities that enhance biodiversity and away from projects that harm it. Private financing of nature-positive projects remains small for at least three reasons: 1) These projects may not generate reliable revenue streams since the public goods they provide are not traded in markets; 2) projects require financial investments that are tailored to specific local conditions, which is both risky and time consuming; 3) investors lack standardized information regarding the outcome of these investments (71). Governments can help alleviate these limitations by changing incentive structures around financial investments. For instance, concessional finance comprises a range of financial and tax instruments aimed at encouraging private investment that brings projects to scale. One prominent example is blended finance which uses public funding (generally in the form of grants and guarantees to cover potential first losses, thus lowering investment risk) to mobilize sources of private funding. Other examples are enabling pooled funds, which aggregate several projects across geography and sectors into one fund to diversify risk, or the issuance of green bonds (125). Governments can also provide clear guidance and standards for these investments by legislating for a common taxonomy to describe the biodiversity impacts of projects (126).

Strategic investment in infrastructure projects that enhance biodiversity, including NbS, provides a pathway for private-sector investors to engage in a nature-positive way. Coordination with the private sector to link capital with opportunities for effective infrastructure investment would generate valuable support for broader implementation of Natural Infrastructure. The insurance sector may be an especially relevant suite of actors, given the risks presented by climate change and biodiversity loss and the large sums of capital that could be mobilized for nature-positive investments (51).

Given the public-good characteristics of the outcomes delivered by nature-positive infrastructure projects, public finance will continue to play a fundamental enabling role. Funding multipurpose infrastructure projects has the inherent advantage of drawing from diverse sources focused on different benefits, freeing up additional financial support (56). For example, a given multi-purpose infrastructure project might be funded by leveraging existing resource allocations and policy mandates around wildlife, ecosystem services, water quality, transportation, agricultural production, and energy (for examples of potential resources and agencies in the United States, see *SI Appendix*, *Supporting Information* 1). While flood hazard reduction benefits might be the initial motivation behind the creation of an urban pond, framing, and management of the project for wildlife habitat may provide opportunities for conservation-focused funding. Existing systems for managing payments for ecosystem services (127) could easily be adapted to include the specific ecological benefits and functions supported by NbS and multipurpose infrastructure projects.

The practice of natural asset management (61, 128) may greatly facilitate the use of diverse portfolios of natural, hybrid, and conventional infrastructure. Where accounting for biodiversity and ecosystems as natural capital is supported by new metrics and practices (see above sections), these aspects of the natural world can be managed and safeguarded as a form of wealth and considered in economic decision-making (129). Managing NbS, and the ecosystems and biodiversity with which they are connected, as strategic investments, is thus a key step in mainstreaming an approach to infrastructure development in the Anthropocene.

At the project scale, examining financial costs and benefits over longer time scales, or with lower or declining discount rates, may also better capture how ecological systems adapt, change, and provide services over longer periods of time (111, 112, 130). Although the ecological and broader societal costs of some conventional infrastructure approaches are increasingly well-studied, they remain unaccounted for in current cost–benefit accounting practices by some infrastructure agencies. A more comprehensive and longer-term accounting of project costs might also alter decision-making to better favor biodiversity positive and equitable outcomes.

6. Conclusions

A new paradigm for civil infrastructure development is needed to meet the challenges of the Anthropocene–one in which the maintenance and enhancement of biodiverse ecosystems is a primary and deliberate objective. Pursued sincerely and at scale with collaboration at national and global levels, such a vision might leverage the upcoming infrastructure investment boom to slow or reverse biodiversity declines while increasing the resilience of infrastructure to a changing climate and begin addressing prevailing social inequities and environmental injustice. While there is a historical trend toward and justification for this shift, it is nonetheless a major challenge. Its prospects of realization depend heavily on critical action and dialogue at local, national, and international scales in the near-term, and sustained investments and cultural and institutional changes in the long-term. The current, rising tide of investment and interest in infrastructure development and NbS across multiple governments, sectors, and stakeholders provides an excellent opportunity to begin the important and feasible work of making this vision a reality. Placing biodiversity and ecosystems at the core of civil infrastructure management and development, decision-makers will find a powerful pathway to address multiple global sustainability challenges simultaneously.

Climate adaptation, biodiversity conservation, and environmental justice challenges are ultimately global problems, requiring coordinated action guided by international agreements. Consequently, a global dialogue on mainstreaming biodiversity in civil infrastructure design and development is urgently needed. This dialogue must include under-represented voices, including those from Indigenous communities and lower-income countries that currently support the majority of the world's biodiversity, and which have been disproportionately burdened by prevailing conservation practices (131). A diverse dialogue will be especially important in equitably achieving nature-positive infrastructure and not placing all responsibility on actively industrializing countries. While international discourse on biodiversity conservation and its connections to issues like climate change has grown considerably, the ties between biodiversity and global infrastructure needs remain poorly recognized. A global summit or agenda item at an existing multinational meeting (e.g., the World Biodiversity Summit) would be an excellent starting point to catalyze a broader dialogue around NbS and nature-positive infrastructure development. Such activities may serve not only to disseminate knowledge of the value of nature-positive infrastructure but also build the necessary groundswell of enthusiasm and interest to drive a broader paradigm shift.

Data, Materials, and Software Availability. There are no data underlying this work.

ACKNOWLEDGMENTS. This research was conducted as part of the Network for Engineering with Nature (N-EWN, https://n-ewn.org) and was supported by the US Army Corps of Engineers Engineering with Nature® Initiative through Cooperative Ecosystem Studies Unit Agreement W912HZ-20-2-0031. The use of products or trade names does not represent an endorsement by either the authors or the N-EWN. Opinions expressed here are those of the authors and not necessarily those of the agencies they represent or the N-EWN. We are grateful to Sarah Buckleitner for sharing her talents in preparing and refining figures for this manuscript, Kelsey Broich for drafting additional art, and Virginia Bacon Talati for organizing logistics for workshops that led to the development of these ideas.

1. C. Kremen, A. M. Merenlender, Landscapes that work for biodiversity and people. *Science* **362**, eaau6020 (2018).
2. T. McPhearson *et al.*, Radical changes are needed for transformations to a good Anthropocene. *npj Urban Sustain.* **1**, 1–13 (2021).
3. E. M. Bennett, B. Reyers, "Navigating the dynamics of people-planet relationships: A social-ecological systems perspective" (UN University Centre for Policy Research and UN Environment Programme, 2022).
4. W. Baldwin-Cantello *et al.*, The Triple Challenge: Synergies, trade-offs and integrated responses for climate, biodiversity, and human wellbeing goals. *Climate Policy* **23**, 782–799 (2023).
5. J. Bluwstein *et al.*, Commentary: Underestimating the challenges of avoiding a ghastly future. *Front. Conserv. Sci.* **2**, 615419 (2021).
6. C. J. A. Bradshaw *et al.*, Response: Commentary: Underestimating the challenges of avoiding a ghastly future. *Front. Conserv. Sci.* **2**, 700869 (2021).
7. S. Thacker *et al.*, Infrastructure for sustainable development. *Nat. Sustain.* **2**, 324–331 (2019).
8. IPBES, "Thematic assessment report on the sustainable use of wild species of the intergovernmental science-policy platform on biodiversity and ecosystem services", J. M. Fromentin *et al.*, Eds. (IPBES Secretariat, 2022).
9. P. C. Williams *et al.*, Impact of climate change and biodiversity collapse on the global emergence and spread of infectious diseases. *J. Paediatr. Child Health* **57**, 1811–1818 (2021).
10. R. Dirzo, G. Ceballos, P. R. Ehrlich, Circling the drain: The extinction crisis and the future of humanity. *Philos. Trans. R Soc. B Biol. Sci.* **377**, 20210378 (2022).
11. E. Dinerstein *et al.*, A global deal for nature: Guiding principles, milestones, and targets. *Sci. Adv.* **5**, eaaw2869 (2019).
12. D. O. Obura *et al.*, Integrate biodiversity targets from local to global levels. *Science* **373**, 746–748 (2021).
13. Global Infrastructure Hub, "Global Infrastructure Outlook: Infrastructure Investment Needs" (Oxford Economics, Oxford, UK, 2022). https://outlook.gihub.org/countries/Canada. Accessed 19 December 2022.
14. D. Perera, V. Smakhtin, S. Williams, T. North, A. Curry, "Aging water storage infrastructure: An emerging global risk" (UNU-INWEH Report Series, Issue 11, United Nations Institute for Water, Environment, and Health, Hamilton, Canada, 2022).
15. H. Nagendra, X. Bai, E. S. Brondizio, S. Lwasa, The urban south and the predicament of global sustainability. *Nat. Sustain.* **1**, 341–349 (2018).
16. W. Barnes, M. Gartland, M. Stack, Old habits die hard: Path dependency and behavioral lock-in. *J. Econ. Issues* **38**, 371–377 (2004).
17. Z. J. Grabowski *et al.*, Infrastructures as socio-eco-technical systems: Five considerations for interdisciplinary dialogue. *J. Infrastruc. Syst.* **23**, 02517002 (2017).
18. C. B. van Rees *et al.*, The potential for nature-based solutions to combat the freshwater biodiversity crisis. *PLOS Water* **2**, e0000126 (2023).
19. S. Díaz *et al.*, Set ambitious goals for biodiversity and sustainability. *Science* **370**, 411–413 (2020).
20. S. K. McKay, S. J. Wenger, C. B. van Rees, B. P. Bledsoe, T. S. Bridges, Jointly advancing infrastructure and biodiversity conservation. *Nat. Rev. Earth Environ.* **4**, 675–677 (2023), 10.1038/s43017-023-00484-z.
21. E. J. Milner-Gulland *et al.*, Four steps for the Earth: Mainstreaming the post-2020 global biodiversity framework. *One Earth* **4**, 75–87 (2021).
22. The White House, "FACT SHEET: Biden-harris administration announces roadmap for nature-based solutions to fight climate change, strengthen communities, and support local economies" (The White House, 2022) (December 15, 2022).
23. M. W. Doyle, D. G. Havlick, Infrastructure and the environment. *Annu. Rev. Environ. Resour.* **34**, 349–373 (2009).
24. A. Benítez-López, R. Alkemade, P. A. Verweij, The impacts of roads and other infrastructure on mammal and bird populations: A meta-analysis. *Biol. Conserv.* **143**, 1307–1316 (2010).
25. T. Newbold *et al.*, Global effects of land use on local terrestrial biodiversity. *Nature* **520**, 45–50 (2015).
26. D. L. Strayer, D. Dudgeon, Freshwater biodiversity conservation: Recent progress and future challenges. *J. North Am. Benthol. Soc.* **29**, 344–358 (2010).
27. B. Collen *et al.*, Global patterns of freshwater species diversity, threat and endemism. *Global Ecol. Biogeogr.* **23**, 40–51 (2014).
28. C. B. van Rees *et al.*, Safeguarding freshwater life beyond 2020: Recommendations for the new global biodiversity framework from the European experience. *Conserv. Lett.* **14**, e12771 (2021).
29. C. J. Vörösmarty *et al.*, Global threats to human water security and river biodiversity. *Nature* **467**, 555–561 (2010).
30. C. Lydeard, R. L. Mayden, A diverse and endangered aquatic ecosystem of the Southeast United States. *Conserv. Biol.* **9**, 800–805 (1995).
31. M. L. McKinney, J. L. Lockwood, Biotic homogenization: A few winners replacing many losers in the next mass extinction. *Trends Ecol. Evol.* **14**, 450–453 (1999).
32. F. Bulleri, M. G. Chapman, The introduction of coastal infrastructure as a driver of change in marine environments. *J. Appl. Ecol.* **47**, 26–35 (2010).
33. C.-Y. Choi *et al.*, Biodiversity and China's new Great Wall. *Divers. Distrib.* **24**, 137–143 (2018).
34. Y. Li *et al.*, Identifying variable changes in wetlands and their anthropogenic threats bordering the Yellow Sea for water bird conservation. *Global Ecol. Conserv.* **27**, e01613 (2021).
35. F.-A. Hoover, S. Meerow, Z. J. Grabowski, T. McPhearson, Environmental justice implications of siting criteria in urban green infrastructure planning. *J. Environ. Policy Plann.* **23**, 665–682 (2021).
36. G. M. Rowangould, A census of the US near-roadway population: Public health and environmental justice considerations. *Transp. Res. D Trans. Environ.* **25**, 59–67 (2013).
37. T. Scudder, "Resettlement outcomes of large dams" in *Impacts of Large Dams: A Global Assessment* (Springer, 2011), pp. 37–67.
38. B. Tilt, Y. Braun, D. He, Social impacts of large dam projects: A comparison of international case studies and implications for best practice. *J. Environ. Manag.* **90**, S249–S257 (2009).
39. A. Lauer, D. English, M. Helton Richardson, How 'green energy' is threatening biodiversity, human health, and environmental justice: An example from the Mojave Desert, California. *Sustain. Environ.* **9**, 2192087 (2023).
40. C. E. Jennings, C. H. Reid, Fuller, Green infrastructure can limit but not solve air pollution injustice. *Nat. Commun.* **12**, 4681 (2021).
41. J. Langemeyer, J. J. Connolly, Weaving notions of justice into urban ecosystem services research and practice. *Environ. Sci. Policy* **109**, 1–14 (2020).
42. M. Leong, R. R. Dunn, M. D. Trautwein, Biodiversity and socioeconomics in the city: A review of the luxury effect. *Biol. Lett.* **14**, 20180082 (2018).
43. P. M. Schmidt, M. J. Peterson, Biodiversity conservation and indigenous land management in the era of self-determination. *Conserv. Biol.* **23**, 1458–1466 (2009).
44. N. van Vliet, "Bushmeat crisis" and "Cultural imperialism" in wildlife management? Taking value orientations into account for a more sustainable and culturally acceptable wildmeat sector. *Front. Ecol. Evol.* **6**, 112 (2018).
45. G. M. Mace, Whose conservation? *Science* **345**, 1558–1560 (2014).
46. S. O. S. E. zu Ermgassen *et al.*, The ecological outcomes of biodiversity offsets under "no net loss" policies: A global review. *Conserv. Lett.* **12**, e12664 (2019).
47. S. B. Hunter, S. O. S. E. zu Ermgassen, H. Downey, R. A. Griffiths, C. Howe, Evidence shortfalls in the recommendations and guidance underpinning ecological mitigation for infrastructure developments. *Ecol. Solutions Evidence* **2**, e12089 (2021).
48. C. Nesshöver *et al.*, The science, policy and practice of nature-based solutions: An interdisciplinary perspective. *Sci. Total Environ.* **579**, 1215–1227 (2017).
49. S. Woroniecki *et al.*, Contributions of nature-based solutions to reducing people's vulnerabilities to climate change across the rural Global South. *Climate Dev.* **15**, 590–607 (2023).
50. N. Frantzeskaki, T. McPhearson, Mainstream nature-based solutions for urban climate resilience. *BioScience* **72**, 113–115 (2022).
51. C. Kousky, Insurance-sector tools to combat biodiversity loss. *Science* **377**, 714–716 (2022).
52. M. Maron, *et al.*, 'Nature positive' must incorporate, not undermine, the mitigation hierarchy. *Nat. Ecol. Evol.* (2023), https://doi.org/10.1038/s41559-023-02199-2.

53. C. B. van Rees, J. M. Reed, Water diplomacy from a duck's perspective: Wildlife as stakeholders in water management. *J. Contemporary Water Res. Educ.* **155**, 28–42 (2015).
54. C. B. van Rees, J. R. Cañizares, G. M. Garcia, J. M. Reed, Ecological stakeholder analogs as intermediaries between freshwater biodiversity conservation and sustainable water management. *Environ. Policy Governance* **29**, 303–312 (2019).
55. F. Nakamura *et al.*, Adaptation to climate change and conservation of biodiversity using green infrastructure. *River Res. Appl.* **36**, 921–933 (2020).
56. J. J. Opperman, G. E. Galloway, Nature-based solutions for managing rising flood risk and delivering multiple benefits. *One Earth* **5**, 461–465 (2022).
57. World Wildlife Fund, "Nature-based Solutions for Climate Change" (WWF International, Geneva, Switzerland, 2020). https://wwfint.awsassets.panda.org/downloads/wwf_nature_based_solutions_for_climate_change_july_2020_final.pdf. Accessed 5 April 2023.
58. D. Smith, S. Miner, C. Theiling, R. Behm, J. Nestler, "Levee setbacks: An innovative, cost-effective, and sustainable solution for improved flood risk management" (Environmental Laboratory (U.S.), 2017), 10.21079/11681/22736 (December 5, 2022).
59. N. Seddon *et al.*, Getting the message right on nature-based solutions to climate change. *Global Change Biol.* **27**, 1518–1546 (2021).
60. I. B. Key *et al.*, Biodiversity outcomes of nature-based solutions for climate change adaptation: Characterising the evidence base. *Front. Environ. Sci.* **10**, 905767 (2022).
61. Municipal Natural Assets Initiative, "Integrating species at risk considerations into natural asset management: Results of a pilot project and considerations for future projects" (MNAI.ca, 2021) (December 5, 2022).
62. C. B. van Rees *et al.*, A framework to integrate innovations in invasion science for proactive management. *Biol. Rev.* **97**, 1712–1735 (2022).
63. D. R. Nelson, B. P. Bledsoe, S. Ferreira, N. P. Nibbelink, Challenges to realizing the potential of nature-based solutions. *Curr. Opin. Environ. Sustain.* **45**, 49–55 (2020).
64. K. B. Watson, T. Ricketts, G. Galford, S. Polasky, J. O'Niel-Dunne, Quantifying flood mitigation services: The economic value of Otter Creek wetlands and floodplains to Middlebury, VT. *Ecol. Econ.* **130**, 16–24 (2016).
65. I. Möller *et al.*, Wave attenuation over coastal salt marshes under storm surge conditions. *Nat. Geosci.* **7**, 727–731 (2014).
66. S. Narayan *et al.*, The effectiveness, costs and coastal protection benefits of natural and nature-based defences. *PLoS One* **11**, e0154735 (2016).
67. J. C. Zinnert *et al.*, Spatial-temporal dynamics in barrier island upland vegetation: The overlooked coastal landscape. *Ecosystems* **19**, 685–697 (2016).
68. J. Bull, S. Brownlie, The transition from No Net Loss to a Net Gain of biodiversity is far from trivial. *Oryx* **1**, 1–7 (2015).
69. E. P. Anderson *et al.*, Understanding rivers and their social relations: A critical step to advance environmental water management. *WIREs Water* **6**, e1381 (2019).
70. H. Randell, A. Curley, Dams and tribal land loss in the United States. *Environ. Res. Lett.* **18**, 094001 (2023).
71. P. Dasgupta, "The Economics of Biodiversity: The Dasgupta review: Full Report" (HM Treasury, 2021) Updated: 18 February 2021 (December 5, 2022).
72. National Research Council, "Watershed management for potable water supply: Assessing the New York city strategy" (National Academies Press, Washington, D.C., 2000), 10.17226/9677. Accessed 6 December 2022.
73. R. C. Brears, *Blue and Green Cities: The Role of Blue-Green Infrastructure in Managing Urban Water Resources* (Springer, 2018), pp. 153–183.
74. P. Skidmore, J. Wheaton, Riverscapes as natural infrastructure: Meeting challenges of climate adaptation and ecosystem restoration. *Anthropocene* **38**, 100334 (2022).
75. J. J. Opperman *et al.*, Sustainable floodplains through large-scale reconnection to rivers. *Science* **326**, 1487–1488 (2009).
76. B. G. Anderson, I. D. Rutherfurd, A. W. Western, An analysis of the influence of riparian vegetation on the propagation of flood waves. *Environ. Modelling Software* **21**, 1290–1296 (2006).
77. B. M. Webb *et al.*, "Nature-based solutions for coastal highway resilience: An implementation guide" (United States. Federal Highway Administration, 2019) (November 20, 2022).
78. S. Keesstra *et al.*, The superior effect of nature based solutions in land management for enhancing ecosystem services. *Sci. Total Environ.* **610–611**, 997–1009 (2018).
79. N. Seddon *et al.*, Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philos. Trans. R Soc B: Biol. Sci.* **375**, 20190120 (2020).
80. The Nature Conservancy, "Large-Scale Levee Setback Playbook: Based on the Missouri River L-536 Levee Setback Project Partners' Experience" (The Nature Conservancy, St. Louis, Missouri, 2021).
81. R. C. Bishop *et al.*, Putting a value on injuries to natural assets: The BP oil spill. *Science* **356**, 253–254 (2017).
82. E. English *et al.*, Estimating the value of lost recreation days from the Deepwater Horizon oil spill. *J. Environ. Econ. Manag.* **91**, 26–45 (2018).
83. B. Kriström, P. O. Johansson, Economic valuation methods for non-market goods or services. *Environ. Sci.* (2019), 10.1093/obo/9780199363445-0044.
84. U. Pascual *et al.*, "The economics of valuing ecosystem services and biodiversity" in *The Economics of Ecosystems and Biodiversity: Ecological and Economic Foundations* (2010), pp. 183–256.
85. N. Hanley, C. Perrings, The economic value of biodiversity. *Ann. Rev. Res. Econ.* **11**, 355–375 (2019).
86. S. Coyle, K. Morrow, *The Philosophical Foundations of Environmental Law: Property, Rights and Nature* (Bloomsbury Publishing, 2004).
87. M. Benson, Intelligent tinkering: The endangered species act and resilience. *Ecol. Soc.* **17**, 8 (2012).
88. The United Nations Conference on Environment and Development, "Rio declaration on environment and development" (United Nations, 1992) (November 21, 2022).
89. The United Nations, *Convention on Biological Diversity* (Treaty Collection, Rio de Janeiro, Brazil, 1992). https://wedocs.unep.org/20.500.11822/8340. Accessed 5 December 2022.
90. C. Clark, N. Emmanouil, J. Page, A. Pelizzon, Can you hear the rivers sing: Legal personhood, ontology, and the nitty-gritty of governance. *Ecol. LQ* **45**, 787 (2018).
91. National Society of Professional Engineers, "NSPE code of ethics for engineers" (NSPE, 2019), (December 5, 2022).
92. American Society of Landscape Architects, "ASLA Code of Environmental Ethics" (ASLA, 2017) (December 7, 2022).
93. M. A. Hersh, Environmental ethics for engineers. *Eng. Sci. Educ. J.* **9**, 13–19 (2000).
94. D. S. Maier, Should biodiversity and nature have to earn their keep? What it really means to bring environmental goods into the marketplace. *Ambio* **47**, 477–492 (2018).
95. A.-S. Tribot *et al.*, Taxonomic and functional diversity increase the aesthetic value of coralligenous reefs. *Sci. Rep.* **6**, 34229 (2016).
96. A. Leopold, *A Sand County Almanac* (Oxford University Press, 1949).
97. M. K. Nelson, *Original Instructions: Indigenous Teachings for a Sustainable Future* (Simon and Schuster, 2008).
98. L. J. Gorenflo, S. Romaine, R. A. Mittermeier, K. Walker-Painemilla, Co-occurrence of linguistic and biological diversity in biodiversity hotspots and high biodiversity wilderness areas. *Proc. Natl. Acad. Sci. U.S.A.* **109**, 8032–8037 (2012).
99. K. N. Irvine, D. Hoesly, R. Bell-Williams, S. L. Warber, "Biodiversity and spiritual well-being" in *Biodiversity and Health in the Face of Climate Change*, M. R. Marselle, J. Stadler, H. Korn, K. N. Irvine, A. Bonn, Eds. (Springer International Publishing, 2019), pp. 213–247.
100. G. H. Donovan, D. Gatziolis, I. Longley, J. Douwes, Vegetation diversity protects against childhood asthma: Results from a large New Zealand birth cohort. *Nat. Plants* **4**, 358–364 (2018).
101. J. Methorst, A. Bonn, M. Marselle, K. Böhning-Gaese, K. Rehdanz, Species richness is positively related to mental health–a study for Germany. *Landscape Urban Plann.* **211**, 104084 (2021).
102. J. R. Bernhardt, M. I. O'Connor, Aquatic biodiversity enhances multiple nutritional benefits to humans. *Proc. Natl. Acad. Sci. U.S.A.* **118**, e1917487118 (2021).
103. M. R. Marselle *et al.*, Pathways linking biodiversity to human health: A conceptual framework. *Environ. Int.* **150**, 106420 (2021).
104. T. Goldtooth, "Protecting the web of life: Indigenous knowledge and biojustice" in *Original Instructions: Indigenous Teachings for a Sustainable Future* (2008), pp. 220–228.
105. F. Ducarme, D. Couvet, What does 'nature' mean? *Palgrave Commun.* **6**, 1–8 (2020).
106. K. Fisher, M. Parsons, River co-governance and co-management in Aotearoa New Zealand: Enabling Indigenous ways of knowing and being. *Trans. Environ. Law* **9**, 455–480 (2020).
107. C. Maller, Re-orienting nature-based solutions with more-than-human thinking. *Cities* **113**, 103155 (2021).
108. G. Ceballos, I.V. Pope Francis' Encyclical Letter Laudato Si', Global environmental risks, and the future of humanity. *Q. Rev. Biol.* **91**, 285–295 (2016).
109. M. W. Hayward *et al.*, Intergenerational inequity: Stealing the joy and benefits of nature from our children. *Front. Ecol. Evol.* **10**, 28 (2022).
110. B. Walker *et al.*, Response diversity as a sustainability strategy. *Nat. Sustain.* **6**, 621–629 (2023), 10.1038/s41893-022-01048-7.
111. A. Bebbington *et al.*, Priorities for governing large-scale infrastructure in the tropics. *Proc. Natl. Acad. Sci. U.S.A.* **117**, 21829–21833 (2020).
112. A. Carse, Nature as infrastructure: Making and managing the Panama Canal watershed. *Soc. Stud. Sci.* **42**, 539–563 (2012).
113. S. Heck, Greening the color line: Historicizing water infrastructure redevelopment and environmental justice in the St. Louis metropolitan region. *J. Environ. Policy. Plann.* **23**, 565–580 (2021).
114. S. B. Pritchard, *Confluence: The Nature of Technology and the Remaking of the Rhône* (Harvard University Press, 2011).
115. C. K. Seigerman *et al.*, Operationalizing equity for integrated water resources management. *JAWRA J. Am. Water Resour. Assoc.* **59**, 281–298 (2023).
116. The White House, "Principles and requirements for federal investments in water resources" (The White House, 2013) (December 7, 2022).
117. The White House, "National strategy to develop statistics for environmental-economic decisions: A U.S. system of natural capital accounting and associated environmental-economic statistics" (The White House, 2022) (October 28, 2022).
118. C. A. Miller, C. Wyborn, Co-production in global sustainability: Histories and theories. *Environ. Sci. Policy* **113**, 88–95 (2020).
119. A. Schick *et al.*, People-centered and ecosystem-based knowledge co-production to promote proactive biodiversity conservation and sustainable development in Namibia. *Environ. Manag.* **62**, 858–876 (2018).
120. K. Brundiers, H. C. Eakin, Leveraging post-disaster windows of opportunities for change towards sustainability: A framework. *Sustainability* **10**, 1390 (2018).
121. C. B. van Rees *et al.*, A strategic monitoring approach for learning to improve natural infrastructure. *Sci. Total Environ.* **832**, 155078 (2022).
122. M. Sobkowiak, The making of imperfect indicators for biodiversity: A case study of UK biodiversity performance measurement. *Business Strat. Environ.* **32**, 336–352 (2023).
123. U.S. Global Change Research Program, U.S. National Nature Assessment. *Global Change* (2022) (December 7, 2022).
124. United Nations Environment Programme, "Financial sector guide for the convention on biological diversity" (United Nations Environment Programme, 2021) (December 21, 2022).
125. OECD, "A comprehensive overview of global biodiversity finance" (Organisation for Economic Cooperation and Development, 2020) (January 4, 2023).
126. European Commission, Platform on Sustainable Finance. https://finance.ec.europa.eu/sustainable-finance/overview-sustainable-finance/platform-sustainable-finance_en. Accessed 21 December 2022.
127. R. C. Brears, "Payments for ecosystem services financing nature-based solutions" in *Financing Nature-Based Solutions* (Springer, 2022), pp. 135–159.
128. P. Dasgupta, The economics of biodiversity: Afterword. *Environ. Resource Econ*. **83**, 1017–1039 (2022).
129. C. Brandon, K. Brandon, A. Fairbrass, R. Neugarten, Integrating natural capital into national accounts: Three decades of promise and challenge. *Rev. Environ. Econ. Policy* **15**, 134–153 (2021).
130. E. Whitelaw, E. MacMullan, A framework for estimating the costs and benefits of dam removal: Sound cost–benefit analyses of removing dams account for subsidies and externalities, for both the short and long run, and place the estimated costs and benefits in the appropriate economic context. *BioScience* **52**, 724–730 (2002).
131. S. T. Garnett *et al.*, A spatial overview of the global importance of Indigenous lands for conservation. *Nat. Sustain.* **1**, 369–374 (2018).