THE PROTECTIVE VALUE OF NATURE

A REVIEW OF THE EFFECTIVENESS OF NATURAL INFRASTRUCTURE FOR HAZARD RISK REDUCTION

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This is the third in a series of reports on the use of natural defenses developed by the National Wildlife Federation in partnership with Allied World. Previous reports are Natural Defenses from Hurricanes and Floods: Protecting America's Communities and Ecosystems in an Era of Extreme Weather (2014) and Natural Defenses in Action: Harnessing Nature to Protect Our Communities (2016).

Cover image: Buffalo Bayou Park in downtown Houston, TX. Natural vegetation and streamside setbacks have reduced the impacts of urban development and flooding in Buffalo Bayou compared to nearby Brays Bayou, which was fully channelized in the 1960s (Juan et al. 2020). Photo: dave15957/iStock.

The Protective Value of Nature is available online at: www.nwf.org/protective-value-of-nature

1200 G Street, NW, Suite 900
Washington, D.C. 20005
www.nwf.org

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Patty Glick, Emily Powell, Sara Schlesinger, Jessie Ritter, Bruce A. Stein, and Amanda Fuller

Buffalo Bayou Park, Houston, Texas. Photo: dave15957/iStock

CONTENTS

EXECUTIVE SUMMARY

The Protective Value of Nature summarizes the latest science on the effectiveness of natural infrastructure in lowering the risks to communities from weather- and climate-related hazards—benefits that we often describe as "natural defenses." Over the past two decades, the body of research evaluating and quantifying the protective performance of natural infrastructure has increased significantly. Both model-based assessments and empirical evidence from recent floods, hurricanes, wildfires, and other natural disasters underscore the considerable risk reduction services that natural systems such as wetlands, reefs, dunes, floodplains, and forests provide. At the same time, natural infrastructure offers numerous additional benefits to society, from provision of food and clean water for people and habitat for fish and wildlife, to recreational opportunities, and cultural and spiritual fulfillment.

Long Island National Wildlife Refuge, New York. Photo: U.S. Fish and Wildlife Service

As we highlight throughout this report, evidence suggests that both natural and nature-based approaches for hazard mitigation can be equally or more effective than conventional structural approaches, and they are often more cost-effective. "Natural" approaches refer to intact or restored systems, such as wetlands, forests, and coral reefs; "nature-based" approaches mimic natural systems but are designed and constructed by people. Since healthy, intact ecosystems are often adapted to natural disturbances such as floods and wildfires, they may have the capacity to withstand or recover from extreme weather- and climate-related hazards and adjust to ongoing environmental changes. Conventional structural approaches (i.e., "gray infrastructure"), on the other hand, often require ongoing maintenance, and may need costly repairs when they fail or are damaged (Gittman and Scyphers 2017, Gray et al. 2017, Smith et al. 2017). Thus, natural defenses can play a critical role in enhancing the resilience of human and ecological systems to natural disasters and climate change.

Yet, the use of natural infrastructure for hazard risk reduction has not achieved its full potential. This is due, in part, to perceptions that conventionally engineered approaches, such as seawalls, levees, or dams, are always more effective—despite numerous instances when they have failed (Briaud et al. 2008, Gray et al. 2017, Koskinas et al. 2019). Further, national policies and programs have encouraged development in hazard-prone areas and have resulted in the degradation of existing natural systems that help to absorb floodwaters and buffer communities. As our human population continues to grow and a changing climate increases the frequency and severity of extreme weather events, risks from natural hazards will continue to escalate. Thus, there is an urgent need to dramatically scale up the application of natural infrastructure to better protect our communities.

This report, which builds on two previous publications published by the National Wildlife Federation, Allied World, and other partners (Natural Defenses from Hurricanes and Floods [Glick et al. 2014] and *Natural Defenses in Action* [Small-Lorenz et al. 2016]), is intended to synthesize and elevate the latest science to enhance awareness of the benefits of natural defenses and increase understanding of their effectiveness. The report also highlights key policy reforms needed to mainstream and increase the use of natural infrastructure in communities across the country.

A green roof in the heart of Denver, Colorado. Photo: U.S. Environmental Protection Agency

OVERVIEW

After more than two decades of increasingly severe, frequent, and costly weather- and climate-related disasters—from catastrophic wildfires and floods, to devastating hurricanes—reducing risks from natural hazards by enhancing the resilience of human communities has become a national priority (USGCRP 2018).

Natural disasters are taking an enormous ecological, social, and economic toll. Since 2010, the United States has experienced more billion-dollar disasters (i.e., events whose economic damages reached or exceeded $1 billion) than in any prior decade (NOAA 2020a). In 2017 alone, Hurricanes Maria, Irma, and Harvey killed thousands of people and caused more than $280 billion in damages. In 2018, the Camp Fire in California killed 88 people and destroyed more than 18,000 structures, with economic damages estimated at more than $16 billion. And in 2019, massive, unprecedented flooding in the Midwest inundated millions of acres of agriculture, homes, and businesses for months at a time. Unfortunately, the risks from natural disasters are expected to grow as an increasing number of people live and work in hazard-prone areas and as changing climatic conditions contribute to more frequent and severe events (USGCRP 2017).

To successfully reduce risks from weather- and climate-related hazards, the nation must be proactive in implementing strategies that reduce vulnerabilities before they happen, not just respond to them afterward. Historically, most U.S. communities have relied on structural approaches, also known as "gray infrastructure," to guard against natural hazards. Examples include use of river levees to protect against flooding, seawalls to protect against coastal storm surge and erosion,

Levee breach in Columbia, South Carolina. Photo: U.S. Air National Guard

and, in the case of forests and other wildlands, firebreaks and suppression to protect against wildfires. Although structural approaches will continue to be essential for safeguarding people and property in some places, recent events have shown that conventional approaches to address natural hazards can have considerable downsides. For example, during the record 2019 Midwest flood event, dozens of levees along the Missouri River and some of its tributaries were breached or overtopped, and hundreds of miles of levees were damaged. After decades of wholesale fire suppression as the default approach for wildfire risk mitigation, overgrown forests near populated areas across much of the West have contributed to increasingly severe and deadly wildfires. In coastal North Carolina during Hurricanes Irene and Matthew, properties with bulkheads sustained more damage and experienced greater shoreline erosion compared to properties with natural shorelines (Gittman et al. 2014, Smith and Scyphers 2019). Across the country, existing hard infrastructure is aging and in poor condition: dams, levees, and inland waterways, for example, all received "D" grades on the most recent report card of the American Society of Civil Engineers (ASCE 2017). Additionally, most existing infrastructure was designed for past conditions, making it more likely that such structures will fail to protect communities in the face of increasingly severe weather- and climate-related events (e.g., Little 2012, Robinson et al. 2017, Sutton-Grier et al. 2018).

Increasingly, attention has been turning toward natural and nature-based approaches for reducing risks to people and property, either as an alternative to, or in tandem with, structural approaches. As we highlight throughout this report, evidence suggests that natural infrastructure can be just as, if not more, effective in reducing risks. In addition, natural infrastructure is often more cost-effective than built infrastructure and offers numerous additional co-benefits. Indeed, the loss of natural systems due to development, resource extraction, invasive species, pollution, and a changing climate has, in hindsight, underscored the importance of natural infrastructure to people on many fronts. Yet, despite the important role that natural systems play in safeguarding our communities, uptake of nature-based measures for risk reduction remains slow. Increasing awareness and understanding about the effectiveness of natural and nature-based approaches for reducing risks, along with much needed reforms to public policies and programs designed to discourage development in hazardous areas, can go a long way toward expanding their use (Langridge et al. 2014, Spalding et al. 2014b).

Beaver dam in the Uinta-Wasatch-Cache National Forest, Utah. Photo: Tom Kelly/Flickr

Mouth of the Elwha River, Washington, where dam removal has restored natural sediment flows. Photo: National Park Service

WHAT IS NATURAL INFRASTRUCTURE?

"Natural infrastructure" refers to natural systems—for example, wetlands, forests, and coral reefs—that provide essential services and benefits to society, such as flood protection, erosion control, and water purification. This broad definition reflects the growing recognition of the vital role that nature plays in supporting and sustaining people and their livelihoods. In the wake of recent hurricanes, floods, wildfires, and other climate-fueled disasters, the role that healthy and intact ecosystems can play in enhancing the resilience of both natural and human communities has gained particular prominence among scientists and policy-makers (e.g., Guerry et al. 2012, Jones et al. 2012, Thompson 2012, Arkema et al. 2013, Nelson et al. 2013, Langridge et al. 2014, Martin and Watson 2016, Renaud et al. 2016, da Silva and Wheeler 2017, Thorne et al. 2018, Dallimer et al. 2020, Donatti et al. 2020).

Although the use of nature to provide risk reduction benefits (among other services) has been labeled in a variety of ways in the scientific literature and in policies and programs (see Box 1), we often refer to these protective services as "natural defenses." Investing in natural defenses entails the use of both natural and nature-based approaches to reduce risks to people, property, or other valued assets. In this context, "natural" approaches are those that rely on existing or restored natural systems (e.g., wetlands, floodplains, mangrove forests, beaches, dunes, barrier islands, and riparian zones) for their risk reduction and other associated benefits. "Nature-based" approaches mimic the risk reduction functions of natural systems but are designed and constructed by people using natural and man-made materials (e.g., living shorelines, engineered oyster reefs, beaver mimicry, engineered dunes). In addition, policies and programs that limit development in hazard-prone and environmentally sensitive areas—which are examples of "non-structural" approaches for risk reduction—are also important to enable, encourage, or mandate the use of natural and nature-based features (Bridges et al. 2015). Such approaches may include regulations, zoning, buyouts, construction standards, and legal protections for natural features like streams, floodplains, and wetlands.

Pelican on oyster reef at Bayview Park, Florida. Photo: Floridalivingshorelines.com

Box 1. Various terms to describe natural infrastructure

As noted by both da Silva and Wheeler (2017) and Escobedo et al. (2019), the concept of "ecosystems as infrastructure" is a powerful metaphor that can help integrate a variety of societal goals (e.g., climate mitigation, adaptation, risk reduction, and biodiversity conservation). Increasingly, it is being considered a complement, or even an alternative to, the built environment (i.e., gray infrastructure) to reduce risks from natural hazards.

Kettle Creek restoration, Colorado Springs, Colorado. Photo: U.S. Fish and Wildlife Service

However, attaching terms such as "ecological," "natural," "green," and "blue" with "infrastructure" is often done in different contexts and with different objectives, which can lead to misunderstandings and fragmentation of the practice, making it more difficult to mainstream the underlying concept (da Silva and Wheeler 2017). The lack of a consistent typology and usage has often led to vague definitions, particularly at the policy level, which may make it challenging to apply such approaches in on-the-ground management (Cohen-Shacham et al. 2019, Martín et al. 2020, Mendes et al. 2020). Among the various terms and usages are:

Ecosystem services

Ecosystem services generally refer to the multiple benefits that people obtain from ecosystems, including but not limited to provisioning services, such as food and water; regulating services, such as flood risk reduction; cultural services; and supporting services, such as oxygen production and carbon sequestration (MEA 2003, Reid et al. 2005, Adamowicz et al. 2019). Comparable term: natural capital (Natural Capital Committee 2017).

Green infrastructure

While the concept of green infrastructure initially referred to the value and role of open space and ecosystem services broadly (e.g., Benedict and McMahon 2006, Young et al. 2014), most recent usage more narrowly focuses on urban stormwater management, including use of plant or soil systems, permeable surfaces, and other approaches to reduce flows to sewer systems or other surface waters (U.S. EPA 2019a). Comparable terms: low-impact development (Ahiablame et al. 2012); blue-green infrastructure (Novotny et al. 2010).

Natural defenses

As used in this report, natural defenses refers to the hazard risk reduction benefits of ecological systems, whether they are the natural systems themselves or nature-based systems designed to emulate natural features. Comparable terms: natural and nature-based features (Bridges et al. 2015); natural infrastructure (da Silva and Wheeler 2017); ecological infrastructure (Adamowicz et al. 2019); nature-based solutions (Hobbie and Grimm 2020).

Nature-based solutions

The International Union for the Conservation of Nature defines nature-based solutions, a term commonly used in Europe, as "actions to protect, sustainably manage and restore natural or modified ecosystems, which address societal challenges (e.g., climate change, food and water security or natural disasters) effectively and adaptively, while simultaneously providing human well-being and biodiversity benefits" (Cohen-Shacham et al. 2016). Comparable terms: natural infrastructure; ecosystem services.

Ecosystem-based adaptation

Ecosystem-based adaptation derives from the ecosystem services concept, but its primary focus is how biodiversity and ecosystems can help people adapt to the growing impacts of climate change (Colls et al. 2009, Jones et al. 2012, Roe et al. 2019, Donatti et al. 2020). Ecosystem-based adaptation is considered a subset of nature-based solutions.

Natural climate solutions

In current usage, natural climate solutions refers to the conservation, restoration, and management of natural systems (e.g., forests, grasslands, wetlands, and mangroves) and agricultural lands to sequester and store carbon (Fargione et al. 2018, Griscom et al. 2019). Comparable term: ecosystem-based mitigation (Epple et al. 2016).

Although some studies have suggested that a more consistent typology is necessary to mainstream the concept of natural infrastructure, we argue that being clear about the underlying goals of using natural and nature-based approaches (e.g., their effectiveness in reducing risks, or their provision of climate protection benefits) is likely to be more important than the specific terminology used (Spalding et al. 2014c, Nesshöver et al. 2017, Escobedo et al. 2019, Mendes et al. 2020).

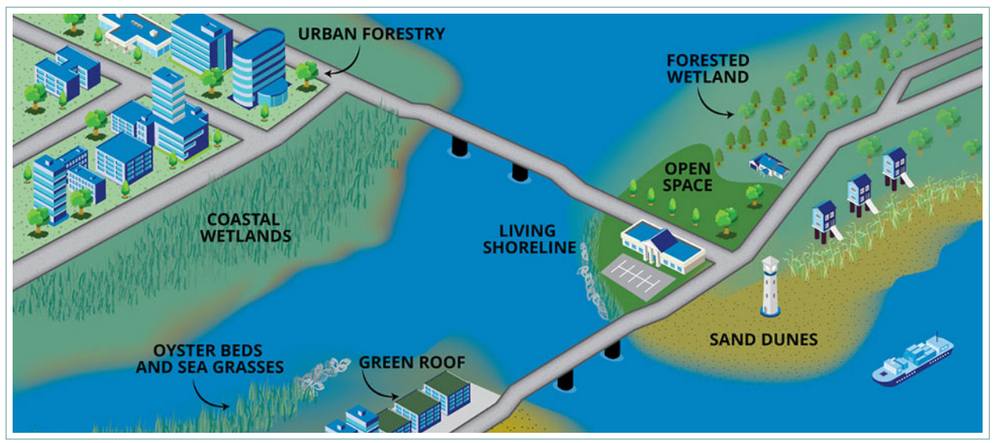
Conventional structural approaches for community protection will remain necessary in some places, but wherever possible, communities should prioritize the use of natural infrastructure given the many additional benefits it provides. This entails determining where natural approaches can be used either instead of, or in combination with, structural approaches to reduce the vulnerability of natural and human communities. Importantly, the efficacy of various natural defenses depends on a range of factors, including site-specific environmental conditions, the vulnerability of communities, and the type and severity of natural hazards to which they may be exposed (Ruckelshaus et al. 2016). Just as standards and guidelines are important for the engineering and application of gray infrastructure, guidance for the appropriate use of natural infrastructure is emerging (see Box 2) (The World Bank 2017).

Box 2. Evaluating the effectiveness of natural infrastructure for hazard risk reduction

As interest in natural infrastructure has grown, so too has the development of guidance and tools to support its application, including by enhancing transparency and quantifying its effectiveness. Indeed, the numerous studies highlighted in this report demonstrate a variety of approaches for evaluating the performance of natural and nature-based features, including indices, numerical models, field-based experiments, and empirical evidence. Evaluation tools and approaches have been developed by government agencies, nongovernmental organizations, academic institutions, and private entities alike.

Looking just at resources offered by U.S. federal agencies, the Engineering with Nature (EWN)® initiative of the U.S. Army Corps of Engineers initiative advances both technical and communication practices to align natural processes with engineering design, and includes a framework to support evaluation and implementation of natural and nature-based features in coastal areas (Bridges et al. 2014, Bridges et al. 2015). The U.S. Environmental Protection Agency's Green Infrastructure Modeling Toolkit (U.S. EPA 2019b) offers a range of models and tools to help project managers model and evaluate the performance of natural and engineered systems for stormwater management. The Federal Emergency Management Agency's report, *Innovative Drought and Flood Mitigation Projects* (FEMA 2017), describes a range of technical considerations and approaches for project design and evaluation, including ways to measure benefits and costs and ensure compliance with relevant federal, state, and local environmental and historic preservation requirements. The U.S. Department of Agriculture's Conservation Effects Assessment Project website (USDA, n.d.) provides links to a wide array of resources and tools from both governmental and nongovernmental entities offering guidance and tools for evaluating natural infrastructure.

In addition, the National Oceanic and Atmospheric Administration provides a range of tools for natural infrastructure, from data and visualization tools to job aids and trainings. The agency also maintains a searchable Green Infrastructure Effectiveness Database, which compiles information from a range of literature sources focused on the effectiveness of natural infrastructure approaches to reduce the impacts of coastal hazards (NOAA, n.d.). And the Joint Fire Science Program, a collaborative effort between the U.S. Forest Service and the Department of the Interior, works with partners across the country to assess the potential effectiveness of fuel treatments, improved community planning, and other approaches to reduce wildfire risks (JFSP, n.d.). These federal resources represent just a subset of a large and growing body of science to support the design and evaluation of natural infrastructure projects for hazard risk reduction.



Types of natural infrastructure. Graphic: National Oceanic and Atmospheric Administration

As highlighted in Table 1 and elaborated throughout this report, numerous types of natural infrastructure approaches for hazard risk reduction are now in use across the country. In addition to protective benefits, natural infrastructure provides communities with a wealth of other ecosystem services, such as improving water quality and helping recharge groundwater, supporting habitat for a multitude of fish and wildlife species, sequestering carbon, and providing aesthetic and recreational opportunities—all of which contribute to enhancing a community's resilience to a range of threats. Globally, the estimated value of ecosystem services provided by natural systems, as a whole, ranges from $125–$145 trillion per year (Costanza et al. 2014). In the United States alone, coastal habitats provide estimated benefits valued at over $100 billion annually (Sutton-Grier et al. 2018).

Table 1. Examples of natural infrastructure for hazard risk reduction

Natural hazard	Conventional approaches	Natural or nature-based approaches	Examples
Inland flooding and erosion	Dams, dikes, levees, stream channelization, stormwater sewers, combined sewers, pumps	• Floodplain and watershed restoration • Green stormwater management • Protecting floodplains from development	• Levee setbacks • Wetland, forest and watershed restorations • Rain gardens and natural infiltration systems • Minimizing stream alterations • Permeable pavement • Voluntary buyouts • Avoiding new development in floodplains • Open space acquisition and protection
Coastal flooding and erosion	Seawalls, bulkheads, dikes, breakwaters, levees	• Coastal habitat protection and restoration • Living shorelines • Protecting sensitive coastal areas from development	• Intact or restored shoreline systems (e.g., wetlands, mangroves, beaches, dunes, and barrier islands) • Coral and oyster reefs • Restored/constructed marsh with sills or breakwater structures • Constructed oyster reefs • Voluntary buyouts • Coastal land acquisition and easements
Extreme heat and drought	Dams and reservoirs, air conditioning	• Watershed protection and restoration • Urban green infrastructure • Water conservation	• Forest and watershed restoration • Beaver restoration • Urban trees and other vegetation • Green roofs and cool pavement • Rain barrels • Xeriscaping
Wildfire	Wholesale suppression of wildfires, clearing firebreaks	• Ecological forest management • Helping communities live with fire • Managing wildfires (when possible) to benefit ecosystems	• Combined fuel reduction treatments • Prescribed fire • Post-fire restoration • Fire-adapted communities, such as through Firewise USA® neighborhood mitigation • Collaborative risk management • Avoiding new development in high-fire-risk areas

KEY CLIMATE CONSIDERATIONS

One of the primary reasons communities are increasingly turning to natural defenses against extreme weather- and climate-related hazards is that many natural systems already are well adapted to natural disturbance regimes and have the capacity to withstand or recover from the impacts (Feagin et al. 2010, Spalding et al. 2014b). For example, the natural deposition of sediments from upstream or upland sources can provide sufficient levels of soil for marshes in deltas and estuaries to rebuild after storms and keep pace with rising sea levels through a process called accretion (Batker et al. 2010). Beaches and other coastal habitats can migrate landward and seaward in response to both acute and gradual changes over time, particularly in the absence of man-made or natural barriers such as seawalls or bluffs (Spalding et al. 2014b, Leo et al. 2019). And in many forest ecosystems, periodic wildfires are essential for forest health by clearing dense undergrowth and contributing to habitat complexity.

Unfortunately, the combination of changing climatic conditions and other anthropogenic stressors have degraded ecosystems in many areas and significantly reduced their natural adaptive capacity (Stott et al. 2016, Seddon et al. 2020). In parts of the West, for example, a combination of increasingly intense, drought-enhanced wildfires and invasive species have reduced the potential for forests to regenerate on their own (Jones et al. 2016, Dey et al. 2019). Along the Gulf Coast, construction of levees and navigation channels, oil and gas operations, and other activities have contributed to land subsidence and starved coastal wetlands of sediments. And around the world, coral reefs are in rapid decline due to a combination of development, pollution, overfishing, storms, climate-related bleaching, and ocean acidification (Hoegh-Guldberg et al. 2017, Beck et al. 2018, Gibbs and West 2019). Climate change is likely to further push these and other systems to their limits as sea levels rise and weather events become more frequent and severe. Of particular concern is the fact that multiple threats are occurring at the same time. For example, while extreme heat and drought on their own pose considerable risks to communities, they are also exacerbating wildfires. In turn, severe wildfires can lead to flooding and erosion, sediment loading, and long-term changes in forest water yield (Hogue et al. 2018). Ultimately, this results in a vicious cycle that threatens the health and sustainability of human and natural communities alike.

Because of these man-made stresses, nature needs our help for it to provide, or continue providing, its protective services. It is important to think not only about the vulnerability of human communities and livelihoods to the impacts of extreme weather and climate-fueled natural disasters, but also the vulnerability of the natural systems on which we depend. Doing so in parallel will allow communities to identify when and where existing and intact natural systems can provide these protective functions, and where it is necessary to restore ecosystems or design adaptation strategies that can enhance the capacity of those systems to provide risk reduction benefits. Thus, managers must consider these complexities in both the design and management of natural infrastructure. This will entail conducting climate vulnerability assessments that consider a range of future scenarios to inform project development and management. It also necessitates investing in consistent, long-term monitoring and evaluation of those projects to keep track of changing conditions and determine whether and how much they are achieving risk reduction benefits and other desired outcomes (Walles et al. 2016, Zellner et al. 2016, Emilsson and Sang 2017, Marsooli et al. 2017, Rosenzweig et al. 2018, Leo et al. 2019, Morris et al. 2019, Reynolds et al. 2019, Sun et al. 2019, Hobbie and Grimm 2020).

2017 La Tuna fire, Los Angeles, California. Photo: Scott L./Flickr

INLAND FLOODING

UNDERSTANDING FLOOD RISKS

Floods are among the most frequent and expensive natural hazards in the United States, often reaching billions of dollars a year in damages (Kousky 2010, Michel-Kerjan and Kunreuther 2011, Pralle 2019, Truhlar and Bergstrom 2019). While flooding occurs naturally and can be beneficial for some ecosystems, floods become "hazards" when they have adverse effects on people and the environment. Floods can have a wide range of impacts, including loss of life, destruction of property and infrastructure, spread of pollutants, and disruption to agriculture and other sources of livelihood.

To identify the best ways to reduce flood risks, it is important to recognize that there are three different types of floods: riverine, surface, and coastal. Riverine floods, also known as fluvial floods, occur when the water in rivers, streams, or lakes overflows and/or erodes their banks. Surface, or pluvial, floods can occur away from existing water bodies. They occur when rainfall exceeds the capacity of drainage systems, such as urban stormwater infrastructure. In general, coastal floods are associated with storm surge, but increasingly also from extreme high tides even in the absence of storms. In this section, we highlight risks and management approaches associated with riverine and surface floods, also referred to as "inland flooding." Coastal flooding is addressed in the next section, although it is important to recognize that coastal communities may simultaneously be affected by coastal, riverine, and surface flooding, sometimes during the same storm.

Risks from flooding are exacerbated by development and other human activities (Mondal and Patel 2018). Urbanization, in particular, can considerably alter flood hydrology (Ntelekos et al. 2010). An increase in paved roads, parking lots, and other impervious surfaces, for instance, contributes to greater runoff into rivers, streams, and low-lying areas, which may lead to flooding and fluvial erosion during both moderate rainfall and heavy downpours (Ogden et al. 2011, ASFPM Riverine Erosion Hazards Workgroup 2016). In addition, construction of levees and the placement of fill materials into areas such as wetlands to allow for development in one part of a floodplain can lead to "increased flooding downstream (Heine and Pinter 2011). Stream straightening, ditching, and armoring to protect streamside investments at one location can lead to increased riverine erosion downstream (Christin and Kline 2017). In addition, construction of wing dikes and related structures intended to improve navigability of rivers can also lead to significant upstream flooding by constricting river channels and blocking flows (e.g., Pinter et al. 2008, Remo et al. 2009, Huthoff et al. 2013). On a broader watershed scale, activities such as clearcutting and conversion of forest land to agriculture and urban development can exacerbate flooding by reducing filtration and increasing runoff (Harman et al. 2012).

In the coming decades, the risks and associated damages for both types of inland flooding (surface and riverine) are expected to grow due to a combination of human population growth, land-use changes, and an increase in the frequency and intensity of heavy rainfall (AECOM and FEMA 2013; Wobus et al. 2013, 2017). Heavy precipitation events (i.e., the most intense 1% of rainfall events) have already increased across much of the conterminous United States (Kunkel et al. 2013, USGRP 2017, Hayhoe et al. 2018). Such events have contributed to historic flooding. For example, Louisiana experienced a devastating flood in August 2016 as a slow-moving storm dumped more than 20 inches of rain across the region over a three-day period (Kunreuther et al. 2019). Tens of thousands of homes were affected by the flood, which scientists have attributed at least in part to climate change (van der Wiel et al. 2017). In 2019, which was the second wettest year on record in the United States, massive, long-lasting flooding devastated much of the Midwest (NOAA 2020b). The Missouri River basin experienced more than a year's worth of runoff from snowmelt and rainfall from March through May 2019, causing an estimated $20 billion in damage and economic losses—nearly half the total cost for all 14 of the billion-dollar disasters that year (NOAA 2020b).

At a Glance

- Floods are among the most frequent and expensive natural hazards in the United States; a combination of historic stream and river channelization, increased development, and heavier rainfall due to changing climatic conditions is exacerbating flood inundation and erosion risks across the country.
- The use of natural infrastructure for stormwater and flood management can effectively reduce risks from flooding, in addition to providing other benefits, such as improved water quality, recreational opportunities, and habitat for fish and wildlife.
- Natural infrastructure approaches for reducing flood risks range from floodplain and watershed restoration and green stormwater infrastructure, to policies and programs that prevent new development in hazard-prone areas and encourage people to move out of harm's way.

Widespread flooding in Port Arthur, Texas, caused by record rainfall from Hurricane Harvey. Photo: South Carolina National Guard

Flooding in Nashville, Tennessee, in 2010. Photo: U.S. Army Corps of Engineers

NATURAL DEFENSES FOR FLOODS

Despite increasing risks, local governments continue to allow for unwise development in flood-prone areas, and reliance on conventional or outdated flood management practices—such as construction of levees and dredging—remains common across the country. There is growing recognition that the use of natural infrastructure for stormwater and flood management can effectively reduce risks from flooding and riverine erosion, in addition to providing other benefits, such as improved water quality, recreational opportunities, and habitat for fish and wildlife (e.g., Kousky and Walls 2013, U.S. EPA 2014, Eckart et al. 2017, Moore et al. 2016, Frantzeskaki et al. 2019, Venkataramanan et al. 2019). Further, evidence suggests that investing in natural infrastructure to reduce flood risks makes economic sense (e.g., Baumgärtner and Strunz 2014, Green et al. 2016, Denjean et al. 2017, Martín et al. 2020). Natural infrastructure approaches for flood risk reduction range from floodplain and watershed restoration and green stormwater infrastructure, to policies and programs that help restore and protect natural systems to reduce flood risks (Carter and Lipiec 2020, Hobbie and Grimm 2020). This may include preventing new development in hazard-prone areas or encouraging people to move out of harm's way.

Andorra Creek floodplain restoration. Photo: Montgomery County Planning Commission

Buffalo Bayou effectively capturing flood waters in downtown Houston, Texas, after Hurricane Harvey. Photo: National Oceanic and Atmospheric Administration

FLOODPLAIN AND WATERSHED RESTORATION

Restoring streams, floodplains, and watersheds to reestablish their natural flows, ecological processes, and functions is one of the most important and beneficial strategies to reduce flood risks to communities, while providing considerable additional ecological and economic benefits. There are numerous techniques for restoring the ecological integrity of streams and floodplains, the most appropriate of which will depend on the unique characteristics and conditions of the area being restored, as well as the desired management outcomes.

2017 Oroville Dam spillway failure in California. Photo: William Croyle/California Department of Water Resources

Levee Setbacks and Dam Removal

In the wake of disastrous floods, many communities across the country have invested in efforts to make "room for the river" through levee setbacks, dam removal, and floodplain restoration. According to the U.S. Army Corps of Engineers (USACE), the additional floodplain storage provided by levee setbacks reduces flood height and slows peak flows, while also providing additional ecosystem and recreation benefits (Dahl et al. 2017). In Washington State, for example, a project involving the reconnection of side channels, moving 1.5 miles of levees farther from the Puyallup River, and installing logjams has dramatically reduced flood risks to the nearby city of Orting (Floodplains by Design 2014). In Yuba County, California, the Three Rivers Levee Improvement Authority worked with the USACE to set back 9,600 feet of levees along the confluence of the Bear and Feather rivers, reconnecting 600 acres of flood-prone agricultural land to the floodplain (River Partners 2014). The project proved successful in capturing floodwaters and reducing flood risks to nearby communities after the Oroville Dam crisis in 2017, when damage to the main and emergency spillways during an extreme rainfall event prompted the evacuation of more than 180,000 people living downstream (Stork et al. 2017, Hollins et al. 2018). In addition, the land has since been restored into riparian and grassland habitat that supports numerous species of fish and wildlife, provides a variety of recreational opportunities, and helps buffer the release of pollutants from nearby agricultural operations into the rivers. A study along the Middle Mississippi River found that a combination of levee setbacks and voluntary buyouts of the resulting unprotected structures would reduce flood losses from both large/infrequent and small/frequent flood events (Dierauer et al. 2012). And in Massachusetts, a Department of Fish and Game Division of Ecological Restoration (DER) project to remove three dams proved to be 60% less expensive than repair and maintenance would have been over the next 30 years by restoring floodplains and removing the risk of dam failure. In addition, the removal significantly reduced flood risk to the surrounding areas. Other benefits cited from the dam removals in the DER report include avoided travel delays, infrastructure damage, and costs of emergency response, in addition to increases in nearby property value, added recreational value, and improved quality and availability of stream habitat (MDFG 2015).

Bear River setback levee in California. Photo: California Department of Water Resources

Wetland and Forest Restoration

Wetlands act as natural sponges, storing and slowly releasing floodwaters after peak flood flows have passed (Antolini et al. 2019, Krasowski 2019). Research suggests that a single acre of wetland can store up to 1.5 million gallons of floodwater (U.S. EPA 2002). A meta-analysis of economic valuation literature for a number of countries around the world suggests that wetlands in agricultural areas provide an estimated $2,802 per acre per year in flood control services (Brander et al. 2013). Here in the United States, an assessment of flood reduction potential of wetlands in the Eagle Creek watershed of central Indiana found that they reduce peak flows from rainfall by up to 42%, flood area by 55%, and maximum stream velocities by 15% (Javaheri and Babbar-Sebens 2014).

Certain forest and other wildland management practices may also reduce risks to nearby communities from flooding and debris flows following high-severity wildfires, which can burn away much of the vegetation that holds soil in place and slows runoff (Garfin et al. 2016). Flood risk can remain significantly higher in severely burned areas until vegetation is restored, which can take years to decades (Floyd et al. 2019). As discussed further in the section on Wildfires (page 24), ecological forest management, including targeted thinning, prescribed fire, and long-term rehabilitation and restoration activities can reduce the severity of future wildfires and help minimize associated risks to communities. In the near term, post-fire treatments, such as application of mulch and erosion barriers and aerial seeding with native grasses and other plants, also may be necessary to mitigate runoff and erosion (Napper 2006, Robichaud 2009, Robichaud et al. 2020). For example, an evaluation of post-fire treatment after the 2012 High Park Fire in the Poudre River basin of Colorado found that areas seeded with a native perennial grass mix had greater vegetation cover one year after the fire than unseeded control areas. In addition to helping reduce erosion, the seeded areas had significantly fewer weeds than the control areas (Miller et al. 2017). However, it is important to recognize that the appropriateness and effectiveness of post-fire treatments will vary, depending on local conditions and the severity of the fire. For instance, tradeoffs may exist between use of seeding to reduce erosion and recovery of natural plant diversity. Ongoing monitoring is essential following treatment to evaluate their effectiveness and help ensure that short-term mitigation benefits do not come at the expense of long-term ecosystem restoration goals (Robichaud 2009).

GREEN STORMWATER MANAGEMENT

Green infrastructure is an integrated approach to stormwater management that uses features such as rain gardens, green roofs, bioswales (i.e., vegetated trenches), and permeable pavement in strategic areas to capture stormwater runoff as close as possible to where it is generated. Conventional stormwater management approaches focus on speeding passage of water downstream, which can result in flooding and degraded water quality. In contrast, green infrastructure approaches are specifically designed to slow the flow of runoff to facilitate absorption in soil and vegetation and take pressure off over-capacity sewage treatment plants. This is particularly important in cities that have older "combined sewer systems," in which one piping system conveys both sanitary sewage and stormwater. Not only does green infrastructure help improve water quality by diverting and filtering pollutants, it can help mitigate surface flooding during storms, often at a significant cost savings.

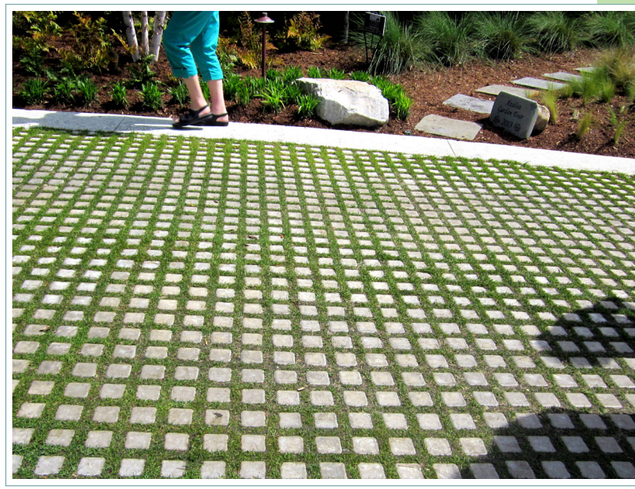
The following are a few examples of green infrastructure approaches:

Rain Gardens and Natural Infiltration Systems

The use of rain gardens, which are planted depressions designed to allow runoff from nearby impervious areas to soak into the ground, has grown in popularity in communities across the country. Research has shown that rain gardens can significantly reduce runoff into storm drains, thereby increasing the capacity of existing drainage systems to handle higher rainfall volumes (Mahler et al. 2019). For example, a study of a rain garden constructed in the Bronx, New York, found that the system retained an average of 78% of inflows during 26 storms over the period between October 2014 and July 2015 (Feldman et al. 2019). The Capitol Region Water District in Ramsey County, Minnesota, has installed a suite of green infrastructure projects, including rain gardens, underground infiltration trenches, and a stormwater retention pond, to address both localized flooding and polluted runoff into nearby waterways. Together, the network of green infrastructure can capture drainage from more than 10% of the watershed area and can filter an estimated 94% of stormwater volume from the sub-watershed (CRWD 2012, Small et al. 2019).

Permeable Surfaces

Increasing the area of pervious, or permeable, surfaces in urban and suburban areas, whether through enhancing vegetated areas or installing gravel or other porous materials, can significantly reduce localized flooding. In natural areas, as much as 85% of rainfall will infiltrate into the ground (FEMA 2005). According to FEMA, the amount of runoff from a five-year storm (i.e., a heavy rainfall event that has a 20% chance of occurring each year) on a developed parcel can be greater than the runoff from a 50-year storm if the parcel had not been developed (FEMA



Permeable paver patio can increase infiltration and reduce stormwater runoff. Photo: ECV-OnTheRoad

2005). In Portland, Oregon, investments in "green streets" (i.e., the use of pervious surfaces in streets and alleyways), along with rain barrels and tree planting, have been estimated to be 3–6 times more effective in managing stormwater per $1,000 invested compared with conventional, gray infrastructure methods (Foster et al. 2011). The city's investment of $8 million in the green infrastructure projects saved an estimated $250 million in avoided hard infrastructure costs. In addition, the city's green street projects retain and infiltrate nearly 43 million gallons per year and have the potential to manage as much as 8 billion gallons—40% of Portland's average annual runoff volume (Foster et al. 2011).

PROTECTING FLOODPLAINS FROM DEVELOPMENT

Keeping people out of harm's way is an important strategy for reducing the costs of major floods and enhancing the natural ability of floodplains to absorb floodwaters and lessen their destructive force.

Open Space Acquisition and Protection

Protecting open space from development can significantly reduce flood damage to nearby communities. For example, instead of being sold to developers, an abandoned golf course in Clear Lake, Texas, was purchased by the Clear Lake City Water Authority and converted to a 178-acre park and wetland, which protected 300 residents and 150 homes from significant flooding during Hurricane Harvey (FEMA 2019, GBF 2019). At the time Harvey came through, the system collected 100 million gallons of water, even with only 80% completion of the first of five phases. Later phases of the project, which are expected to be finished by 2022, include creating detention ponds, wetlands, a nursery for native trees, miles of hike/bike trails, areas of native bushes and grasses, and athletic fields. When fully completed, the project is expected to drain half a billion gallons of stormwater and protect 2,000 homes (FEMA 2019). Preserved floodplain and wetlands around Otter Creek upstream of Middlebury, Vermont, helped reduce the damage from Tropical Storm Irene by 84–95% and provide between $126,000 and $450,000 in annual flood mitigation services. The wetlands are mainly composed of forested swampland and span 18,000 acres (Watson et al. 2016). Additionally, Kousky et al. (2014) estimate that the Meramec Greenway, which comprise 28,000 acres of forest and other conservation lands along the Meramec River in southern Missouri, contributes about $6,000 per acre in avoided flood damages annually.

Restoration of Sims Bayou in Houston, Texas consisted of earthen channels and tree plantings to reduce flood risks.. Photo: SWA Group

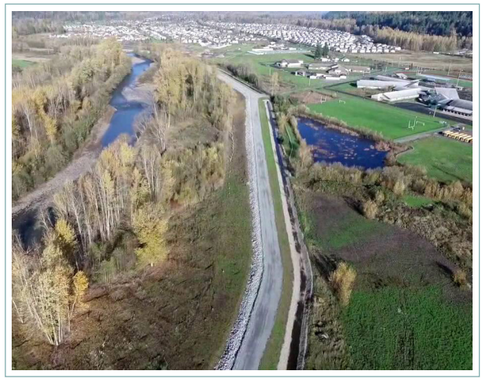
For the conterminous United States as a whole, scientists estimate that preventing development in the more than 100,000 square miles of remaining unprotected natural lands that lie within the current 100-year floodplain would avoid as much $397 billion in potential flood damages to new development by 2050 (Wing et al. 2018). Although the cost of purchasing land may outweigh the potential flood mitigation benefits in some areas, targeting investments based on preservation costs and expected flood damages could yield significant net benefits (Kousky et al. 2013, Kousky 2014). Indeed, Wing et al. (2018) found that the benefit of avoiding flood damages associated with future development exceeds the cost of acquiring undeveloped land in the majority (70%) of the counties they studied.

Voluntary Buyouts

In places where properties have been extensively and repetitively damaged by flooding, voluntary buyouts—the acquisition and removal of properties in hazard-prone areas—can be a cost-effective response to reduce risks from future flooding (Siders 2019). A number of communities across the country have engaged in buyout programs in response to major flooding events. For example, after a massive flood in 2008 that dislocated 18,000 people, damaged more than 7,000 properties, and caused billions of dollars in losses, Cedar Rapids, Iowa, undertook a major buyout and relocation program, purchasing 1,300 damaged properties (Carter 2009). Many of the properties were commercial, and owners used the funds to relocate their businesses elsewhere within the city. Cedar Rapids is now moving forward in creating a system of parks and open space along its riverbanks that will be designed to accommodate floods. In Charles County, Missouri, a buyout program following the major flooding of 1993 is estimated to have prevented losses of nearly $97 million from flooding events that occurred between 1999 and 2008. This represented a 212% rate of return on the $44 million dollars that Missouri and FEMA had spent on the properties (FEMA 2009). Since 1999, the City of Charlotte and Mecklenburg County in North Carolina have overseen a voluntary buyout program that has combined the relocation of families and businesses from flood prone areas with subsequent stream and wetland restoration. As of September 2019, the program has spent $67 million to acquire more than 400 properties and has restored 185 acres of the floodplain to public open space. The effort has helped communities avoid approximately $25 million in property damage, and it is expected to prevent an estimated $300 million in future losses (City of Charlotte 2019).

Although buyout programs have been implemented for decades, they have often been done through piecemeal approaches that leave a patchwork of remaining structures and vacant lots, which do not offer the flood reduction benefits that larger green space could provide (Mach et al. 2019). Further, it is important that buyout programs be founded on sound social and ecological principles (Kousky and Kunreuther 2010, Kousky and Walls 2013, Berke et al. 2014). First, the community as a whole must be truly engaged in decisions (Verchick and Johnson 2013). Without full community participation, not only would the benefits of such buyouts for flood risk reduction over a large scale be minimized, but there could be animosity among remaining property owners toward participating households if such buyouts are perceived to lower property values (Glick et al. 2014). Second, decision-makers must incorporate the needs of the socially vulnerable into buyout programs, such as by taking measures to ensure that affordable homes and jobs are available in areas where people will be relocated (Siders 2019).

Disadvantaged communities are often particularly vulnerable to natural disasters. Social equity issues are important to address in flood risk reduction programs and buyout policies. Photo: Jocelyn Augustino/ Federal Emergency Management Agency



Calistoga Reach floodplain restoration in Washington. Photo: CSI Drone Solutions and Washington Rock Quarries, Inc.

Farmland with wetland buffer, prairie potholes region, Iowa. Photo: Mark Vandever/U.S. Geological Survey

COASTAL HAZARDS

UNDERSTANDING COASTAL HAZARD RISKS

The coastal zone is a naturally dynamic place. Beaches, barrier islands, marshes, and other coastal systems change over time as storms, erosion, sedimentation, and other natural forces shape these landscapes. Coasts are also magnets for population centers due to their natural beauty and rich, biodiverse ecosystems that support vibrant economic, recreational, and cultural activities. As of 2017, about 94.7 million people in the United States live in coastline counties, an increase of 15.3% since 2000 (U.S. Census Bureau 2019). Those living in the coastal zone know, however, that the benefits also come with risks from storms, coastal flooding, and shoreline erosion. These existing threats are compounded by urbanization, aging infrastructure, and changing climatic conditions, including warming oceans and rising sea levels (Fleming et al. 2018). Recent studies suggest that climate change is contributing to an increase in tropical cyclone activity, which scientists have linked to warmer oceans and an accompanying increase in atmospheric moisture content. In the coming decades, both wind and rainfall intensity associated with these storms are projected to increase, which could translate into a greater proportion of storms reaching Category 4 and 5 (IPCC 2014, Knutson et al. 2019).

In addition, sea-level rise is exacerbating storm surge and contributing to more frequent flooding during high tides (Tebaldi et al. 2012, Marsooli et al. 2019). During the past century, the average global sea level rose about 8 inches, and since the early 1990s the rate of sea-level rise has been accelerating (Nerem et al. 2018). In some areas, such as along parts of the Gulf and Atlantic coasts, relative sea levels have increased even more due to land subsidence and other factors. As global temperatures increase with continued greenhouse gas emissions, further sea-level rise is inevitable due to the thermal expansion of oceans and increased melting of land-based ice, placing areas farther inland at increased risk (Sriver et al. 2012, Bamber and Aspinall 2013, Miller et al. 2013, Kopp et al. 2014, USGCRP 2017).

At a Glance

- Coastal communities face considerable risks from storms, coastal flooding, and shoreline erosion; as climate change contributes to rising sea levels and an increase in the intensity of tropical cyclones, the frequency and severity of these hazards will continue to grow.
- Although hard armoring, such as seawalls and bulkheads, continues to expand along populated coastal areas, people are increasingly embracing natural infrastructure to reduce risks; coastal communities have been important test beds for demonstrating the efficacy of natural infrastructure to address a range of natural hazards.
- Coastal natural infrastructure approaches range from protection and restoration of natural systems and use of living shorelines, to voluntary buyouts and protection of coastal open space.

Beach and dune restoration in Louisiana. Photo: Coastal Protection and Restoration Authority

Damage from Hurricane Ike in Texas in 2008. Photo: Federal Emergency Management Agency

NATURAL DEFENSES FOR COASTAL HAZARDS

Following two decades of particularly destructive tropical storms and hurricanes, coastal communities are expanding their tools for keeping people safe and protecting property and infrastructure. Although hard armoring continues to expand along populated coastal areas across the country (Gittman et al. 2016), communities are increasingly embracing natural infrastructure as part of the solution. Approaches range from protection and restoration of natural systems and use of living shorelines, to voluntary buyouts and protection of coastal open space. Indeed, coastal communities have been important test beds for demonstrating the efficacy of natural infrastructure for reducing risks from a range of natural hazards (Spalding et al. 2014b, 2014c).

COASTAL HABITAT RESTORATION

Coastal habitats, such as freshwater and salt marshes, mangrove forests, beach and dune complexes, and coral and oyster reefs, can provide significant risk reduction benefits to coastal communities (Rezaie et al. 2020). For instance, field-based studies from around the world reveal that coastal habitats can reduce wave heights by 35–71% (Narayan et al. 2016).

Florida mangroves. Photo: National Oceanic and Atmospheric Administration

Coastal Wetlands

A recent analysis of all 88 tropical storms and hurricanes that impacted the United States between 1995 and 2016 found that affected counties with greater areas of wetland coverage experienced significantly less property damages than those with little or no wetlands (Sun and Carson 2020). Although the expected economic value of the protective benefits provided by wetlands varies from one region and storm to the next, wetlands can provide an average value of about $700,000 per square mile annually (Sun and Carson 2020). During Hurricane Sandy in 2012, coastal wetlands prevented an estimated $650 million in direct flood damages (Narayan et al. 2017). Along the Gulf Coast, the benefit–cost ratio of wetland restoration for flood risk reduction is estimated to be 8:1, compared with only 0.99:1 for local levees in high-risk areas (Reguero et al. 2018).

Scientists estimate that mangrove forests around the world reduce property damage by more than $65 billion and protect more than 15 million people per year from coastal flooding (Menéndez et al. 2020). Evidence has shown that mangroves can reduce wind- and swell-driven waves by 13–66% per 328 feet of mangrove (Mazda et al. 2006, Quartel et al. 2007, Spalding et al. 2014a). In southern Florida, for instance, research found that intact mangroves and riverine mangrove habitat reduced peak storm surge heights by as much as 3 inches for per half mile

during Hurricanes Charley (2004) and Wilma (2005) (Krauss et al. 2009). In addition, mangrove forests in the region were found to slow the rate of Hurricane Wilma's storm surge and reduce inundation of inland wetlands by an area of nearly 700 square miles (Zhang et al. 2012).

Beaches, Dunes, and Barrier Islands

The broad range of benefits to communities from ecologically-sound beach and dune restoration projects can significantly outweigh the costs, even when considering that beaches and dunes may require periodic sand nourishment and plantings to persist and keep pace with rising sea levels and more intense storms (Taylor et al. 2015). Recent storm events have demonstrated the effectiveness of beach and dune restoration from a risk reduction perspective. Following a nor'easter in 1992 that flattened dunes and caused major flooding to coastal communities in New Jersey, dunes in some areas were restored to a height of 25 feet and a width of 250 feet using snow fencing and dune plantings. When Hurricane Sandy hit the region in 2012, the dunes suffered some damage, but adjacent beachfront communities avoided severe flooding and damages. A neighboring community without restored dunes suffered major losses (Barone et al. 2014).

As their name implies, barrier islands can also play a significant role in buffering the mainland coastline against waves and storm surge (Oliver and Ramirez-Avila 2019). A study of Hurricane Ike's storm surge along the Texas–Louisiana coast found that both Bolivar Peninsula and Galveston Island deflected much of the surge waters eastward, reducing its impact on Galveston Bay (Rego and Li 2010). Research also suggests that large-scale restoration of barrier islands in Louisiana and Mississippi can reduce wave heights by up to 90% and slow peak storm surge by up to two hours relative to a degraded system (Grzegorzewski et al. 2009).

Coral and Oyster Reefs

Coral and oyster reefs act as breakwaters that reduce shoreline erosion and attenuate wave height and energy as waves move landward (Ferrario et al. 2014, Manis et al. 2014, Beck et al. 2018). A meta-analysis of risk reduction benefits provided by coral reefs around the world suggests that they can reduce wave energy by an average of 97% compared with areas without coral reefs (Ferrario et al. 2014). Using process-based flood models, Beck et al. (2018) estimate that, across the world's reef-lined coasts, coral reefs reduce annual expected damages from storms by more than $4 billion. Without reefs, annual damages would be more than double that amount. In the United States, Storlazzi et al. (2019) estimate that coral reefs would reduce flood risks for more than 18,000 people and save more than $1.8 billion in avoided damages under a range of potential coastal storm scenarios. Restoration of natural

Breaking wave over coral. Photo: U.S. Geological Survey

oyster reefs also has become increasingly popular as a measure to reduce coastal erosion, while providing a range of other ecosystem services (Scyphers et al. 2011). In San Francisco Bay, for example, a project that included restoration of both native oysters and eelgrass was found to reduce wave energy by 30% compared with unrestored areas, in addition to increasing habitat, food resources, and biodiversity (Newkirk et al. 2018). Healthy, growing oyster reefs may also have the ability to keep pace with rising sea levels naturally, particularly in intertidal zones, which would help maintain their protective benefits over time (Rodriguez et al. 2014).

LIVING SHORELINES

Living shorelines refer to a range of shoreline stabilization techniques to reduce erosion through the use of ecological approaches, as opposed to strictly gray infrastructure (NOAA 2015, Hilke et al. 2020). A living shoreline generally incorporates natural materials, such as vegetation, rocks, and shells, either used alone or in combination with engineered structures for added stability. Commonly used structural components include constructed reefs, sills, revetments, and biologs (e.g., coir or fiber logs). Living shorelines typically serve to reduce shoreline erosion in ways that enhance habitat value and support natural coastal processes, while also providing added storm protection. The application of living shorelines spans the full range of approaches—from completely natural ("soft") approaches like newly placed vegetation, to hybrid ("green-

A living shoreline with an offshore oyster reef in Florida attracts wildlife and protects the shoreline. Photo: Kaila Drayton, NWF.

gray") approaches. Like other forms of natural defenses, living shorelines have the capacity to adapt to changing conditions and self-repair following storms, and they are often more cost-effective for shoreline stabilization compared to conventional forms of shoreline armoring like bulkheads.

Vegetation Only

In some areas, enhancing vegetation in degraded areas or creating vegetative cover in non-vegetated tidal areas can be sufficient to reduce wave height and erosion (Subramanian et al. 2008). Field observation research in the Chesapeake Bay, for example, found that areas planted with *Spartina alterniflora* demonstrate significant wave attenuation capacity during storms (Garzon et al. 2019). During a 100-year storm, the marsh was found to reduce wave height by 70% (Garzon et al. 2019). In addition, for every dollar spent to construct vegetative shoreline stabilization, as much as $1.75 is returned to the economy in the form of improvements to ecological resources, including submerged aquatic vegetation, fish, benthic organisms, shellfish, waterfowl, and wetland habitat (Subramanian et al. 2008). Further, Gittman et al. (2016) found that shorelines hardened with seawalls support 23% lower biodiversity and 45% fewer organisms than natural shorelines. Importantly, monitoring may be necessary in the early stages of project implementation to ensure that newly planted areas have conditions sufficient to enable the establishment, survival, and growth of associated plants (Shao et al. 2020).

Combined Vegetation and Structural Approaches

Hybrid approaches that blend vegetation and other natural structural materials may offer greater protective benefits than vegetation alone, and at a lower cost than conventional hard armoring. A comparative cost analysis of ten shoreline protection measures in the Hudson River estuary, for instance, found that, under a scenario of rapid sea-level rise, sites with ecologically enhanced features such as vegetated geogrids (i.e., successive layers of soil wrapped in geotextile fabric) and rock sills would have significantly lower maintenance, damage, and replacement costs when compared with those with hard armoring (Rella and Miller 2014). In addition, property owners with bulkheads in North Carolina have reported paying more for installation, annual maintenance, and storm-related repairs compared with those with revetments and natural shorelines (Gittman and Scyphers 2017, Smith et al. 2017). Recent analysis of 17 living shoreline sites with sills along the coast of North Carolina found that shoreline change rates at 12 of the sites exhibited a significant reduction in the rate of erosion compared to control sites, and six of those sites were observed to be accreting (Polk and Eulie 2018). During Hurricane Matthew in 2016, a living shoreline project on the Outer Banks composed of restored salt marsh and rock sills proved more effective at reducing shoreline erosion than bulkheads (Smith et al. 2018). Based on monitoring data from five fringing oyster reef projects in coastal Louisiana, La Peyre et al. (2015) found that the reefs reduced the rate of marsh edge erosion by an average of 3.2 feet per year along moderate- and high-exposure shorelines. In addition, a project to construct and restore more than 3.5 miles of oyster reefs in Mobile Bay, Alabama, to protect a natural vegetated shoreline is expected to reduce wave heights by 51–90% and reduce wave energy at the shore by 76–99%, while also supporting the local fishery and improving coastal water quality (Kroeger 2012).

Living shorelines with rock sills can enhance salt marsh resilience to erosion and storms. Photo: Carter Smith

PROTECTING COASTAL AREAS FROM DEVELOPMENT

Protecting and restoring natural open space offers one of the best opportunities to reduce risks to coastal communities. Strategies can include voluntary buyouts and restoration of acquired lands, as well as policies and programs to protect coastal open space from new development in current and future hazard-prone areas.

Voluntary Buyouts

As is the case in areas where properties have been heavily damaged from inland floods, some coastal areas are engaged in voluntary buyouts and property relocation to protect both people and assets—steps that will likely become unavoidable in some areas along the U.S. coastline as sea-level rise increases risks from erosion, storm surge, and tidal inundation (Fleming et al. 2018). Several communities have already begun removing properties damaged or destroyed by erosion and flooding and investing in habitat restoration efforts to enhance coastal resilience. For instance, the City of Pacifica in San Mateo County, California, has been partnering with local land trusts and other nongovernmental organizations to purchase and remove vulnerable structures and invest in marsh restoration to address worsening erosion and flooding along the community's beach (Estuary News Magazine Team 2013). Although the project required considerable upfront investment to implement, it had widespread support from local government leaders and the public and will ultimately save the community money in avoided losses. The City of Ventura, California, has completed a managed retreat project at Surfer's Point, which has experienced frequent damage from erosion. Key public infrastructure, including a parking lot, pedestrian path, and path bikeway were relocated, and sand dunes and bioswales have been maintained with native vegetation to reduce stormwater runoff and provide protection from waves. Success of the project was credited to collaboration across all major stakeholders and strong grassroots support (Kochnower et al. 2015).

Coastal Open Space Protection

There are a number of lands in both current and projected future high-risk areas that could be protected from further development, which not only would avoid risks to people who otherwise might inhabit those areas, but would also provide natural buffers for existing communities and support the preservation of wildlife habitats (Smith 2009, Brody and Highfield 2013, Berke et al. 2014). For example, a 2009 study of "intermediate lands" (i.e., areas characterized as low-density development, such as some agricultural lands, but with expected future development) found that conservation easements, land acquisitions, zoning regulations, transfer of development rights, and other non-structural measures could effectively limit development and reduce risk along the Atlantic coast for areas below 3.2 feet in elevation (Titus et al. 2009). Indeed, existing policies that have encouraged open space protection in hazard-prone coastal areas have proven successful in reducing risks. The Coastal Barrier Resources Act (CBRA), which established the John H. Chafee Coastal Barrier Resources System (CBRS), helps protect undeveloped areas on the coast by prohibiting federal subsidies and services for developments in environmentally sensitive areas (Milleman 2010). Today, the CBRS covers nearly 3.5 million acres of coastal land, including islands, beaches, wetlands, and associated aquatic habitat. Recent analysis estimates that, between 1989 and 2013, the CBRA reduced federal coastal disaster expenditures by $9.5 billion from what otherwise would have occurred had the lands included in the CRBS been developed at a rate comparable to other coastal areas (Coburn and Whitehead 2019).

EXTREME HEAT AND DROUGHT

At a Glance

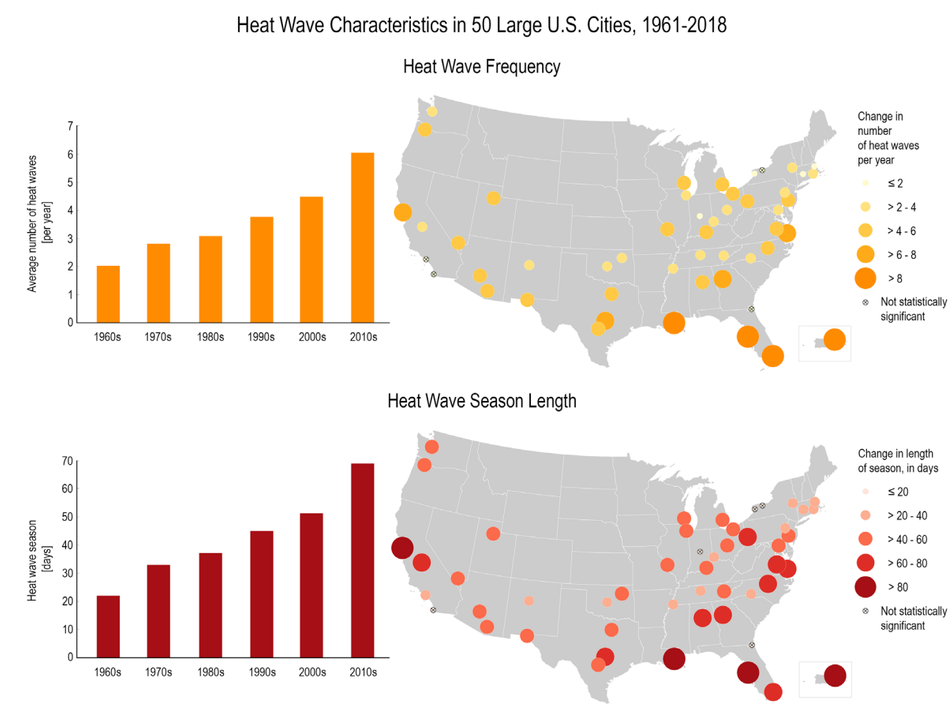
- Together, extreme heat and drought are contributing to a range of challenges, including water shortages, crop losses, damage to aquatic and terrestrial habitats, and severe wildfires; together, drought and heat waves were responsible for the second-highest number of deaths among all of the billion-dollar weather and climate disasters from 1980 to 2019, behind tropical cyclones.
- A number of natural infrastructure approaches are effective in mitigating extreme heat and drought, often in tandem. Strategies range from watershed protection and restoration and urban green infrastructure—such as planting trees and installing green roofs—to water conservation at a variety of scales.

UNDERSTANDING RISKS FROM EXTREME HEAT AND DROUGHT

While many weather- and climate-related disasters are caused by too much water, natural disasters can also result from too little water. Extreme drought conditions across the Southwest and Plains in the summer and fall of 2018, for instance, contributed to more than $3 billion in damages to the agricultural sector. From 1980 to 2019, economic losses from drought amounted to nearly $250 billion, compared with just under $147 billion from inland flooding (NOAA 2020b). Further, drought and heat waves were responsible for the second-highest number of deaths among all of the billion-dollar weather and climate disasters over this same period, behind tropical cyclones (NOAA 2020b).

Climate change is contributing to an increase in both extreme heat and drought conditions across much of the United States (USGCRP 2018). Heat waves are occurring more often than they used to in major cities across the United States, from an average of two heat waves per year during the 1960s to more than six per year during the 2010s. In addition, the average heat wave season across 50 major cities is 47 days longer than it was in the 1960s (USGCRP, n.d.). Over the past two decades, there have been twice as many high-temperature records as low-temperature records across the country, and the number of new highs has surpassed the number of new lows in 15 of the past 20 years (USGCRP 2017). If climate change continues unabated, scientists project twice as many days per year with a heat index over 100°F, and four times as many days with a heat index above 105°F by the 2050s (UCS 2019). In addition, a combination of higher air temperatures and altered precipitation patterns are contributing to increasingly severe droughts, which are compounded by increasing human demand for water (AghaKouchak et al. 2015).

Together, extreme heat and drought are contributing to water shortages, crop losses, public health risks, damage to aquatic and terrestrial habitats, and severe wildfires. Across much of the United States, there has been a substantial increase in concurrences between both heat waves and meteorological drought (i.e., drought associated with dry weather) over the past 50 years (Mazdiyasni and AghaKouchak 2015). Such combined events can have considerable social and ecological implications. For example, the 2011–2016 drought in California, which was characterized by both low precipitation and high temperatures, killed more than 125 million trees (AghaKouchak et al. 2015, Diffenbaugh et al. 2015, USFS 2019).



Heat waves have become longer and more frequent across the United States. Graphic: U.S. Global Change Research Program

NATURAL DEFENSES FOR EXTREME HEAT AND DROUGHT

A number of natural infrastructure approaches are effective in mitigating extreme heat and drought, often in tandem. Strategies range from watershed protection and restoration and urban green infrastructure, to water conservation at a variety of scales. In cities, for instance, increasing pervious surfaces through vegetation cover can reduce localized air and surface temperatures and help replenish groundwater by capturing and filtering rainfall. In addition, urban forest canopies can keep localized temperatures lower through shading and evaporative cooling, reducing the so-called "urban heat island effect"—an increase in air temperature in cities relative to surrounding areas (Levinson et al. 2019). In rural areas, strategies such as beaver restoration and riparian vegetation restoration can help store water and keep nearby streams cooler. And forest restoration efforts across the country help safeguard water resources for people and wildlife alike.

Sign rendered pointless by drought. Photo: Peripitus/Wikimedia Commons

WATERSHED PROTECTION AND RESTORATION

Restoring wetlands, forests, and other natural systems can offer considerable drought mitigation benefits.

Watershed Restoration

Because of their connection to groundwater, wetlands, and subsurface water flows, headwater streams are particularly important for maintaining base flow in larger streams. In the conterminous United States, headwater streams comprise 79% of total river length, and they directly drain more than 70% of the land area (Colvin et al. 2019). In addition, forested areas within watersheds support the hydrologic system by collecting and filtering rain and snow and releasing water into rivers, streams, and groundwater aquifers. Protecting and restoring natural watersheds is essential for sustaining plentiful water resources. Indeed, forests alone provide about 50% of the surface water supply in the West, and up to 35% of consumed water in the South (Brown et al. 2008, Caldwell et al. 2014). In California, so-called "source watersheds"—the forests, meadows, and streams that supply water to its reservoirs—are considered, by law, as an integral part of the state's water system infrastructure (Pacific Forest Trust 2017). Scientists estimate that restoring natural water infrastructure through activities such as mechanical thinning, prescribed fire, and restoration of natural stream channels in five of the state's major watersheds could yield an average of 300,000 acre-feet, or almost 100 trillion gallons of water, annually (Pacific Forest Trust 2017). In addition, several studies have investigated how various forest thinning techniques might help forests accumulate more snow, which is an essential source of summer water in many parts of the West (Bales et al. 2011a, 2011b; Heffelfinger 2012). For example, a study of three unique canopy types in an Arizona ponderosa pine forest found significant differences in snowpack accumulation, with the more open areas that received treatment accumulating 50–70% more snow than the areas of dense (untreated) canopy (Heffelfinger 2012). In the southeastern United States, research suggests that restoring more than 4,600 square miles of agricultural land along the Altamaha River basin to loblolly pine would have a positive impact on surface water supplies by providing 11.4% water yield for 46-inch average annual precipitation (Hallema et al. 2019).

Beaver Restoration

North American beavers are ecosystem engineers. Prior to their near extirpation in the early 1900s, beavers helped create and maintain wetlands and riparian ecosystems across much of the United States (Dittbrenner et al. 2018, Bailey et al. 2019). In addition to supporting numerous species of fish and wildlife, beaver-created wetlands can recharge groundwater, sustain summer water flows, provide natural firebreaks, and reduce downstream flood risk by slowing and retaining floodwaters (Norman et al. 2019). Given this, there has been growing interest in restoring beavers to portions of their former range to enhance stream conditions and help mitigate drought (Pilliod et al. 2018). In some cases, beavers have been relocated into formerly occupied habitats or encouraged to recolonize on their own by enhancing attractive habitat features. In others, managers have implemented "beaver mimicry" by installing instream structures that play a similar role in stream geomorphology and hydrology. A number of studies have demonstrated the increased water storage benefits provided by beaver restoration projects. For example, a study of wetlands and beaver activity over a 54-year period in eastern Alberta, Canada, found that during wet and dry years, the presence of beaver populations was associated with a 9-fold increase in open water when compared with a period when the animals were absent from those sites (Hood and Bayley 2008). In Colorado, research suggests that the presence of beavers in wide river valleys can create a physically complex hydrologic environment that buffers the impacts of high and low flows (Wegener et al. 2017). Further, beaver dams have been found to raise the water table and flood surrounding areas, recharging nearby water sources (Westbrook et al. 2006).

URBAN GREEN INFRASTRUCTURE

In addition to helping communities address risks from inland flooding, urban green infrastructure can help reduce temperatures or provide relief during heat waves.

Urban Trees and Other Vegetation

Expanding the area of trees and other vegetation in cities is considered to be one of the most effective and least costly approaches to reducing the urban heat island effect (Livesley et al. 2016). Establishing a tree canopy, in particular, can reduce local temperatures by providing shade. In addition, trees, grass, and other vegetation can reduce heat through the process of evapotranspiration, which draws heat from a surface when liquid moisture is converted into vapor (Peters et al. 2011, Coutts et al. 2013, Bounoua et al. 2015, Feng 2018). A review of multiple studies found that vegetation in urban areas can reduce the surrounding air temperature by 0.9–7.2°F (Qiu et al. 2013). Research by Loughner et al. (2012) found that expanding vegetated areas throughout a city can reduce surface air temperatures by as much as 7°F. Further, Zölch et al. (2016) suggests that planting trees can reduce heat stress by as much as 13%, particularly if plantings occur strategically in heat-exposed areas.

A study of the surface temperature–reduction benefits of ten different species of trees found that asphalt in shaded areas ranged from 24.8° to 41°F cooler than areas exposed to sun (Napoli et al. 2016). In addition, shade provided by trees can reduce surface temperatures on exterior walls and rooftops by as much as 45°F, and it can reduce a building's interior temperature by reducing the amount of sunlight that passes through windows (U.S. EPA 2008). A study in Phoenix, Arizona, also found that vegetated surfaces provided as much as a 45°F surface cooling compared with bare soil on low-humidity summer days (Jenerette et al. 2011).


Beaver activity can improve the capacity of watersheds to hold water during dry periods. Photo: Pat Gaines/Flickr

Green Roofs and Cool Pavement


Green roofs can help moderate the urban heat island effect. Photo: S. Woodside/Flickr

A "green roof" consists of a waterproofing membrane, a growing medium such as soil, and vegetation on a structure's rooftop to provide a range of environmental benefits (GSA 2011). Using green roofs in urban areas can help moderate the urban heat island effect, particularly during daytime hours (U.S. EPA 2008). For example, research has shown that the temperatures on green roofs can be 30–40°F lower compared with conventional roofs (e.g., DeNardo et al. 2005, U.S. EPA 2008, GSA 2011, Sailor et al. 2011, Berardi et al. 2014, Santamouris 2014, Sun et al. 2016). A comparison of temperature data collected at a green roof site and nearby black roofs in the New York City area found that a green roof offers a demonstrable cooling benefit (Gaffin et al. 2010, Culligan et al. 2018). In particular, peak temperatures on green roofs were, on average, 60°F cooler than black roofs during summer. And a study of green roofs from around the world shows that, compared with the ambient temperature, the cooling effect of a green roof on surface temperature can

range from 1.4° to 54°F, with the variation reflecting different study approaches, localized conditions, and other factors (Qiu et al. 2013). On a broader scale, researchers have found that the use of green roofs could provide ambient cooling of as much as 5°F across entire cities (e.g., Liu and Bass 2005, Rosenzweig et al. 2006, Santamouris 2014). Not only will such projects help reduce risks to vulnerable populations, but they can help communities reduce energy consumption for both winter heating and summer air conditioning (Castleton et al. 2010).

The use of "cool pavement" as an alternative to conventional materials, such as impervious concrete and asphalt, has also been shown to reduce outdoor air temperatures, often at a lower cost than green roofs. Conventional pavement can reach peak summertime temperatures of 120–150°F due to factors such as low solar reflectance (i.e., the percentage of solar energy reflected by a surface) and thermal emittance (i.e., how readily a material sheds heat) (Pomerantz 2000, U.S. EPA 2008, Sen and Roesler 2017). Current cool pavement approaches, which may entail using lighter-colored and permeable materials, can moderate both factors by reducing the amount of heat that is absorbed and stored (Liu et al. 2018, Sen and Roesler 2019). For example, research suggests that if pavement reflectance throughout an urban area were increased by 10–35% through use of alternative materials, air temperatures could be reduced by 1°F, depending on the city geography and climate (Pomerantz 2018).

WATER CONSERVATION

Reducing water consumption is an important approach to improve water security in communities faced with frequent drought (Reeve and Kingston 2014). For example, reducing urban outdoor water use, which includes limiting the amount of water that is used for landscaping in yards, parks, and other green spaces, can help communities meet their water consumption goals. Strategies may include conserving water by capturing rainfall for reuse, using less water in landscape management, and encouraging landowners to replace lawns with native, drought-resistant plants. In addition, farmers across the country have found that certain practices, such as no-till farming and use of cover crops, can reduce their annual water requirements.

Rainwater Harvesting

In response to worsening droughts and a desire to enhance water conservation, interest in rainwater harvesting has grown in many areas (Ennenbach et al. 2018, Radonic 2018). In general, rainwater harvesting involves collecting runoff from impervious surfaces such as roofs, driveways, and parking areas, and putting it into systems such as rain barrels and cisterns. Although results vary by rainfall levels, the size of the drainage area, and water use patterns, in some regions, a single 50-gallon rain barrel installed at a residential parcel has been estimated to provide as much as a 50% water-saving efficiency for non-potable indoor water demand (Steffen et al. 2013). Ennenbach et al. (2018) assessed the viability of rainwater harvesting at the county level across the conterminous United States and found that residential water demand could be met with greater than 90% reliability over much of the country from rainwater collected from the typical roof area. In particular, low-population-density counties have the potential to meet as much as 100% of their annual residential water needs, compared with about 20% of needs in high-density counties.

Cover crops on dryland wheat field. Photo: Garrett Duyck/Natural Resources Conservation Service

Los Angeles Air Force Base uses xeriscaping to conserve water. Photo: Sarah Corrice/U.S. Air Force

Xeriscaping

Outdoor irrigation is the single largest residential end use of water in the United States. Thus, water utilities across the country are seeking ways to reduce outdoor water use through a variety of programs. Xeriscaping, which is the practice of replacing lawns and other irrigation-dependent landscapes with drought-tolerant plants, mulch, and efficient irrigation, is being incentivized through innovative programs by a number of utility providers (Nolon 2016). In southern Nevada, a five-year study showed that homes that had converted turf lawns to xeriscaped landscapes saw a 30% annual reduction in total household water use, equating to nearly 100,000 gallons annually (Sovocool et al. 2006). In California, average annual turf-replacement water savings for among programs at ninewater agencies range from 18% to as much as 83%, depending on geographic climate differences, programmatic variability in landscape and irrigation replacement options, and other factors (Seapy 2015).

Water-saving Agricultural Practices

As droughts have continued to worsen across much of the country, farmers are seeking cost-effective ways to manage water resources. Practices such as no-till farming and using certain types of cover crops, for instance, have proven to have significant water-saving benefits. Plot studies at a wheat farm in Akron, Colorado, during a severe 2011 drought showed that the conventional tillage production system employed prior to wheat planting resulted in 3.4 inches less available soil water at planting compared with the no-till system (Lal et al. 2012). Following the extensive 2012 drought, which affected more than 80% of agricultural lands nationwide, farmers using cover crops with corn experienced about 79% of typical yields, more than 10% more than those not using cover crops (O'Connor 2013, Bergtold et al. 2019). In an analysis of potential changes in agricultural practices in Iowa, Basche (2017) found that continuous cover systems make an average of 9% more water available to plants than do annual crop systems.

WILDFIRES

UNDERSTANDING WILDFIRE RISKS

Wildfires are a natural and integral part of many forest ecosystems. By contributing to shifts in ecosystem structure, composition, and function, fires can create heterogeneity across the landscape and enhance biodiversity (Brown and Smith 2000, Thom and Seidl 2016). Over the past few decades, however, the severity and extent of wildfires have grown considerably, as have the impacts to human communities and the natural ecosystems themselves (McKenzie et al. 2004, Running 2006, Westerling et al. 2006, Hicke et al. 2016, Westerling 2016, Seidl et al. 2017, Stephens et al. 2018). This trend is due to a combination of factors, including overly dense forests due to historical and present-day fire suppression, the expansion of highly flammable invasive species in places, and changing climatic conditions, which have led to intense droughts and altered hydrology (Millar and Stephenson 2015). In California, for instance, higher average temperatures and a 30% decline in fall precipitation over the past four decades have doubled the number of days with extreme (95th percentile) fire risk (Goss et al. 2020). Across much of the West, the occurrence of so-called "mega-fires"—those with areal extents greater than 100,000 acres—has increased considerably (Adams 2013, Heyck-Williams et al. 2017).

A growing concern is the significant increase in people living in the so-called "wildland–urban interface" (WUI), which is the area where houses are in or near wildland vegetation (Radeloff et al. 2018). As of 2010, the WUI of the conterminous United States contained about 44 million houses, with the highest concentrations in California, Texas, and Florida (Martinuzzi et al. 2015). These areas are often at higher wildfire risk due the proximity of structures to flammable vegetation as well as the potential for human-caused ignitions.

At a Glance

- Although wildfire is a natural process in many forest, shrubland, and grassland systems, wildfires have posed heightened risks to human communities in recent decades, owing in part to historical and current land-use practices and suppression of natural fire regimes, development in fire-prone areas, expansion of invasive species, and changing climatic conditions.
- Ecological forest management, such as restoring natural fire regimes, targeted thinning, prescribed fire, and post-fire restoration, can help ameliorate the threat of wildfire while providing co-benefits that include increased water quantity and quality and improved habitat for fish and wildlife.
- Helping communities prepare for fires and adapt to fire-prone surroundings in a variety of ways (including creating "defensible space" around structures, retrofitting structures to be more fire-resistant, and engaging in collaborative community planning) is essential to addressing wildfire risk in communities and will also improve fire managers' ability to increase the use of managed wildfires and prescribed fire.

Satellite view of the 2018 Camp Fire in California. Photo: NASA

NATURAL DEFENSES FOR WILDFIRES

Wildland fire management in an era of climate change can have several objectives, including reducing risks to people and property and enhancing the health and resilience of ecosystems. Although fire management may achieve both objectives simultaneously, the ability to do so depends on a number of factors (Vaillant and Reinhardt 2017). In areas where the risks to public safety, property, and natural resources are particularly high, options skew toward fire prevention (e.g., reducing ignitions) and suppression (e.g., incident response), in addition to fuels management (e.g., mechanical thinning and prescribed fire). Yet, management efforts must also account for the effects of more frequent and severe wildfires on forest ecosystems more broadly. Natural and nature-based approaches for wildfire risk reduction range from ecological forest management practices, such as restoring natural fire regimes (including letting fires burn where safely possible) thinning, prescribed fire, and post-fire restoration, to policies and programs that help communities adapt to a fire-prone landscape.

ECOLOGICAL FOREST MANAGEMENT

Ecological forest management has emerged as an important concept for addressing wildfire risks as well as enhancing the health of forest ecosystems (D'Amato et al. 2011, 2018; Kelsey 2019). Specifically, ecological forest management may include a combination of strategic thinning, prescribed fire, and managed wildfire to reduce the risk of high-severity wildfire and promote healthier, more resilient forests (Stephens et al. 2016, Kelsey 2019). Done thoughtfully, the approach can help balance tradeoffs between short-term impacts of treatment with long-term benefits of reduced risks of large, high-severity fires (Kelsey 2019, Krofcheck et al. 2019). Further, restoring ecological functions and processes of forest systems can protect water resources and reduce flooding in communities within the watershed.

Treatment prescriptions vary depending on treatment objectives (which should be clearly established up front) and forest type. Different forest types have different natural fire regimes. There is a body of literature showing that treatments can modify wildfire behavior and result in better wildfire outcomes (e.g., Johnson et al. 2011, Kerhoulas et al. 2013, Stevens-Rumann et al. 2013, Loudermilk et al. 2014, Kalies and Kent 2016, Walker et al. 2018). The following are examples of ecological forest management to reduce wildfire risk:

Combined Fuel Reduction Treatments

A post-fire assessment of the high-severity Angora Fire, which destroyed 254 homes in the Lake Tahoe Basin, California, in 2007, found that areas that received fuel reduction treatments (including thinning and burning of slash piles) prior to the fire experienced considerably lower degrees of damage and tree mortality than those that had not been treated, with the exception of areas where slope steepness led to lower levels of fuel removal due to local standards for erosion prevention (Safford et al. 2009). A study by Waltz et al. (2014) similarly found that areas that received fuel reduction treatments experienced lower burn severity during the 2011 Wallow Fire in Arizona, which covered more than 469,000 acres to become the largest wildfire in the state's history. On average, trees killed in untreated units numbered six times as many as those killed in treated units. In addition to providing firefighters with opportunities to protect residences during the fire, treatments that allowed for clumps of trees and buffers for wildlife habitat were even more effective in reducing fire spread than those that resulted in evenly distributed trees with complete removal of ladder fuels (Kennedy and Johnson 2014). A combination of thinning and prescribed fire in eastern and southern California was found to have significantly reduced burn severity in trees during 12 wildfires that occurred between 2005 and 2011 (Safford et al. 2012). In 2018, the Golf Course Fire caused the evacuation of 300 homes as it burned west of Grand Lake, Colorado; but no lives or structures were lost due to the success of strategic fire management planning and risk-reduction measures (Colorado State Forest Service 2018). Since 2015, the Colorado State Forest Service and its partners conducted fuel treatments, including removal of beetle-killed trees and creation of fuelbreaks, on more than 200 acres of land adjacent to subdivisions that were ultimately impacted by the fire.

Forst thinning on Turnbull National Wildlife Refuge, Washington. Photo: Ken Meinhart/U.S. Fish and Wildlife Service

Both firefighters and emergency responders praised those efforts as significantly aiding their ability to protect the community (Colorado State Forest Service 2018).

Prescribed Fire

Prescribed fire, which entails the deliberate application of fire in ecological systems to achieve a variety of management goals, has proven to be an effective tool in reducing the areal extent and severity of wildfires across a range of forest types (Fernandes and Botelho 2003, Calkin et al. 2014, Fernandes 2015). Indeed, as noted by Kolden (2019), prescribed fire is one of most widely advocated management practices for mitigating wildfire risk and restoring the ecological health of fire-adapted systems. The U.S. National Cohesive Wildland Fire Management Strategy, for instance, specifically identifies prescribed fire as the most cost-effective solution over the largest potential area of the United States, when compared with both non-fire vegetation treatment and managed wildfire (Wildland Fire Leadership Council 2014).

Prescribed fire-treated forest stand, Fremont-Winema National Forest. Photo: U.S. Forest Service

In the southeastern United States, prescribed fire has been a long-standing practice. In Fort Benning, Georgia, for example, researchers evaluated a 30-year record of wildfire, prescribed fire, and drought to determine how prescribed fire has affected wildfire incidence in the region (Addington et al. 2015). From 1982 to 2012, there was an overall increase in the area burned by prescribed fire corresponding with Fort Benning's increased use of fire for meeting both fuel reduction and ecosystem management objectives. Over the same period, wildfire incidence declined, and annual wildfire incidence appears to have stabilized at or below 100 wildfires per year, in contrast to the 300–500 annual wildfires earlier in the record. Although the authors acknowledge that the effects of prescribed fire in managing wildfire in the future may be undermined by prolonged drought and a changing climate, managers may be able to continue to take advantage of its effectiveness in reducing wildfire activity when weather conditions are favorable. In Florida's Osceola National Forest, evidence suggests that a program of regular prescribed burns (every 2–5 years) between 1998 and 2008 reduced the likelihood of high-burn severity up to five years after treatment (Malone et al. 2011). Although prescribed fire has also been an effective management strategy in the West, the practice has lagged due to a variety of factors, including public health concerns about smoke, narrow burn windows, and lack of capacity (Melvin 2018, Kolden 2019, Schultz et al. 2019). Recent policy changes and greater reliance on collaborative governance have the potential to create greater opportunities for use of prescribed fire across the region (Schultz et al. 2019).

Post-fire Restoration

Post-fire management can provide an important opportunity to implement climate-informed forest restoration at a large scale (Millar et al. 2007, Peterson et al. 2011, Halofsky et al. 2018, Schumann et al. 2020). However, forest managers will need to consider where and when to prioritize active reforestation (including planting and control of understory vegetation and removing snags), versus allowing passive recovery following a major wildfire (White and Long 2019). Indeed, active management may be increasingly important in some areas, as the impacts of climate change and other stressors, such as invasive species, have reduced the potential for forests to regenerate on their own (Davis et al. 2019; Dey et al. 2019; Kemp et al. 2019; North et al. 2019; Parks et al. 2019a, 2019b; Stevens-Rumann and Morgan 2019). Uncharacteristically large and severe fires in dry forest ecosystems eliminate seed sources of dominant tree species. Without active restoration these areas may never return to forests. To ensure that post-fire restoration efforts maximize the resilience of the recovering forests to changing climatic conditions, scientists recommend that approaches focus on enhancing habitat complexity and heterogeneity, planting fire-adapted species, and minimizing removal of organisms, organic material, and other elements of a post-fire disturbance forest system that are important for forest regeneration (Leverkus and Castro 2017, Leverkus et al. 2018, Thorn et al. 2018, Donovan et al. 2019).

LEARNING TO LIVE WITH FIRE

From a risk management perspective, Calkin et al. (2014) note that neither pre-fire fuel treatments nor post-fire management stop fire—they only change fire behavior. Thus, if the goal is to keep wildfire out altogether, it is likely to be unobtainable (Calkin et al. 2014). Accordingly, there is growing recognition of the need for communities to learn to live with and adapt to fire (Schoennagel et al. 2017, McWethy et al. 2019). Better community planning, including building codes and zoning regulations as well as proactive evacuation planning, can improve public safety and reduce property damage in the event of wildfire. Strategies may include creating "defensible space" through development of firebreaks (i.e., areas cleared of vegetation) and fuelbreaks (i.e., areas where vegetation is reduced), and "home hardening," which consists of renovating existing structures using fire-resistant materials and designs and ensuring that new structures are built with fire-resistance in mind. It will also be necessary to allow some wildfires to burn, particularly where the risks to human communities are low.

Community Planning and Collaborative Risk Management

Across the country, efforts aimed at helping communities live with fire have been driven by both regulations (e.g., codes and ordinances) and voluntary, incentive-based approaches. It's widely recognized that there is no one-size-fits-all solution because every community has its own unique ecological and socioeconomic contexts. Regulatory approaches to encourage mitigation may or may not work in all cases (Edgeley and Paveglio 2019). In highly rural areas, for example, residents are often more receptive to options that strengthen community identity and allow for community-based oversight rather than to regulatory approaches (Edgeley and Paveglio 2019, Paveglio et al. 2019). Since 2003, thousands of communities have developed and implemented community wildfire protection plans (CWPP), as recommended under the Healthy Forests Restoration Act of 2003 (Evans et al. 2013, 2015). This success is due, in part, to the fact that the CWPP process allows communities to develop plans that best fit their local and ecological contexts (Jakes et al. 2011). The Firewise USA® recognition program, a collaborative effort between state and federal agencies and nongovernmental organizations, has been working with communities across the country to reduce wildfire risks by encouraging homeowners to work together and improve defensible space in their neighborhoods. Recent fires have demonstrated the program's success in some areas. For example, in 2017, two consecutive fires in the community of Indian Lake Estates, Florida, spared numerous homes and structures due to risk reduction preparations that homeowners made under the program (NFPA 2018).

Home protected by defensible space during the 2010 Nahahum Canyon Fire, Washington. Photo: Sarah Foster/Washington Department of Natural Resources

Effective wildfire risk reduction strategies need to focus not just on strategies to reduce impacts to property and infrastructure, but also on wildfire emergency response to reduce risks, such as identification of effective evacuation routes and emergency shelters (Steelman and Nowell 2019). This requires effective collaboration and communication across a range of stakeholders, as well as integrated efforts to prioritize appropriate risk reduction measures. Dunn et al. (2020), for instance, present a novel risk science approach that combines a range of tools, including quantitative wildfire risk assessment, mapping of suppression difficulty, and atlases of potential control locations, to provide a foundation for collaborative and adaptive governance in fire management. To minimize future risks, it will also be important to discourage new development in areas where the wildfire hazard is high (Schoennagel et al. 2017). Doing so can offer a variety of benefits. For instance, a simulation of housing growth in San Diego County, California, suggests that purchasing conservation lands to prevent development would offer both fire risk reduction and biodiversity benefits, regardless of whether those lands were chosen because of high fire hazard or high species richness (Syphard et al. 2016).

Managed Wildfire

Allowing wildfires to burn naturally, with suppression only under defined management conditions, is increasingly being considered as an important approach to restoring natural fire regimes in parts of the West. This approach differs from prescribed fire in that it relies on natural ignition events, with suppression done only in instances where other management goals, such as community safety, are jeopardized (Boisramé et al. 2017, Schoennagel et al. 2017). Indeed, recognizing the importance of fire in many ecosystems, the 1995 Federal Wildland Fire Management policy led to the reintroduction of more wildfire in national parks and other public lands. In parts of Yosemite National Park, for instance, 40 years of managed wildfire has contributed to increased landscape heterogeneity, and evidence suggests that it has helped improve the resilience of habitats to drought and fire (Boisramé et al. 2017). As with prescribed fire, gaining public acceptance of more wildfire as both inevitable and potentially beneficial will require education and community engagement.

RECOMMENDATIONS TO ADVANCE NATURAL INFRASTRUCTURE SOLUTIONS

As detailed above, nature can play a significant role in reducing risks from a variety of weather- and climate-related hazards. In many places, protection and restoration of natural systems can enhance community resilience in the face of increasing risks from inland flooding, coastal hazards, extreme heat and drought, and wildfires.

Despite the clear and growing body of evidence demonstrating that natural defenses are both effective and cost-effective solutions for risk reduction, deployment of these solutions by communities remains relatively low. Not only are the risk-reduction benefits nature offers underutilized, but recent federal policy changes threaten to degrade remaining natural systems and damage their capacity to buffer communities.

Federal policy-makers have an important role to play in bolstering the use of natural infrastructure across the country and across different societal sectors. Below we outline some approaches that would help ensure that as a nation we successfully expand the use of—and receive the greatest benefit from—our natural defenses.

PROTECT & RESTORE EXISTING FEATURES PROVIDING NATURAL DEFENSES

Oftentimes the most effective hazard risk reduction comes in the form of undisturbed and healthy natural systems. As aptly noted by the Reinsurance Association of America: "One cannot overstate the value of preserving our natural systems for the protection of people and property from catastrophic events" (Restore America's Estuaries 2011).

Nevertheless, intact ecosystems continue to face pressure from population growth and development, destructive water and land resource management practices, and new stresses linked to rapid climate change. By protecting or restoring existing natural features, we can maintain their ability to provide protective benefits to communities.

Rain over the U.S. Capitol. Photo: Architect of the Capitol

- Support conservation programs like the Land and Water Conservation Fund that acquire, protect, and/or restore environmentally sensitive natural systems and open space.
- Identify where natural systems provide hazard protection and other critical services to communities, including through robust mapping and planning efforts at the local, state, and federal levels. Prioritize protection or restoration of these systems in appropriate plan updates and revisions (e.g., State Hazard Mitigation Plans, Coastal Zone Management Plans, etc.).
- Allow floodplain ecosystems to better serve their natural functions by adopting policies that encourage new or reconstructed levees to be set back from the water's edge to sustain and enhance wetlands and riparian habitat, reduce erosion and scour, and lower flood levels.
- Defend and strengthen bedrock environmental laws and regulations that support healthy ecosystems and guarantee communities a voice in decisions that may harm the natural systems that protect their communities. Recent rollbacks to Clean Water Act protections threaten over half the nation's wetlands and millions of stream miles, and should be rescinded. Similarly, recently proposed changes to implementation of the National Environmental Policy Act would dramatically weaken environmental protections by allowing projects to advance without full disclosure of foreseeable impacts, and suppressing meaningful public engagement in decisions impacting public health and the environment.

MAINSTREAM USE OF NATURAL INFRASTRUCTURE ACROSS SECTORS

Improving the nation's resilience to natural disasters will require preparedness and planning across governmental agencies and societal sectors. Most communities historically have relied on gray infrastructure to provide protection from flooding and other natural hazards, even where natural or hybrid solutions might be equally or more effective and provide a suite of ancillary benefits. There is an urgent and compelling need to integrate, or mainstream, the use of natural infrastructure in sectors ranging from flood mitigation and stormwater management to transportation. To do this, we must remove existing barriers to the adoption of natural solutions and ensure that such approaches are an equally accessible option for communities from both regulatory and funding perspectives. At minimum, natural and nature-based projects should be both eligible and competitive for federal dollars across sectors. Ideally, these solutions should be the first option considered to reduce hazard risk, and used whenever practicable and appropriate to address the resilience needs of the community.

- Ensure that natural infrastructure is an eligible use of the Surface Transportation Block Grant program as part of the next surface transportation reauthorization bill. Congress should also invest additional resources specifically to help states improve the resilience of their surface transportation infrastructure, including through the use of natural features. This would complement recent efforts at the Federal Highway Administration to provide technical assistance to help transportation agencies improve transportation systems using natural infrastructure (FHWA 2018).
- Codify a 20% set-aside of Clean Water State Revolving Loan Fund dollars for the Green Project Reserve to invest in green infrastructure solutions ranging from floodplain restoration to green roofs and permeable pavement.
- Ensure that the U.S. Army Corps of Engineers (USACE) fully complies with its existing mandates to evaluate natural infrastructure project alternatives where practicable for flood and storm damage risk reduction. Additionally, Congress should create new incentives for the use of natural infrastructure solutions for flood protection, including by lowering the nonfederal sponsor cost-share for such USACE projects.
- Thoroughly value and account for ecosystem services in federal and state agency decision-making. Ensure that the USACE, Federal Emergency Management Agency (FEMA), and other agency cost–benefit analyses account for both the ecological services lost and gained as a result of a project.
- Improve the tools available through FEMA for assessing the cost-effectiveness of nature-based projects, such as living shorelines. Currently, many such projects are disadvantaged in the mitigation grant application process because of challenges applicants face in meeting benefit–cost analysis requirements using available data and tools.
- Ensure that natural infrastructure projects are not subject to longer permitting timelines or more complicated permitting processes than structural alternatives. For example, despite the creation of USACE Nationwide Permit 54 for living shorelines, in many states, environmentally damaging structural shoreline stabilization projects, like bulkheads and seawalls, are still faster and easier to permit than more ecologically friendly living shorelines (Hilke et al. 2020).

Yolo Bypass Wildlife Area in California, part of the Sacramento River flood control system. Photo: Dave Feliz/Yolo Bypass Wildlife Area

IMPROVE RISK ASSESSMENT AND ENCOURAGE SMART DEVELOPMENT

Over time, the United States has experienced a considerable increase in the number of people living in hazard-prone environments, from coastlines and floodplains to the fire-prone wildland–urban interface. People in these environments often have an incomplete understanding of their actual risk level, and some government programs even provide incentives that encourage people to live in harm's way.

For example, the National Flood Insurance Program (NFIP), although well-meaning, has inadvertently encouraged development in flood-prone areas by masking true risks through subsidized insurance rates. This has resulted in a program deeply in debt to taxpayers that promotes continued development in risky areas, which in turn contributes to loss of the very natural systems, like functioning floodplains, that could reduce flood damages. Outdated and incomplete national flood maps and insufficient real estate disclosure requirements have exacerbated the problem, blinding property owners and communities to their actual risk levels and denying them the information they need to make decisions to mitigate that risk.

Federal programs must be reformed to improve mapping and communication of natural hazard risks, to increase incentives that promote smart development and pre-disaster mitigation, and to actively discourage new development in the most hazardous areas.

- Significantly increase resources to swiftly complete new national flood maps, particularly in data-sparse regions, and to maintain accurate maps thereafter. It is estimated that only one-third of the river and stream miles in the nation have flood hazard information available (ASFPM 2020). FEMA must be required to update its maps using the best available technology, such as Light Detection and Ranging (LiDAR), to get property-level elevation data, and to account for the latest climate modeling, including precipitation, sea-level rise, and flood projections.
- Reauthorize and reform the NFIP, breaking the chain of short-term program extensions. Any reform bill should keep communities on a glide path to risk-based rates for all properties, with means-tested assistance for those who cannot afford to pay actuarial rates. Instead of perpetuating widespread subsidies, the program should be reformed to promote increased proactive and pre-disaster mitigation to lower risk, and thereby lower flood insurance rates. Community-wide, natural, and nature-based mitigation should be used and encouraged wherever possible.
- Fully support programs providing other critical data inputs for accurate flood maps. For example, both the U.S. Geological Survey stream gauge network and the National Oceanic and Atmospheric Administration's (NOAA) rainfall frequency modeling efforts must be fully resourced to ensure that up-to-date information feeds into flood models.
- Advance development and amplification of up-to-date digital map products depicting local and regional hazards, such as NOAA's Digital Coast tools, which help coastal communities visualize sea-level rise and flooding.
- Continue the process of updating Coastal Barrier Resources System (CBRS) maps, to ensure that federal subsidies do not provide incentives for new development in these environmentally sensitive and hazard-prone areas. Strategically expanding the CBRS shoreward, in consideration of anticipated sea-level rise scenarios, would make good fiscal, environmental, and public safety sense and would enable migration of natural protective features like salt marsh.
- Support continued development of fire risk assessment mapping efforts by the U.S. Forest Service for use in communicating risk levels and mitigation needs to communities in key firesheds, and to inform timely decisions regarding fire prevention and mitigation campaigns, fire suppression responses, active wildfire management, and forest restoration including use of prescribed fire.
- Enhance collaborative efforts to build community resilience to wildfires in high-risk areas, including support for improved Community Wildfire Protection Plans, Firewise USA®, the Fire Adapted Communities Learning Network, and other programs to facilitate locally driven wildland fire risk management, planning, and mitigation.

DRAMATICALLY SCALE UP INVESTMENTS IN COMMUNITY RESILIENCE AND SUPPORTING RESEARCH

We can accelerate the adoption of natural infrastructure solutions by increasing their prevalence in communities, including through federal funding opportunities. More on-the-ground applications of natural infrastructure also provide an opportunity to expand efforts to monitor and evaluate the performance of these features during different types of extreme weather events and across different geographies. Such work can help create or refine design and engineering standards, and increase the comfort level and social acceptance of natural and nature-based features among decision-makers, communities, and contractors. There is also a need to ensure that social equity considerations are a component of community resilience strategies. Climate impacts are unevenly distributed across society, and frontline communities directly impacted by climate change and natural disasters should be engaged in resilience planning to help ensure durable and shared benefits.

- Expand targeted research on the performance and effectiveness of various forms of natural defenses for meeting risk reduction objectives; continue to improve specifications on when, where, and how these approaches can be used most reliably.
- Ensure the design and implementation of natural infrastructure solutions, including activities such as forest restoration, takes future precipitation patterns, sea-level rise, and other climatic factors into account; encourage designs that are functional across multiple scenarios of future change.
- Boost research, monitoring, and evaluation to identify the most appropriate ecological fire management options within diverse forest systems.
- Ensure that robust allocations for enhancing ecosystem resilience and deploying nature-based risk reduction measures are a part of major funding programs, such as disaster recovery and mitigation efforts (e.g., FEMA's Hazard Mitigation Assistance programs and the U.S. Department of Housing and Urban Development's Community Development Block Grant Disaster Recovery and Mitigation funds), as well as water resource development programs.
- Support competitive grant programs for implementation of natural and nature-based features, and require project monitoring and data reporting as a condition of the grant. Grant opportunities can spur and cultivate innovative resilience-building approaches. In addition, they often create incentives for private investment and result in leveraging of dollars. For example, the National Coastal Resilience Fund leverages federal and private sector funds for projects that reduce risks to people and wildlife.
- Increase the U.S. Forest Service budget for proactive and climate-informed pre- and post-fire restoration and management activities, based on principles of ecological forest management. Identify new sources of federal funding to support climate-informed restoration on both public and private forest lands.
- Create a national revolving loan fund for community resilience. This fund could provide low- to zero-interest loans for communities to invest in projects and programs that improve disaster preparedness and long-term resilience in the face of increasingly severe storms, flooding, drought, wildfires, and other natural hazards, with an emphasis on use of natural infrastructure to achieve those goals. To support efforts in lower-income communities, the revolving loan fund should be administered alongside a grant program with aligned goals, or should include a mechanism to ensure access to the program for communities that otherwise would not have the resources available to participate and allow for near-term implementation of solutions.

Savannah sparrow in the Willamette Valley, Oregon.
Photo: Jim Leonard/Natural Resources Conservation Service

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