Nature-Based Solutions

EVIDENCE FOR HAZARD RISK REDUCTION AND ECOSYSTEM SERVICES

Scaling Up Implementation and Accelerating Learning

EXECUTIVE OFFICE of the PRESIDENT of the UNITED STATES
OFFICE OF SCIENCE AND TECHNOLOGY POLICY

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About This Publication

This report is an initiative of the White House Office of Science and Technology Policy (OSTP) to advance the Nature-Based Solutions Roadmap. This report was developed by Douglas Mason (OSTP), with technical support from a team led by Rebecca Miller (Science and Technology Policy Institute; STPI). It is the product of a collaboration among federal, academic, private sector, and civil society organizations. We owe our thanks to all the contributors to this effort, who are listed at the end of this report, for their valuable insights. We are especially grateful to Monica Dean and the University of Southern California Dornsife Public Exchange (PX) for co-hosting the June 18, 2024 Workshop on Science-Based Approach to Nature-Based Solutions.

STPI's support for this report was carried out under contract NSFOIA-0408601, Project TP-20-1005.GB, "Examining the Evidence for Nature-Based Solution (NBS) for Disaster-Resilient Infrastructure," for the Office of Science and Technology Policy. The views, opinions, and findings should not be construed as representing the official positions of the National Science Foundation or the sponsoring agency.

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The authors are grateful to Aliyah D. Averette and Patricia K. Sadiq for designing this report.

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SUMMARY

Climate change, development in hazard-prone areas, and the loss of services provided by natural systems are increasing risks to people, infrastructure, and economies. To manage these risks, we need to understand the performance of engineering systems (such as built or grey infrastructure) and nature-based solutions (such as green infrastructure) and how to best use them. Nature-based solutions are actions to protect, sustainably manage, or restore natural or modified ecosystems to address societal challenges such as reducing risks from natural hazards or improving air quality, and simultaneously provide benefits for people and the environment. To scale up their deployment, the Biden-Harris Administration released the ***Nature-Based Solutions Roadmap (2022)*** as part of an ambitious investment to address climate change and the loss of nature, including through the Bipartisan Infrastructure Act and the Inflation Reduction Act.

This report integrates academic and practitioner perspectives to evaluate the effectiveness of 23 nature-based solutions to address 7 hazards and provide 4 ecosystem services. It reflects inputs of representatives from 30 organizations. The assessment began with a review of the academic literature, parallel review by practitioners, and collaborative synthesis of the two. The effect of nature-based solutions on hazard mitigation or ecosystem services was assessed using a five-point scale ranging from no effect (indicated by 0), low effect (indicated by 1), intermediate effect (indicated by 2), strong effect (indicated by 3), and very strong effect (indicated by 4). Based on this review, participants developed recommendations to scale up nature-based solutions where supported by the evidence and accelerate learning to address knowledge gaps.

Evidence for Nature-Based Solutions: Findings

Nature-based solutions can address hazards and deliver environmental benefits. Positive effects of nature-based solutions on each of the 11 hazards and ecosystem services were evaluated. Positive effects refer to either reduction of hazard-related risk or expansion of societal or ecosystem benefits. While local context always matters, this report identifies potential for strong or very strong positive effects of nature-based solutions on each of the 11 hazards and ecosystem services evaluated.

Nature-based solutions can be used independently or in combination with built infrastructure as hybrid solutions. They can be applied from small to landscape scales. When accounting for a diverse range of performance outcomes, nature-based solutions can be more effective than grey infrastructure solutions, particularly for lower-intensity hazards. For high-intensity hazards, hybrid infrastructure (which combines built and natural elements) can be more effective than either solution on its own. Hybrid infrastructure should increasingly become a standard practice, particularly for high-intensity hazards for which nature-based and conventional infrastructure can work together for greater benefits.

Over time, nature-based solutions may be less expensive to maintain than conventional infrastructure. Nature-based solutions have the potential for self-repair and can adapt as the climate changes. They can be readily modified or repaired. Some solutions may strengthen over time rather than deteriorate. These factors can lower maintenance costs compared to conventional solutions and make nature-based solutions more attractive either alone or as part of a hybrid solution.

Conserving existing natural ecosystems can be the most cost-effective method for achieving immediate and long-lasting resilience. The return on investment for nature-based solutions can be high. In addition, nature-based solutions can be less expensive to implement and maintain than built infrastructure.

Nature-based solutions can produce a diversity of economic, social, and environmental benefits. The simultaneous provision of multiple benefits distinguishes them from conventional solutions, which are usually oriented toward fulfilling a limited function. The diverse benefits available from nature-based solutions are often not fully considered in benefit-cost analyses, leading to underestimates of their economic value. In addition, these ecosystem services are not always monetized in benefit-cost analyses. The diversity of benefits from nature-based solutions also enhances their sustainability.

Recommendations

Implementing nature-based solutions depends on the expertise, experience, and resources of a diversity of individuals and institutions. The recommendations provided here reflect that diversity, which includes actions by governmental, academic, civil society, and private sector institutions.

SYSTEMATICALLY CONSIDER NATURE-BASED SOLUTIONS

Developing policies and project requirements to consider nature-based solutions would expand their adoption. This is the approach taken by several agencies, including the ***Federal Emergency Management Agency's Federal Flood Risk Management Standard*** rule and ***Department of Housing and Urban Development's commitment*** to use nature-based floodplain management approaches, where practical.

- **Support community co-production of nature-based solutions.** Active engagement with relevant communities helps ensure decisions are informed by local knowledge (including local Indigenous Knowledge), perspectives, and needs.
- **Streamline permitting and reviews to accelerate implementation.** Natural and hybrid solutions can be harder to permit than conventional infrastructure, even for solutions with clear environment benefits.
- **Develop policy, requirement statements, standards, guidance, and reference materials for natural and hybrid infrastructure.** These will increase appropriate consideration, guide successful application and performance, and facilitate their adoption as accepted practice. Tools and techniques are needed to inform development of nature-based solutions that meet multiple objectives and perform effectively over time. Such materials should include best practices to account for benefits appropriately in benefit-cost analyses and tradeoff studies.
- **Improve communication of federal funding opportunities for nature-based solutions.** Significant federal and private funding is available to finance nature-based solutions. Yet given the complexity of funding streams, it is challenging to match projects and funding sources. Agencies need to eliminate barriers to ensure rapid deployment of these critical resources and improve interagency coordination and collaboration. In addition, federal grants could expand research opportunities and increase our understanding of nature-based solutions.

ACCELERATE RESEARCH, INNOVATION, AND ADAPTIVE LEARNING

Accelerating research and learning will inform application. Building knowledge will be particularly helpful in understanding the efficacy of nature-based solutions for specific hazards such as drought, heat waves, forest fires, ecosystems (such as marine offshore), geographies (such as low- and middle-income countries), and applications (such as benefit-cost analysis or monitoring and evaluation).

- **Improve ease of sharing information.** A clearinghouse could facilitate better information sharing, leading to more expansive implementation of nature-based solutions. In addition to technical documentation, it could include lessons learned about constraints, barriers, and opportunities. Such technical information sharing could help support partnership development, faster permitting, technical assistance, market viability assessment, and matchmaking to funding opportunities.
- **Build institutional and individual capacities to implement nature-based solutions.** One of the biggest local challenges in designing and implementing resilience strategies is a lack of technical expertise and experience. Workforce development for a diversity of professions—from design engineers, to contractors, to landscapers who will be maintaining these nature-based solutions—will enable implementation. Both formal (such as university or continuing education) and informal (such as events or webinars) training can be used to reach technical and general audiences.
- **Document performance of nature-based and conventional solutions.** Additional studies that evaluate the efficacy, multiple effects, and tradeoffs of nature-based and conventional solutions will help inform decision-making.
- **Accelerate research in less studied areas.** Less studied ecosystems include grasslands, savannas, and coral reefs. Other less studied topics include contexts like post-disaster recovery and humanitarian efforts, and underserved communities. Low- and middle-income countries are also less studied geographies. Research is also needed to understand the effectiveness of nature-based and conventional solutions as the climate changes. Given hybrid (green and grey) solutions may be the most effective approach in many circumstances, better understanding of how to most effectively integrate the two is also a priority.
- **Learn from experience through effective local engagement.** Local context always matters for nature-based solutions. There is a growing body of both evidence and on-the-ground experience to draw from that can inform future development of nature-based solutions.
- **Deepen engagement with academics, practitioners, and government agencies on the health and economic impacts of hazards and measures to mitigate them.** Increasing frequency and severity of hazards has led to higher health risks and economic costs. Future research should explore important questions such as how nature-based solutions can address these threats to public health and the economy.

Harnessing nature-based solutions can help address the hazards communities face (such as fires, floods, and heat waves), support public health, and catalyze economic development.

CONTEXT

Increasing risks to people and infrastructure

Climate change, economic development, and urbanization of hazard-prone areas have increased risks to people and infrastructure. In the 1980s, the United States experienced a $1 billion or more disaster (adjusted for 2023 dollars) on average every 4 months (Smith 2024). Today, such disasters occur in the United States every 2 weeks on average (Smith 2024). Globally, between 2015 and 2021, disasters resulted in economic losses of over $330 billion per year, and countries reported more than $261 billion in direct economic losses in addition to the destruction or damage of more than 140,000 critical infrastructure units and facilities (United Nations Office for Disaster Risk Reduction 2023).

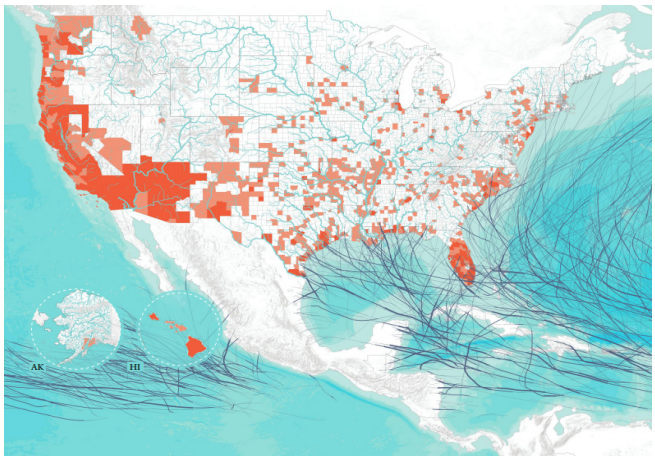


Figure 1. EPA's Disaster Resilient Design Concepts maps hurricane paths between 1842-2022 and counties most at risk for natural hazards.

Economic losses are driven by urbanization, an increasing number of assets in harm's way, and climate change, which will be a key driver of future losses (Swiss Re Institute 2024).

The fundamental challenge is how to address these risks. Two options are to use conventional or *grey* infrastructure (such as structures built with concrete and steel) and natural (or green) infrastructure that relies on natural features and services. The latter is often referred to as nature-based solutions: actions to protect, sustainably manage, or restore natural or modified ecosystems to address societal challenges, while simultaneously providing benefits for people and the environment (White House Council on Environmental Quality, White House Office of Science and Technology Policy, and White House Domestic Climate Policy Office 2022; IUCN n.d.).[1] These solutions offer opportunities to reduce risk from hazards and provide other ecosystem services. There is a diversity of nature-based solutions, across different designs and habitat types—including forests, oyster reefs, and prairies. In this report, we assess the existing evidence for how different types of nature-based solutions can provide societal and environmental benefits and identify recommendations for expanding their application.

Harnessing nature to reduce risks

Nature-based solutions can help address some of our biggest challenges, including adapting to risks associated with hazards such as fires, floods, and heat waves (Sudmeier-Rieux et al 2021; Zavar and Lavy 2021; Seddon 2022; Ferrario et al. 2024, Bertram et al. 2024), as well as emissions mitigation, such as through carbon sequestration (Buma et al. 2024). To scale up their deployment, the Biden-Harris Administration released the ***Nature-Based Solutions Roadmap (2022)***. As the Roadmap underscores, to implement nature-based solutions effectively, we need to understand where and when they are most effective and integrate them into resilience-enhancing investments (The White House Council on Environmental Quality, White House Office of Science and Technology Policy, and White House Domestic Climate Policy Office 2022).

1 Nature-based solutions may also include blue infrastructure, which refers to water-based natural systems like rivers, ponds, and wetlands. We use the term nature-based solutions in this report to refer to the many types of green, blue, or hybrid infrastructure.

METHODS

The White House Office of Science & Technology Policy (OSTP) led a collaborative process to develop a shared understanding of the evidence base for nature-based solutions. To integrate academic and practitioner perspectives, the University of Southern California Dornsife Public Exchange (PX) co-hosted the Workshop on the Science-Based Approach to Nature-Based Solutions in June 2024. This work reflects the contributions of thought leaders from more than 30 public, private, academic, and civil society organizations that participated involved in planning, implementing, and evaluating nature-based solutions.

The goal of this research workshop was to assess the overall effectiveness of nature-based solutions and to identify which approaches have the greatest potential to address particular hazards. A secondary objective was to identify priority actions for increasing adoption of nature-based solutions for risk reduction. In cases where they show potential but lack a well-developed evidence base, this report explores how we can foster research, innovation, and adaptive learning to support their development, and how we can scale up their application where there is strong evidence for nature-based solutions

The methods for this work followed four steps:

1 Rapid review of the academic literature on 23 nature-based solutions

Led by the Science and Technology Policy Institute (STPI), this initial review focused on the potential effects of nature-based solutions in mitigating hazards (such as floods, heatwaves) and generating positive outcomes (such as improved water or air quality, enhanced water quantity). The literature review relied on a combination of gray literature and peer-reviewed journal articles. Key words for each of the 23 individual nature-based solutions and relevant outcomes (such as "water quality," "coastal erosion") were used. The rapid review incorporated more than 300 papers and provided a starting point for the integration of academic and practitioner perspectives. For the purposes of this analysis, *effect* refers to the strength of the evidence for a nature-based solution to have a significant or consequential effect. The level of effect was assessed using a five-point scale ranging from no effect (indicated by 0), low effect (indicated by 1), intermediate effect (indicated by 2), strong effect (indicated by 3), and very strong effect (indicated by 4). The scores indicate only positive relationships between nature-based solutions and a particular benefit (though there can be tradeoffs). They reflect our current understanding of the potential of nature-based solutions to provide specific benefits, which are, in turn, informed by the strength of the evidence. Each score represents the maximum potential for a nature-based solution to provide a benefit (i.e., under ideal conditions, such as where there is sufficient space and a mature ecosystem).

2 Review of the efficacy of nature-based solutions by practitioners

While the academic literature can provide a rigorous basis for evaluating nature-based solutions, it may be a lagging indicator. Academic studies require significant time to be developed, funded, reviewed, and eventually published in academic journals (if they reach publication at all due to time, resource, and financial constraints). This can create a significant knowledge gap on new and emerging areas of study. Therefore, we also engaged practitioners—including professionals who assess, oversee, and implement nature-based solutions—to independently share their perspectives. Practitioner reviewers scored the effectiveness of nature-based solutions using the same scoring protocol that was used for the literature review.

3 Collaborative synthesis of academic and practitioner perspectives

We compared scores from the academic and practitioner perspectives. Participants then worked to reconcile both, producing a synthetic score. This flowed from individual conversations with partners with specialized expertise at the workshop, and subsequent virtual collaborations.

4 Peer review and integration

Draft results of the evidence base were peer reviewed and refined with input from the authors of recent meta-analyses of nature-based solutions (Sudmeier-Rieux et al. 2021; Vicarelli et al. 2024). In addition, reviewers provided additional context and caveats to the language of this report to reflect our collective understanding of the evidence behind nature-based solutions.

Limitations

Our review of the academic literature included systemic reviews (including the Environmental and Energy Study Institute 2019, Chausson et al. 2020, Sudmeier-Rieux et al. 2021, Seddon 2022, Hansen et al. 2023, Paxton et al. 2024, and Vicarelli et al. 2024), case studies, and meta-analyses. Integrating academic perspectives with those of practitioners implementing nature-based solutions provided a more comprehensive perspective. However, the approach has several limitations.

- **Most studies of nature-based solutions used data to empirically evaluate their effectiveness.** Approximately half of the studies reviewed in Chausson et al. (2020) derive at least some information on efficacy from scenario modeling. The scenario modeling approach is particularly common for evaluations of restoration and management; nature-based solutions in forest, mangrove, riparian, and wetland ecosystems; and those related to freshwater flooding, wildfire risk, and storm surge (Chausson et al. 2020). Similarly, approximately half of the studies in the meta-analysis by Vicarelli et al. (2024) include some type of modeling and simulation in addition to an empirical analysis approach. Only 4% of studies relied exclusively on a modeling and simulation approach, indicating a strong trend toward empirical methods (Vicarelli et al. 2024).

- **Some geographies are better studied.** Urban environments, coastal ecosystems, mangroves, wetlands, forests, and riparian areas are among the most extensively studied systems in which nature-based solutions have been evaluated (Johnson et al. 2022; Vicarelli et al. 2024; IPBES 2022, Paxton et. al 2024). In addition, most research on nature-based solutions has focused on Europe, North America, and Asia, despite significant risks in other areas that could be addressed by nature-based solutions (Dunlop et al. 2024; Chausson et al. 2020; Sudmeier-Rieux et al. 2021; Vicarelli et al. 2024; Nassary et al. 2022; Woroniecki et al. 2022; IPBES 2022). For example, Small Island Developing States have been represented in only approximately 10% of studies on nature-based solutions analyzed in Chausson et al. (2020), despite being among the most vulnerable to the impacts of climate change. Most studies of nature-based solutions have been carried out in developed countries (Chausson et al. 2020).

- **Further research is needed to forecast the impacts of climate change on nature-based solutions and their effectiveness.** Studies suggest that climate change will threaten some of the ecosystems used as nature-based solutions (Seddon et al. 2020; Gómez Martín et al. 2021). Ecosystem functions are changing in response to long-term temperature and precipitation changes (Rosenzweig et al. 2008; Hoegh-Guldberg and Bruno 2010; Poloczanska et al. 2013), with negative impacts and stressors expected for affected species around the world (Root et al. 2003). The ENACT Partnership (Enhancing Nature-based Solutions for Accelerated Climate Transformation) cautions that significant global warming may cripple the capacity of nature-based solutions to provide the social and ecological benefits for the environment they were designed to serve (IUCN 2024).

Most studies of nature-based solutions have been carried out in developed countries.

- **There are important opportunities to pair science methods traditionally used in the United States and Indigenous Knowledge, which has historically been dismissed.** Integrating Indigenous and other local knowledge can build trust, avoid conflicts, better informed decisions, and lead to more sustainable outcomes (IPBES 2022). This can provide deeper understanding and broader perspectives for nature-based solutions. Indigenous communities have long innovated and utilized nature-based solutions to adapt to environmental changes, enhance climate resilience, and sustain their ways of life (Jang 2024). To include all forms of relevant evidence, federal agencies and their partners should follow the "***Guidance to Federal Departments and Agencies on Indigenous Knowledge***" and consult and engage with Tribes and other Indigenous communities (White House Council on Environmental Quality 2022). Emphasis should be placed on Tribal sovereignty, with support given for co-management, co-stewardship, and consideration of Indigenous Knowledge in decisions, as desired by Tribes and Indigenous communities.

- **Other analytical challenges exist related to evaluating nature-based solutions.** There are many different types of actions that may qualify as nature-based solutions, complicating efforts to assess their overall efficacy. Studies may not provide sufficient comparison to non-nature-based solution approaches or integrated analyses; this gap can result in evidence that is incomplete and scattered across disciplines, with ripple effects on decision-making (Chausson et al. 2020). Moreover, research is also often focused on newly created and restored ecosystems (Chausson et al. 2020). Meta-studies of nature-based solutions point to the need for more quantitative evidence (van Zanten et al. 2023), systematic considerations of the full scope of social and economic impacts as an ongoing process (Nelson et al. 2020; Sowińska-Świerkosz and García 2021), and recognition of tradeoffs as they apply to present and future effects (Nelson et al. 2020). Traditional benefit-cost analyses also fail to fully account for intangible aspects of human well-being, intrinsic values, distributional effects, and biases in the choice of spatial and temporal boundaries of an evaluation (Wegner and Pascual 2011). In addition, nature-based solutions may be implemented for one purpose but provide additional co-benefits. For example, living shorelines are typically associated with reducing coastal erosion, but they also sequester carbon and provide wildlife habitat (NOAA 2024a). Studies often consider a single benefit rather than multiple benefits. When multiple benefits are considered, they are often underestimated (Vicarelli et al. 2024; Sutton-Grier et al. 2015). Long-term benefits, such as reducing the burden of disease or increasing resiliency to sea level rise, are challenging to capture (Heilmann 2017).

FINDINGS

The results summarized below reflect the academic literature and the contributions of thought leaders from more than 30 federal government, local government, academic, non-governmental, and private sector institutions. They focus on the effectiveness, benefits, challenges, constraints, and opportunities for implementing nature-based solutions to reduce hazard risks.

CROSS-CUTTING FINDINGS

Nature-based solutions can be cost-effective in mitigating hazards and providing other environmental benefits

Nature-based solutions can be used independently or in combination with built infrastructure as hybrid solutions. Globally, there is high confidence that nature-based solutions contribute to sustainable development and provide adaptation and mitigation benefits (IPCC 2022). While local context always matters, in general:

- **Nature-based solutions can be more cost-effective than grey infrastructure, particularly for low-intensity hazards.** Cost-effectiveness refers to achieving desired outcomes at a lower cost compared to alternative (grey) approaches. When accounting for a diverse range of performance outcomes, nature-based solutions can be more effective than grey infrastructure solutions, particularly for lower-intensity hazards (Seddon et al. 2020; Vicarelli et al. 2024). Vicarelli et al. (2024) found that 71% of the studies they reviewed in a meta-analysis identified nature-based solutions as consistently cost-effective. Among the subset of studies within this meta-analysis that compared green and grey infrastructure, none found nature-based solutions less cost-effective than engineering solutions, and 65% of such studies found nature-based solutions consistently to be more cost-effective. Mangroves, forests, and coastal ecosystems are particularly cost-effective in reducing disaster risks—including floods, storms, and erosion—compared to conventional solutions (Vicarelli et al. 2024; Reguero et al. 2018). Benefit-cost analyses also often omit negative costs of grey infrastructure (such as decreases in biodiversity or increased erosion), which can artificially inflate its net benefits (Sutton-Grier et al. 2015).

- **Over time, nature-based solutions may be less expensive to implement and maintain than built infrastructure** (Sutton-Grier et al. 2018; Bassi et al. 2021). They can be more readily modified or repaired. Some nature-based solutions may strengthen rather than atrophy over time. For example, the vertical growth of oyster reefs can keep pace with sea level rise, allowing such reef sanctuaries to remain preserved (Rodriguez et al. 2014). Some nature-based solutions have potential for self-repair and adapting to climate change (Seddon et al. 2020; Seddon 2022). Bassi et al. (2021) highlight that meeting global infrastructure needs over the next 20 years using only grey infrastructure would cost $4.29 trillion annually; however, 11% of the infrastructure needs could be met with nature-based solutions that would cost less than half of the $489 billion per year required for the grey infrastructure it would replace. The nature-based infrastructure would also yield a 28% greater value than the replaced grey infrastructure (Bassi et al. 2021). That said, additional research and documentation on the costs and benefits of nature-based solutions compared to grey infrastructure could better inform decision-making (EPA 2013; Somarakis et al. 2019). More research is needed on operations and maintenance for green infrastructure (EPA 2013), as well as data on associated costs (Somarakis et al.

2019). The specific maintenance needs will likely depend on the relevant nature-based solution and its local context (EPA 2013).

- **Conserving existing natural ecosystems is generally more cost-effective than restoration.** For example, natural wetlands already provide important and multiple ecosystem services, including carbon storage. Thus, their conservation should be prioritized because restoring a degraded landscape can be more costly than protecting an existing one, require a long period of time for full restoration, and may not result in restoring all original functions (Schuster et al. 2024; Cook-Patton et al. 2021). Indeed, conservation is a top natural resource management priority for biodiversity and ecosystem services (World Bank 2024), and more recently for climate mitigation (Cook-Patton et al. 2021). Conserving ecosystems provides protection at a lower cost compared to ecosystem restoration and is therefore more cost-effective (Vicarelli et al. 2024).
- **The return on investment can be high**. The Economic and Energy Study Institute (EESI 2019) noted that every $1 spent on restoring wetlands and reefs yields $7 in direct flood reduction benefits for many regions along the Gulf of Mexico, in other words, preventing costly damages. These analyses tend to underestimate the total benefits yielded by public ecosystem services, as traditional benefit-cost analyses do not fully capture intangible aspects of human well-being, intrinsic values, or complex ecosystem relationships (Wegner and Pascual 2011).

Nature-based solutions can be applied from small to landscape scales

Nature-based solutions can be implemented at different scales, depending on local conditions. Space is often limited in urban environments. However, even small-scale interventions can generate positive outcomes (Pataki et al. 2021), such as urban tree canopies to reduce the impacts of extreme heat, improve stormwater absorption, and provide health benefits. These smaller projects can support hazard risk reduction and provide other ecosystem and societal benefits even within a small spatial area, though the magnitude and spatial distribution of their impacts is also constrained.

Nature-based solutions can also be implemented at landscape scales. More expansive solutions such as wetlands restoration may generate broad and interlinked benefits across the landscape, such as greater water retention, reduced soil erosion, and improved biodiversity (Keesstra et al. 2018). The ecosystem benefits associated with large-scale nature-based solutions can also translate into more expansive societal benefits (Hutchins et al. 2021). Nevertheless, there is still limited knowledge on how to effectively scale up nature-based solutions to achieve wider social and environmental benefits (Odongo et al. 2022).

Decision-makers must balance spatial, temporal, and societal needs (Odongo et al. 2022). Table 1 summarizing our findings reflects the maximum potential impact from a given nature-based solution. To address the growing impacts of hazards, the scale and diversity of approaches will need to increase.

Urban canopy reduces extreme heat

Tree planting along a neighborhood street in Tacoma, Washington
Photo courtesy of Hannah Letinich and The Nature Conservancy

A 2022 study in South Tacoma, Washington, demonstrated the significant influence of urban trees on local air temperatures and heat exposure risk (Ettinger et al. 2024). Researchers found that air temperatures varied by 2.57 degrees Celsius (4.63 degrees Fahrenheit) on average across the study area, with tree canopy cover having a measurable cooling effect. Areas lacking tree coverage within 10 meters were up to 5 times more likely to experience temperatures exceeding regulated thresholds compared to areas with full canopy. The cooling effect increased steadily with greater canopy cover, showing that even small increases in urban canopy contribute meaningfully to lowering air temperatures (Ettinger et al. 2024). These findings underscore the potential of urban forestry as a nature-based solution in addressing urban heat islands and reducing related health risks in vulnerable neighborhoods.

Nature-based solutions can produce a diversity of economic, social, and environmental benefits

A single nature-based solution can provide a wide range of benefits, including risk reduction and many other ecosystem services (O'Leary et al. 2024). The simultaneous provision of multiple benefits distinguishes green from grey solutions, which are usually oriented toward fulfilling a more limited function (Ofosu-Amaah et al. 2024). Nature-based solutions can be cost-effective for meeting a diversity of sustainable development goals (IPBES 2019). A systematic review of 363 empirical observations published in the scientific literature determined that nature-based solutions were the only ones to be effective in terms of both risk reduction and development outcomes (Villamayor-Tomas et al. 2024). The diverse benefits of nature-based solutions enhance their local acceptance.

Nature-based solutions can contribute to economic resilience and provide substantial economic benefits, including job creation and income diversification (Chausson et al. 2023). For example, mangrove forests can provide coastal protection while also generating economic benefits via sustainable fisheries, job creation, and tourism (Debrot et al. 2022). Mangrove forests also have significant climate mitigation benefits, as they effectively sequester and store carbon (NOAA 2024b). Additionally, many nature-based solutions support physical and mental health, quality of life benefits, and cultural values that are unaccounted for in typical benefit-cost analyses.[2]

Evaluations of nature-based solutions are most accurate when the full range of benefits is considered. Without comprehensive assessments, the full suite of benefits from these interventions

2 This is the welfare change aspect of benefit-cost analysis accounting for ecosystem services: ***https://www.whitehouse.gov/wp-content/uploads/2024/02/ESGuidance.pdf.***

Constructed wetlands reduce pluvial flooding

The stormwater management hub project converted by the Clear Lake City Water Authority, in collaboration with Exploration Green
Photo courtesy of Benoit LaMarche

Homes in Clear Lake in Greater Houston have faced significant flood risks—especially since Hurricane Harvey in 2017. To combat these challenges, the Exploration Green project transformed a 200-acre former golf course into a stormwater detention facility (Carothers 2023). Designed to reduce flooding from heavy rainfall, the project established 5 large detention ponds capable of holding 100 million gallons of stormwater each. Following Hurricane Harvey, the facility successfully saved 200 homes by allowing stormwater to completely fill the detention pond before spilling over the top of its containment structure as intended, demonstrating its effectiveness during extreme weather events. Engineers collaborated closely with residents to create a multi-purpose space that now encompasses 153 acres of natural habitat, 39 acres of wetlands, and Americans with Disabilities Act-accessible trails, while providing vital bird habitats and enhancing local biodiversity; the number of documented bird species in the area increased from 40 to 215 after the project's implementation. Additionally, the project has fostered community engagement and revitalization, transforming the 60-year-old neighborhood into a vibrant, walkable green space that hosts organized family events and encourages residents to take pride in their homes, ultimately leading to rising property values. Exploration Green serves as a model for communities nationwide dealing with stormwater management issues (Texas Standard 2022).

is not accounted for and, in effect, can be misjudged as inferior in relation to grey solutions, as the latter offer outcomes that are more commonly evaluated (Huthoff et al. 2018). Comprehensive assessments of co-benefits in a single study assessing a nature-based solution are unusual (Chausson et al. 2020; Cheng et al. 2023; Vicarelli et al. 2024). Some of the benefits of nature-based solutions are experienced by outside markets, such as climate regulation and sociocultural elements (Nelson et al. 2020). Some benefits can take time to fully develop and can fluctuate depending on the incidence and intensity of disturbances such as floods, wildfires, storms, or other events against which nature-based solutions protect (Huthoff et al. 2018; Sowińska-Świerkosz and García 2021; Giordano et al. 2020; Seddon et al. 2020), providing additional challenges for conventional accounting and analysis.

Nature-based solutions contribute to the global humanitarian imperative of preventing and alleviating human suffering arising out of disasters and conflicts. The United States Agency for International Development (USAID) has prioritized nature and climate-positive approaches across the humanitarian-development-peace nexus (USAID 2022), in particular through the portfolios and action plans of the Bureau for Humanitarian Assistance and the Bureau for Resilience, Environment, and Food Security.

Vicarelli et al. (2024) found that the scientific literature documents a large variety of ecosystem services, including cultural services (Figure 2). Unfortunately, these benefits are not consistently studied. Large research funds and interdisciplinary teams may be necessary to measure these benefits.

Due to the challenges with valuing nature, economic and political decisions have predominantly not included ecosystem or societal benefits when determining which investments to pursue for hazard risk reduction (White House 2023a). The Biden-Harris Administration has been leading efforts to address this issue by capturing the diverse values of nature in decision-making, including by integrating ecosystem-services into benefit-cost analysis for rulemaking by agencies (Office of Management and Budget 2023) and the ***National Strategy to Develop Statistics for Environmental-Economic Decisions*** (The Office of Science and Technology Policy, The Office of Management and Budget, The Department of Commerce 2023). The guidance applies to infrastructure

Regulating Services		Provisioning Services	Cultural Services
Protective Services	Other Regulating Services		
Disaster Risk Reduction	Benefits obtained from regulation	Products obtained from ecosystems	Nonmaterial benefits obtained from ecosystems
■ Flood protection ■ Landslide protection ■ Avalanche protection ■ Soil erosion protection ■ Heat wave mitigation	■ Carbon capture and sequestration ■ Pollution mitigation ■ Heat mitigation ■ Water quality improvement ■ Water regulation ■ Disease regulation ■ Pollination	■ Provision of food and free water ■ Livestock fodder ■ Fuelwood ■ Genetic resources ■ Biochemicals ■ Other harvestable resources	■ Opportunities for recreation and ecotourism ■ Spiritual and religious benefits ■ Aesthetic benefits ■ Cultural heritage ■ Educational benefits

Figure 2. Ecosystem services analyzed in Vicarelli et al. (2024) Reproduced with permission from the author.

investments, risk reduction investments and many other kinds of federal decisions. It helps agencies avoid situations in which the value of specific ecosystem services is implicitly given no weight or, conversely, disproportionate weight in an analysis. Application of this guidance will provide a more transparent and robust approach to assessing multiple benefits from nature-based solutions.

For high-intensity hazards, hybrid infrastructure (which combines natural and built elements) can be more effective at reducing risk

Many nature-based solutions incorporate some built elements (such as sloping and geotextiles to support the development of a living shoreline). While nature-based solutions can be considered as alternatives to grey infrastructure, a combination of the two (called hybrid or green-grey infrastructure) can be the most effective in some situations (Sutton-Grier et al. 2015).

Nature-based solutions can enhance the risk reduction of grey infrastructure in a number of ways. They can increase stormwater infiltration, attenuate runoff, and improve water quality (Casal-Campos et al. 2015; Voskamp and Van de Ven 2015; Tansar et al. 2023). In some cases, such as in response to a category 1 hurricane, natural and hybrid solutions have performed better than grey infrastructure alone (Sutton-Grier et al. 2015). A hybrid approach can optimize risk reduction by combining diverse flood attenuation mechanisms and has been found in some cases to provide the most rainwater flood damage risk reduction in urban environments (Martínez et al. 2021; Moon et al. 2024). Hybrid solutions also enable cities to mitigate urban pluvial flooding from cloudbursts and other extreme precipitation events that grey infrastructure like stormwater pipes cannot accommodate on their own (Haghighatafshar et al. 2018; Alves et al. 2019; Chen et al. 2021).

Nature-based solutions may be better at reducing risk than grey infrastructure because they can improve ecosystem or community resilience (Cohen-Shacham et al. 2016; Ozment et al. 2015; World Business Council for Sustainable Development 2017). However, more research is needed to assess the impacts of climate change on their long-term efficacy (Seddon et al. 2020; Gómez Martín et al. 2021). Although the benefits usually manifest over a longer period, green infrastructure grows with the environment within which it is situated and can address multiple needs. In addition to providing aesthetic value, green infrastructure is often more flexible and adaptable than grey solutions to changing conditions (Huthoff et al. 2018). Adding natural elements to existing grey infrastructure can help mitigate additional flood risk caused by climate change without requiring wholesale overhauls of the grey infrastructure (Hendricks and Dowton 2023).

Hybrid solutions can provide the risk reduction of grey infrastructure while also providing improved system resiliency and sustainability (Tansar et al. 2023). They can also require less space than pure nature-based solutions, making them easier to implement in some urban settings (Sutton-Grier et al. 2015).

The optimal hybrid combination may include large-scale nature-based solutions at a regional level combined with small-scale hybrid (grey and green) infrastructure at the local level (Vojinovic et al. 2021). The combination of grey and green infrastructure can protect the nature-based solutions as they are becoming established, ultimately reducing risk to people in the interim.

To accurately analyze infrastructure options, it is important to consider a wide array of benefits, extending beyond those targeted by the investment. Nature-based solutions can deliver a more diverse range of benefits than grey infrastructure, while grey infrastructure can be better at reducing specific risks (Sutton-Grier et al. 2015). Hybrid infrastructure can strike a

balance, producing strong risk reduction and providing other social benefits. Nature-inspired design can augment the biodiversity benefits of grey infrastructure, such as adding rockpools to sea walls (Sutton-Grier et al. 2015).

A sample of studies about public perception of nature-based solutions found that respondents emphasized the benefits of green infrastructure, yet they placed greater trust in grey infrastructure for disaster risk reduction (Anderson and Renaud 2021). Some quantitative studies supported those views, demonstrating that grey infrastructure is more effective than green infrastructure at reducing flood risk, particularly for extreme rainfall events, though studies may classify *green infrastructure* differently (Alves et al. 2019; Chen et al. 2021; Dong et al. 2023; Webber et al. 2020). Hybrid solutions can overcome this concern as they incorporate the well-recognized reliability of grey infrastructure with the co-benefits of green infrastructure (Alves et al. 2019). In addition, for both grey and green infrastructure, public acceptance and trust in the infrastructure were strongly related to observing perceptions of success, another reason why community engagement is key (Anderson and Renaud 2021).

Hybrid infrastructure should increasingly become an expected or a standard practice, particularly for high-intensity hazards where nature-based and conventional infrastructure can complement each other.

Maintenance is a key consideration for both green and grey infrastructure

Both green and grey infrastructure require proper maintenance to successfully serve their functions in the long term (EPA 2013). While maintenance needs for grey infrastructure are well-established and have national standards,

there is less information, research, and data on operations and maintenance of green infrastructure, as well as their costs, indicating a knowledge gap (EPA 2013; Somarakis et al. 2019). Ultimately, maintenance costs will depend on context (EPA 2013), and should be incorporated into operating expense considerations at the outset of any green infrastructure project (van Zanten et al. 2023).

Some scholars argue that nature-based solutions have the potential to self-repair, adapt, and strengthen over time (Sutton-Grier et al. 2015; Huthoff et al. 2018). This enables a longer lifespan for nature-based solutions and may also contribute to reduced maintenance costs for nature-based solutions compared to conventional solutions, which often grow weaker over time (Seddon 2022; Maes and Jacobs 2017; Sutton-Grier et al. 2018). However, more research is needed to assess the performance of nature-based solutions in a changing climate (Seddon et al. 2020). When conventional structures are designed poorly or without considering the impact of natural forces, they can require continuous maintenance and repair, whereas nature-based solutions that are designed from the start to harness natural forces can experience lower construction and maintenance costs over their lifetimes (Keesstra et al. 2018). Grey infrastructure may also require emergency repairs or replacements, which tend to be more costly than regular repair or replacement costs (Sutton-Grier et al. 2018).

In certain cases, the construction and maintenance costs for green infrastructure could exceed those for grey infrastructure (Liquete et al. 2016), though green infrastructure often provides greater multidimensional benefits. In other cases, green infrastructure could require more intensive maintenance while still achieving greater net cost savings (EPA 2013). Ultimately, both benefits and costs should be considered, and maintenance needs must be assessed on a case-by-case basis.

POTENTIAL IMPACTS OF INDIVIDUAL NATURE-BASED SOLUTIONS

The synthesis of academic and practitioner perspectives on nature-based solutions is presented below in Table 1. The table is a heat map in which higher scores (and darker colors) indicate greater potential for the nature-based solution to provide benefits related to hazard risk reduction, water quality and quantity outcomes, and atmospheric outcomes related to carbon sequestration and air quality.

One or more nature-based solutions have strong potential to address each hazard and additional service assessed

Local conditions always matter, and adaptation is site-specific; not all nature-based solutions are effective in all situations. Green infrastructure, like grey infrastructure, must be matched to appropriate locations and desired outcomes (Cohen-Shacham et al. 2019). The potential impacts of compounding and cascading events should be taken into account during hazard planning. That said, for analytical purposes, hazards are listed separately in Table 1.

The analysis identified a variety of nature-based solutions with strong or very strong potential to deliver hazard reduction and other benefits. Early consideration of nature-based solutions with high potential gives planners options to address local needs. The greatest diversity of benefits is expected from investing in, protecting, restoring, or improving management of the following:

Findings: Potential Effects of Nature-Based Solutions

Nature-Based Solutions		Hazard Risk Reduction							Water Outcomes		Atmospheric Outcomes		
		Pluvial Floods	Riverine Floods	Coastal Floods	Coastal Erosion	Landslides and Erosion	Wildfire	Extreme Heat	Water Quality	Water Quantity	Carbon Sequestration	Air Quality	Aggregate Benefit
Watersheds	Slope stabilization	1	1	1	2	4	0	0	3	1	1	0	13
	Forests	2	2	1	1	4	4	4	4	4	4	4	32
	Agroforestry/ silvopasture	2	2	0	1	3	3	2	3	3	3	3	24
	Grasslands and other vegetation	2	2	1	1	3	3	1	3	2	3	1	22
	Farmland best practices	2	2	0	0	3	2	1	4	2	2	3	20
	Riverbeds, riparian areas	2	3	1	1	3	2	1	3	3	2	1	22
	Inland wetlands	2	3	0	0	2	2	1	4	3	4	2	23
	Floodplains and bypasses	3	4	2	1	1	2	1	3	4	2	1	23
	Setback levees (riverbeds and riparian areas)	1	4	2	1	2	0	1	3	3	2	1	19
Coastal	Mangroves	1	1	4	4	0	0	2	3	0	4	1	20
	Marshes and other coastal wetlands	1	2	4	4	0	2	1	3	0	4	1	22
	Living shorelines	0	1	2	4	0	0	1	2	0	3	1	12
	Coral reefs	0	0	3	4	0	0	0	1	0	1	0	9
	Oyster Reefs	0	0	2	4	0	0	1	3	0	1	0	10
	Sediment transport management	1	2	1	4	0	0	0	3	0	2	0	13
	Seagrasses and submerged aquatic vegetation	1	1	3	3	0	0	1	3	0	3	0	14
	Sandy beaches and dunes	1	0	3	4	0	0	1	1	0	0	0	10
Urban	Urban canopy	3	2	1	1	1	1	4	3	3	3	4	24
	Urban green spaces (parks, water plazas)	3	2	1	1	1	1	4	3	3	3	4	25
	Bioretention areas/rain gardens/bioswales	4	2	1	1	1	1	2	4	4	2	3	24
	Constructed and urban wetlands	4	3	1	1	1	1	3	4	4	3	2	25
	Green roofs, facades, walls	3	2	0	0	0	0	3	2	3	2	2	16
	Permeable pavement, urban water harvesting	4	2	1	0	1	0	1	2	3	0	0	14

NBS may be implemented thorugh a variety of land management categories, ranging from private lands to protected areas.

Effect

- 0 No effect
- 1 Low effect
- 2 Intermediate effect
- 3 Strong effect
- 4 Very strong effect

Maximum potential positive impact of a nature-based solution under ideal conditions (e.g., enough space, maturity

- **Watersheds**[3] to support regulation of water quality, water quantity, landslides and erosion, reduction of riverine floods, and carbon sequestration;
- **Coastal areas** to promote reduction of coastal erosion and coastal floods, regulation of water quality, and carbon sequestration; and
- **Urban areas** to benefit from reduction of pluvial floods, regulation of water quantity, extreme heat, and water quality.

The scope of impacts of nature-based solutions varies:

- **Some nature-based solutions have documented effects on a narrow set of benefits**. For example, investments in coral reefs have demonstrated potential for reducing coastal flood and erosion risks, but not other categories we assessed. It is important to choose options that best fit a given purpose.
- **Nature-based solutions may provide broad benefits.** Investments in protection, restoring, or improving the management of native forests are examples that are discussed below. Table 1 may support efforts to consider alternatives tailored to desired outcomes.

Oxford University's Nature-based Solutions Evidence Platform echoes findings from Table 1 by providing peer-reviewed literature into the effectiveness of various solutions across specific contexts (Nature-Based Solutions Initiative 2024). It is also consistent with the ***DOI NBS Roadmap***, which provides technical guidance, expected benefits, and over 400 case studies on the benefits of nature-based solutions.

Investments in trees and forests have particularly broad aggregate benefits

Investments in the protection, restoration, or improved management of native forests, agroforestry systems, urban forests, and mangroves can produce a diversity of benefits. They vary across scales, from neighborhoods or a city (such as flooding, air and water quality, cooling effect) to populations around the world (such as carbon sequestration).

Forests and trees offer significant benefits related to climate change and human health (Harris and Gibbs 2021; USDA Forest Service 2020, Arshad et al. 2020; Cheng et al. 2023). This includes the removal of some air pollutants and sequestration and storage of carbon (USDA Forest Service 2020; United Nations Economic Commission for Europe 2024). Trees on city streets have significant impacts on cardiovascular health; the loss of 100 million ash trees as the emerald ash borer swept across the United States was associated with more than 21,000 additional human deaths due to respiratory and cardiovascular conditions (Donovan et al. 2013).

Agroforestry, slope stabilization, urban canopy and green spaces, and bioswales and bioretention basins[4] are associated with reduced risks from flooding (NOAA 2015; Janzen et al. 2024).

Effective forest protection, restoration, and management are natural solutions that provide significant benefit for reducing wildfire risk. Forest management for wildfire risk reduction can involve thinning, reducing fuel loads, prescribed fire, or establishing fire breaks (Johnston et al. 2021; Prichard et al. 2021). Prescribed fire can reduce the likelihood of high-intensity wildfires, though it requires regular maintenance (Ryan et al. 2013). Mechanical

3 Watersheds refers to land areas that channel rain and snowmelt to shared water bodies (EPA 2024b).
4 Other names include low impact development and urban drainage system. See: ***https://www.mdpi.com/2073-4441/6/4/1069 Liu et al. 2014.***

Oyster reefs improve water quality

Sneak peek of oysters at low tide on Creek off Chesapeake Bay
Photo courtesy of Lynn Haynie Kellum

The Chesapeake Bay, spanning 11,600 miles through Maryland and Virginia, faces ongoing risks from centuries of oyster reef degradation and climate change. However, restoration efforts have demonstrated significant water quality benefits (Chesapeake Bay Foundation 2024). Monitoring studies conducted over several years (2014–2022) have shown that successfully restored reefs, such as the 350-acre Harris Creek project, remove approximately 20,000 pounds of nitrogen annually, with nutrient cycling rates increasing as oyster density raises clarity (Bruce et al. 2021; Chesapeake Bay Foundation 2024). A single oyster can filter pollutants out of 50 gallons of water in one day (NOAA 2022). In comparison, restored reefs remove up to seven times more nitrogen per day than their unrestored counterparts (Bruce et al. 2021). These findings, based on years of monitoring and data collection, underscore the critical role of oysters in addressing the Bay's nutrient pollution and enhancing water quality in tributaries targeted for restoration. Ongoing efforts aim to expand these benefits across the region and are projected to enhance fishery landings and generate $23 million in economic benefits annually for the Choptank River region (Chesapeake Bay Foundation 2024).

thinning (especially when combined with prescribed burning) can also decrease future wildfire severity when used as part of a plan to maintain ecosystem services. Regular fuel treatments are also critical to ensure their efficacy (Davis et al. 2024).

The benefits of investments in forests and tree canopy depend on local conditions. For example, investments in mangroves or other native coastal species help maintain coastlines, including alleviating coastal flooding as mangroves can withstand brackish and salt water. Urban forests, bioswales, and bioretention basins can help with pluvial flooding and control stormwater runoff (NOAA 2015). Forests can support water retention in watersheds to reduce potential riverine flooding. As forests retain and filter water, they help reduce water pollution, support water quantity, and improve soils (Folkard-Tapp et al. 2021), reducing soil erosion. Trees also provide cooling effects in urban environments, saving energy and contributing to health and quality of life (EPA 2024a). Agroforestry can provide an income source; reduce exposure to heat, floods, and erosion; and maintain wild animal species by providing food resources resilient to climate change (USDA n.d.). Forests and trees also support socioeconomic adaptive capacity by empowering communities to address environmental and societal challenges (Wang et al. 2023). Other benefits include greater biodiversity (Folkard-Tapp et al. 2021) and beautification (Ando and Netusil 2016), which can also generate direct economic benefits for governments, homeowners, and businesses, including via costs savings and increasing property values (EPA 2015).

While the benefits of forests and trees are highly prevalent in the literature, recent research has pointed to potential challenges that need to be addressed or taken into account in urban environments (Gaffney 2024; Pfannerstill et al. 2024). Though most trees help improve air quality, some species of trees can make air quality worse in urban environments due to interactions between typically harmless chemicals that trees emit (isoprene) and fossil fuel emissions from cars, buildings, and power plants (Wei et al. 2024). As a result, planting certain tree species can create harmful levels of air pollution (such as ozone), causing health issues for humans and animals (Wei et al. 2024; Pfannerstill et al. 2024). In addition, trees planted along streets in urban areas grow faster but have higher mortality rates and accelerated rates of carbon cycling compared to rural forests (Smith et al. 2019). This points to the importance of initiatives to maintain the health of street trees, as otherwise high mortality rates can lead to a net loss of carbon storage over time. This is also why it is important to match nature-based solutions to local environments and conduct site-specific research to avoid unintended negative impacts.

Forest restoration reduces wildfire risks

Forest land near Flagstaff, Arizona, showing the before (left) and after (right) effects of thinning
Photo courtesy of United States Department of Agriculture (USDA)

In 2011, the Wallow Fire, Arizona's largest and most severe wildfire, burned over half a million acres in the White Mountains and surrounding areas near the town of Alpine. However, Alpine itself was spared from destruction due to forest management efforts, including thinning, completed prior to the fire as part of the White Mountain Stewardship Project. The success in Alpine highlights the potential of forest restoration efforts to enhance the resilience of Arizona's ponderosa pine forests (The Nature Conservancy 2021). According to research by The Nature Conservancy, large-scale thinning planned for a forest restoration collaborative between The Nature Conservancy and the U.S. Forest Service could lead to a 15% increase in carbon storage, a 20% boost in stream flow, a 30% rise in tree growth, and a 25% reduction in tree mortality—demonstrating a nature-based solution to protect ecosystems and human settlements from catastrophic wildfires.

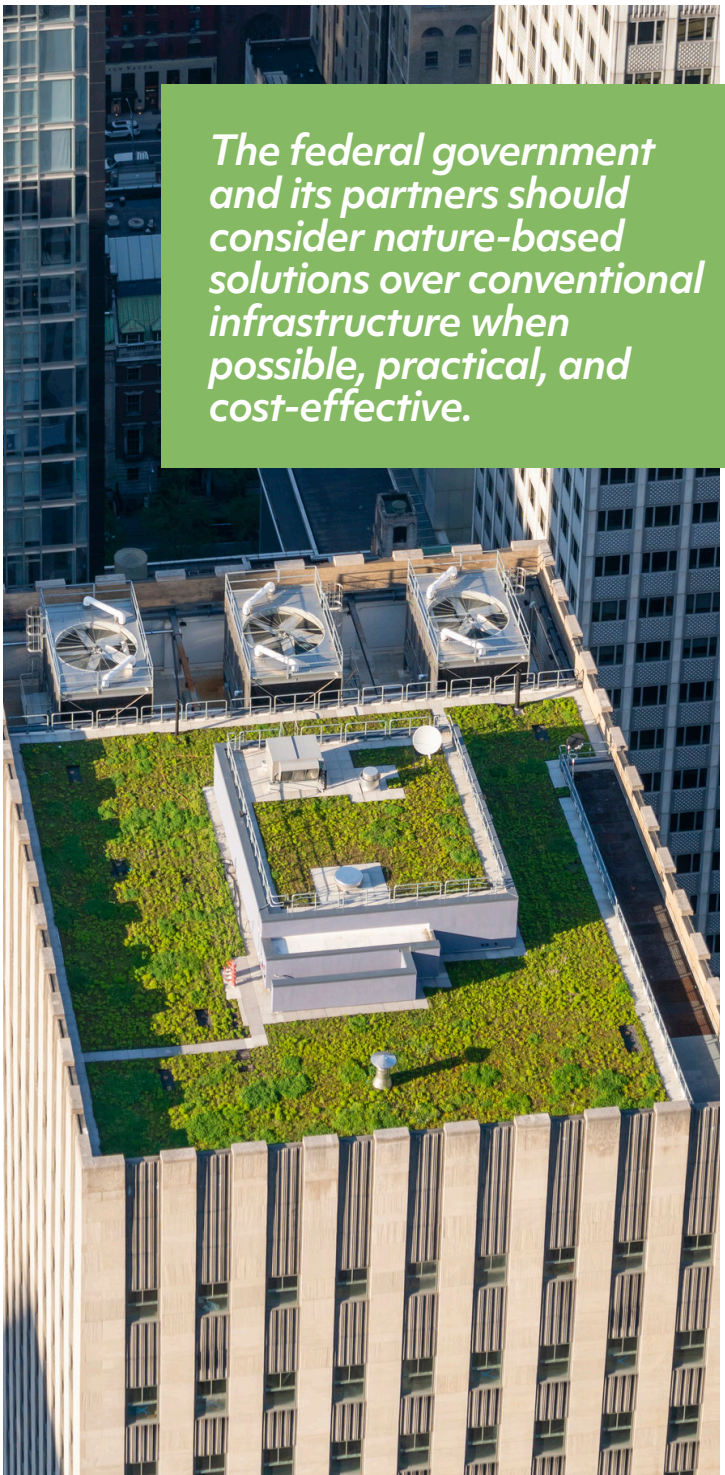
RECOMMENDATIONS

Implementing nature-based solutions depends on the expertise, experience, and resources of a diversity of individuals and institutions. The recommendations provided here reflect that diversity, which includes actions by governmental, academic, civil society, and private sector institutions.

SYSTEMATICALLY CONSIDER NATURE-BASED SOLUTIONS

This review of available evidence highlights that nature-based solutions, either independently or in combination with built infrastructure, have the potential to effectively address hazards and deliver other environmental benefits. They can be an important element of a systems approach to infrastructure, which is resilient to hazards and able to provide essential services (PREPARE 2024). The federal government and its partners should consider nature-based solutions as elements or options when developing hazard mitigation and ecosystem resilience activities. They should be a core consideration in planning and project design alongside grey infrastructure. This is the approach already taken by the Federal Emergency Management Agency's ***Federal Flood Risk Management Standard***. In addition, the Department of the Interior's ***Nature-based Solutions Policy*** encourages bureaus and offices to prioritize nature-based solutions by choosing natural or green infrastructure over conventional infrastructure when possible, practical, and cost-effective. This is consistent with a systems approach to infrastructure planning (PREPARE 2024).

Though not an exhaustive list of all possible nature-based solutions or associated benefits, the accompanying Tables 2–4 identify nature-based solutions that have been rated as having *strong* or *very strong* effects in relation to specific hazards and other environmental services. In generating these scores, contributors intuitively were able to distinguish no, low, and intermediate effects from those that were strong or very strong (as in there was more discussion over the difference between scores of 3 and 4). For that reason, in presenting the short list of nature-based solutions with the greatest potential to address a hazard or benefit, we grouped scores of 3 and 4 together as *high* effect. They provide a starting point for considering alternatives. Local conditions will always be a critical factor in determining the suitability of both green and grey infrastructure.



The federal government and its partners should consider nature-based solutions over conventional infrastructure when possible, practical, and cost-effective.

Watershed

Nature-Based Solutions	Pluvial Floods	Riverine Floods	Landslides and Erosion	Wildfire	Extreme Heat	Water Quality	Water Quantity	Carbon Sequestration	Air Quality
Forests			●	●	●	●	●	●	●
Agroforestry/ silvopasture			●	●		●	●	●	●
Slope stabilization			●			●			
Grasslands and other vegetation			●	●		●		●	
Farmland best practices			●			●			●
Riverbeds, riparian areas		●	●			●	●		
Inland wetlands		●				●	●	●	
Floodplains and bypasses	●	●				●	●		
Setback levees (riverbeds and riparian areas)		●				●	●		

Coastal

Nature-Based Solutions	Coastal Floods	Coastal Erosion	Water Quality	Carbon Sequestration
Mangroves	●	●	●	●
Marshes and other coastal wetlands	●	●	●	●
Seagrasses and submerged aquatic vegetation	●	●	●	●
Living shorelines		●		●
Coral reefs	●	●		
Oyster Reefs		●	●	
Sediment transport management		●	●	
Sandy beaches and dunes	●	●		

Urban

Nature-Based Solutions	Pluvial Floods	Riverine Floods	Extreme Heat	Water Quality	Water Quantity	Carbon Sequestration	Air Quality
Urban canopy	●		●	●	●	●	●
Urban green spaces (parks, water plazas)	●		●	●	●	●	●
Constructed and urban wetlands	●	●	●	●	●	●	
Bioretention areas/rain gardens/bioswales	●			●	●		●
Green roofs, facades, walls			●		●		
Permeable pavement, urban water harvesting	●				●		

TABLES 2–4: Investments in nature-based solutions that have a high potential for attenuating specific hazards and providing ecosystem services

Streamline permitting and reviews to accelerate implementation

Natural and hybrid solutions can be more difficult to permit than conventional infrastructure, even for actions likely to improve the environment (White House Council on Environmental Quality et al. 2022). Governance at every level (federal, state, local, tribal, territorial) should prioritize effective, efficient, and transparent permitting processes to scale the implementation of nature-based solutions (White House 2023b). To make permitting more efficient and accessible, the following items are suggested:

- **Use general permits for nature-based solutions.** General permits can be quicker and more cost-effective than individual permits because they cover a large number of individual actions (White House Council on Environmental Quality et al. 2022). One example is the U.S. Army Corps of Engineers' nationwide permits for living shorelines and aquatic habitat management (U.S. Army Corps of Engineers 2017), which increased use of these approaches in cases with minimal environmental impacts (Council on Environmental Quality 2022). As practical applications of nature-based solutions evolve and mature, agencies can develop new general permits using updated knowledge. The nature-based solutions identified here as having strong or very strong probability of positive effects should be considered for general permits.
- **Develop programmatic environmental reviews.** Programmatic environmental reviews are effective where the same actions are done repeatedly, are likely to have similar impacts, and can therefore be evaluated at a broad scale (White House Council on Environmental Quality et al. 2022). An example is the National Marine Fisheries Service's programmatic environmental review of coastal habitat restoration activities. As agencies work to scale up and coordinate use of nature-based solutions in specific regions (such as a watershed) to address large-scale problems (such as regional flooding or water quality problems), they can develop additional programmatic approaches to accelerate permitting. The nature-based solutions identified here as having strong or very strong probability of positive effects could be good candidates for exploration of additional programmatic reviews.
- **Deploy appropriate categorical exclusions.** A categorical exclusion is a class of actions that do not have a significant effect on the human environment and therefore are excluded from the requirement for an environmental assessment or an environmental impact statement (White House Council on Environmental Quality et al. 2024). Categorical exclusions can streamline project implementation by reducing paperwork, which can save time and resources. The Council on Environmental Quality has a list of categorical exclusions for federal agencies, which can help agencies review and revise their categorical exclusions (White House Council on Environmental Quality et al. 2024). The nature-based solutions reviewed here that have strong or very strong benefits could be candidates for categorical exclusions.

Develop policies, requirement statements, standards, guidance, and other reference materials for nature-based and hybrid solutions

Engineering standards, guidance, and other reference materials from federal agencies and engineering organizations provide confidence and consistency in the development of natural infrastructure. While guidance for built infrastructure is widely available, there are fewer reference materials for natural and hybrid infrastructure. This presents opportunities for public-private partnerships to fill this gap.

To increase the number of organizations implementing nature-based solutions, more technical engineering guidance needs to be publicly available. This is an opportunity to develop guidelines specific to different nature-based solutions applications. For example, the U.S. Army Corps of Engineers led the development of the ***International Guidelines on Natural and Nature-Based Features for Flood Risk Management*** (Engineering With Nature 2024) and is in the process of developing technical reports for some specific nature-based solutions. These efforts should be expanded to cover a broader range of nature-based solutions, potentially starting with those identified here as having strong or very strong benefits. Another priority is to develop hazard-driven fragility curves, which show the probability a structure will be damaged or fail under various conditions. Materials should include best practices to account for benefits appropriately in benefit-cost analyses and tradeoff studies.

Facilitate information sharing

To date, information on nature-based solutions is decentralized, making it difficult to identify and assess the viability of different opportunities. Directories and clearinghouses can facilitate information sharing, learning, and quicker and more widespread implementation. They could include case studies, best practices, partnership opportunities, and matching resources to support partnership development, faster permitting, technical assistance, market viability assessment, and matchmaking to funding opportunities (White House 2024).

This could include a library of engineering project documentation for nature-based solutions (including green infrastructure), coupled with a smart interface to match engineering with the best material available. This would help them meet the engineering standard of care, even in the absence of a specific nature-based solutions standard.

Government agencies, engineering organizations, and academia could support this effort.

Improve communication on federal funding opportunities for nature-based solutions

Significant federal and private funding is available to finance nature-based solutions. The Bipartisan Infrastructure Law and Inflation Reduction Act together will make investments of greater than $1 trillion, with significant funding for both built and natural infrastructure. Yet given the complexity of funding streams, there is limited awareness of the funding available that can support nature-based solutions, and it can be challenging to match projects with funding sources. Federal resources (such as the ***Nature-Based Solutions Resource Guide 2.0***) and individual agency tools can help (such as the Environmental Protection Agency's ***Climate Resilience and Adaptation Funding Toolbox).*** However, many institutions are not aware of the full suite of funding opportunities available. Government agencies and their partners should continue to communicate funding opportunities, and explicitly note when nature-based solutions are eligible. Efforts to do this include the Green Infrastructure Federal Collaborative's ***Green Infrastructure Funding List*** and the Bureau of Indian Affairs' ***Tribal Capital Clearinghouse***. Supporting the creation of forums, communities of practice, and grant opportunities to foster knowledge sharing and collaboration will help institutions to access and leverage funding effectively. Consistent funding to support long-term maintenance, management, and monitoring is important.

Build institutional and individual capacities to implement nature-based solutions

The capacity to identify, assess, design, implement, maintain, and evaluate a nature-based solution is key to scaling up use. Building

capacity requires a mix of formal training (programs through a college or university, continuing education required in some professional fields, or landscaper training) and informal approaches (gatherings, webinars, podcasts, and short courses). There is a good foundation on which to build, as federal agencies, universities, firms, and their partners are working to build capacity (such as the Network for Engineering with Nature). These initiatives should continue and expand, engaging a diversity of people (including underrepresented communities) and fostering a diverse workforce perhaps with certifications for their skills in nature-based solution implementation.

Formal training should include partnerships between community colleges, vocational schools, and local environmental organizations, ensuring that workers from diverse backgrounds, including underrepresented communities, are equipped with the knowledge and technical expertise needed to implement, maintain, and scale nature-based solutions. By integrating these skills into existing public works training and creating new certification opportunities, the workforce can better support long-term hazard mitigation and environmental resilience. One example is the Natural Infrastructure Certificate developed by the University of Georgia.

ACCELERATE RESEARCH, INNOVATION, AND ADAPTIVE LEARNING

Accelerating research and learning will inform application. Building knowledge will be particularly helpful in understanding the efficacy of nature-based solutions for specific hazards (such as drought, heat waves, or forest fires), ecosystems (such as marine offshore), geographies (such as low- and middle-income countries), and applications (such as benefit-cost analysis, monitoring and evaluation).

Prioritize interdisciplinary collaboration to close knowledge gaps

Work on natural and built infrastructure crosses many disciplines. Collaboration across groups, work streams, communities of practice, and institutions can lead to a better and more inclusive understanding of challenges and opportunities. Enhanced collaboration between academia and practitioners, including professional and community organizations, can deliver more applied research, with greater applicability for real-world implementation.

Document performance of nature-based solutions

More studies should evaluate the efficacy of nature-based solutions (Chausson et al. 2020; Sudmeier-Rieux et al. 2021; Seddon 2022; Hansen et al. 2023) and how climate change could affect them (Seddon et al. 2020; Vicarelli et al. 2024). The same is true for conventional (grey) solutions, and comparisons between the two can better inform decisions. Documenting and analyzing the additive effects (and tradeoffs) of nature-based solutions across geographies and watersheds may also provide a better view of the co-benefits of adopting a nature-based approach. Assessments of effectiveness should include individual, household, and community data to ensure benefits reach those most at risk or in need (Villamayor-Tomas et al. 2024).

Mangroves support carbon sequestration

Mangroves along the coast of South Florida Courtesy of the National Oceanic and Atmospheric Administration
Photo courtesy of Olivia Williamson

Blue carbon refers to the carbon captured by ocean and coastal ecosystems, including wetlands and tidal ecosystems like mangroves. Blue carbon has significant potential in supporting carbon sequestration efforts, but more research is needed to fully understand its effectiveness. One study quantified the differences in carbon sequestration of tidal mangroves along disturbed and undisturbed creek beds in Southwest Florida, near Naples and Dollar Bay. The undisturbed site was Susan's Creek near Dollar Bay, left relatively undisturbed due to its proximity to Rookery Bay National Estuarine Research Reserve. By contrast, the northern Naples Bay and nearby Hamilton Avenue Creek have been disturbed by extensive urbanization, dredging and channelization, and upstream development. Researchers took soil core samples from distinct parts of the mangrove ecosystems (basin, river, fringe) to calculate sedimentation and sequestration rates. Carbon sequestration was higher in the undisturbed tidal creek (113 g-C per meter squared on average) compared to the disturbed tidal creek (83 g-C per meter squared per year on average). These results indicate that mangroves are a productive ecosystem for carbon sequestration, though sea level rise threatens the survival of mangrove sites (Marchio et al. 2016).

Collaboration across groups, work streams, communities of practice, and institutions can lead to a better and more inclusive understanding of the challenges and opportunities.

Accelerate research in less studied areas

This report identified gaps in understanding of specific nature-based solutions that future research could address. These include the following areas:

- **Less studied ecosystems**. Urban environments, coastal ecosystems, mangroves, wetlands, forests, and riparian areas have been studied extensively across the world. Investments in some other ecosystems (such as grasslands, savannas, and coral reefs) have received less attention but may be able to provide significant benefits (Johnson et al. 2022; Vicarelli et al. 2024).
- **Less studied contexts**. Climate change as well as conflict and humanitarian crises are on the rise, often co-existing in degraded environments, presenting both complex and urgent life-saving and longer-term life-sustaining needs (Baxter et al. 2022). The role of nature-based solutions supporting economic recovery from crises ranging from conflicts to pandemics is unexplored (Chausson et al. 2024). There may be opportunities for nature-based solutions to support humanitarian efforts.
- **Less studied geographies**. Most studies on nature-based solutions come from developed countries, while less wealthy countries are heavily underrepresented (Sudmeier-Rieux et al. 2021; Vicarelli et al. 2024; Debele et al. 2023). These countries are often especially vulnerable to climate impacts and nature loss and could particularly benefit from nature-based solutions (Chausson et al. 2020).

- **Social, economic, and health impacts.** Given the diversity of potential impacts of nature-based solutions, more research is needed on economic and social outcomes (Vicarelli et al. 2024; Paxton et. al. 2024, Kumar et al. 2021). This includes benefits, capital, living standards, and health and synergies and tradeoffs (Eggermont et al. 2021). Federal priorities for better understanding ecosystem services benefits and costs have been summarized in recent reports (NSTC 2023; NSTC 2024).
- **Integrating green and grey infrastructure.** Evidence suggests that we need to move beyond the debates of green versus grey and focus instead on finding synergies between interventions and combinations of interventions (Villamayor-Tomas 2024). Hybrid (green and grey) solutions may be the most effective approaches in many circumstances; better understanding of how to most effectively integrate the two is a priority (Ruangpan et al. 2020).
- **Nature-based solutions in a changing world.** Nature-based solutions can be used to address climate change. Chausson et al. (2020) report that of 386 studies they considered, 376 were related to climate impacts (such as drought, floods, and forest fires). This has been reflected in policy, as the ***National Climate Resilience Framework*** prioritizes approaches—including nature-based solutions—that enhance climate resilience, while simultaneously advancing other community, economic, and societal objectives. Yet as the climate changes, there is uncertainty around local conditions and their impact on nature-based solutions (Seddon et al. 2020; McQuaid et al. 2021), pointing to a need for ongoing research.

Improve monitoring, evaluation, and learning for nature-based solutions

Monitoring and evaluation approaches should evaluate the effectiveness of nature-based solutions. Many different methodologies have been used for assessing nature-based solutions, but they are rarely integrated (Fu 2023). This lack of integration could translate to inconsistent application and practice. Just as crucial is a post-implementation assessment that uses standardized metrics across different projects to create broader understanding and acceptance of nature-based solutions. Nature-based solutions change and evolve over time; similarly, frameworks used to evaluate nature-based solutions should also change and evolve. Iterative learning, adaptation, and enhancement loops are critical (Fu 2023).

Local context always matters for nature-based solutions. Local engagement is key to learning from experience and developing effective approaches. There is a growing body of evidence from academic research and lived experiences to draw from that can inform the future development of nature-based solutions.

Partnerships between universities and project implementors can be a useful model (Huthoff et al. 2018). Integration of multiple evaluation methodologies could contribute to better monitoring and assessment of nature-based solutions (Fu 2023). Generating and evaluating quantitative evidence is another aspect in which an objective assessment is a valuable tool that could encourage more uptake of nature-based solutions. Academic research could explore scenario comparison, index-based assessments, and other valuation approaches, all of which could support future assessments (van Zanten et al. 2023).

Setback levees reduce riverine flood risk

Levee setback project in Atchison and Mills Counties, Missouri
Photo courtesy of Karine Aigner

Atchison and Mills Counties in northwest Missouri faced severe flooding in 2019, with seven levee breaches along the Missouri River L-536 levee system causing millions of dollars in damage to homes, businesses, roads, and farm fields (Schnarr 2021). To address the ongoing risk of repetitive flooding and levee breaches, local authorities worked with The Nature Conservancy, the U.S. Department of Agriculture's Natural Resources Conservation Service, the U.S. Army Corps of Engineers, and many other partners to implement a levee setback, relocating the levee up to 3,500 feet further from the river and reconnecting over 1,000 acres of floodplain. Constructed between August 2020 and November 2024 (construction is ongoing as of this date), the project used advanced hydraulic modeling to predict and optimize benefits, including a reduction of peak flood stages by up to 0.8 feet for the 100-year flood and a decrease in water velocity, which lowers erosion and scouring risks along the levee. The success of this project has catalyzed plans for a larger levee setback at the confluence of the Missouri and Mississippi Rivers, reconnecting 2,000 more acres of floodplain, as well as plans for a setback further upstream in Atchison County, Missouri. Additionally, multiple research and monitoring efforts are in place, supported by the U.S. Army Corps of Engineers' Engineering With Nature Program and a National Aeronautics and Space Administration grant to use remote sensing and primary data collection for tracking biodiversity, habitat, and ecosystem service improvements in the reconnected floodplain. This ongoing research contributes to the U.S. Army Corps of Engineers' development of technical guidance for nature-based solutions in flood risk management, highlighting the significant, quantifiable impact of levee setbacks on flood reduction and ecosystem resilience. Overall, this project underscores the critical role of continuous monitoring, evaluation, and iterative improvements throughout the project lifecycle to enhance effectiveness and sustainability.

Informed decision-making

Multidimensional assessments are important because nature-based solutions can generate a range of impacts. Fully accounting for benefits and tradeoffs better informs decisions (European Commission 2021).

Informed decision-making should involve local engagement and knowledge. Business (and in some sense governments) depends on social license: the ongoing acceptance by communities, the broader public, and other stakeholders in the areas where they operate. To maintain social license, the actions of companies and governments must maintain the ecosystem services on which those communities rely.

Deepen understanding of health and economic impacts

There is growing evidence that the natural environment provides major public health benefits (Donovan et al. 2013). These benefits can occur at the level of individuals and communities. They occur through three primary pathways: reducing harm (such as pollution mitigation), restoring capacities (such as faster recovery from stress), and building community-level capacities (such as fostering social cohesion). Within this framework, nature-based solutions not only have the potential to remove harmful influences, but can also give rise to beneficial ones (Markevych et al. 2017; Kalaidjian et al. 2024). For example, greener residential areas reduce the likelihood of mental disorders (Sarkar et al. 2018) and cardiovascular disease (Yeager et al. 2018).

Deepening understanding of the health impacts of nature-based solutions is a priority. For example, heat kills more people than any other extreme weather event (National Weather Service, n.d.), and the urban heat island effect can add up to 20 degrees Fahrenheit to local temperatures. Over the last half century, 47 of the 50 largest U.S. cities have seen an increase in extremely hot (>95 degrees Fahrenheit) days, generating frequent health emergencies. The pattern is national, with big cities in Texas, Arizona, and California experiencing the greatest increase (O'kruk and Dewan 2024). Tree cover can help reduce this impact, especially in cities where forests are native, but questions remain on how they can most effectively be used and paired with complementary approaches when conditions become extreme. Moreover, natural disasters disrupt the provision of health care and key life support systems (food, water, energy, etc.), so averting and minimizing such events is critical to protecting public health. The health outcomes of rural, agricultural, and coastal nature-based solutions are less well studied than those in urban settings (Dick et al. 2020).

The economic implications of the hazards assessed in this report are significant. Tropical cyclones (including hurricanes) are the costliest category of weather and climate disaster in the United States, followed by drought, wildfire, and flooding (***NCEI 2024***). Flooding affects the most people globally compared to other types of hazards (Vasagiri 2024). Impacts of both are increasing with climate change.

Urban greenery improves air quality and human health

The Watterson Expressway, showing before (top) and after (bottom) 8,000 trees were planted
Photo courtesy of The Nature Conservancy

The Watterson Expressway, a major highway bisecting South Louisville, Kentucky, has long been a significant source of air pollution for nearby residents. In the fall of 2017, The Nature Conservancy, in partnership with the University of Louisville's Christina Lee Brown Envirome Institute and other collaborators, launched the Green Heart Louisville Project to investigate the link between neighborhood greening and human health (The Nature Conservancy 2018). As part of their baseline study, the team gathered health data from 745 participants living in South Louisville and measured tree coverage and air pollution levels. To address the pollution, the team planted 8,000 trees and shrubs throughout target neighborhoods, focusing on a living wall of trees along the Watterson Expressway. A longitudinal clinical trial was conducted to assess the health effects of increased urban greenery, particularly in filtering highway pollution. After years of monitoring, in August 2024 the team announced groundbreaking findings: residents in greener neighborhoods experienced a 12–20% decrease in inflammation, which contributed to improved cardiovascular health (Coffman 2024). The Green Heart Louisville Project was the first of its kind, offering robust scientific evidence that increasing urban green spaces, especially as buffers against highway pollution, can significantly enhance human health. The effects of the Green Heart Louisville Project manifested particularly fast because the planted trees were fully mature, which significantly increased the cost of the project but also enabled the benefits to be realized quickly.

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We wish to thank the professionals who supported this work.

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