

Equitable and Resilient Infrastructure Investments

Committee on Hazard Mitigation
and Resilience Applied Research
Topics

Policy and Global Affairs

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This Consensus Study Report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making its published proceedings as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

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Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by Chris Poland, Independent Consultant. He was responsible for making certain that an independent examination of the report was conducted in accordance with standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

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Executive Summary

Communities across the United States are subject to ever-increasing human suffering and financial impacts of disasters caused by extreme weather events and other natural hazards amplified in frequency and intensity by climate change (IPCC, 2022). According to the National Oceanic and Atmospheric Administration, there were 20 weather disaster events in 2021 with losses exceeding \$1 billion each, and 323 weather and climate disasters, including wildfires and drought, since 1980 in which overall damage and costs reached or exceeded \$1 billion each. The total cost of these 323 events in 2022 dollars exceeded \$2.2 trillion. Missing from this accounting are thousands of less costly hazard events and disasters not meeting the \$1 billion threshold. While media coverage sometimes paints these disasters as affecting rich and poor alike and suggests that natural disasters do not discriminate, the reality is that they do. As reiterated at the March 17, 2022, workshop, there have been decades of discriminatory policies, practices, and embedded bias within infrastructure planning processes. Among the source of these policies and practices are the agencies that promote resilience and provide hazard mitigation and recovery services, and the funding mechanisms they employ. These practices have resulted in low-income communities, often predominantly Indigenous people and communities of color, bearing a disproportionate share of the social, economic, health, and environmental burdens caused by extreme weather and other natural disasters. It remains unclear which research strategies can ensure that infrastructure investments help increase resilience and improve equitable decision-making—and do not inadvertently impact—vulnerable and disadvantaged communities.

Toward that end, the Resilient America Program of the National Academies of Sciences, Engineering, and Medicine convened two committees to address applied research topics in the field of hazard mitigation and resilience to assist the Federal Emergency Management Agency (FEMA) in reducing the immense human and financial toll of disasters caused by natural hazards and other large-scale emergencies. FEMA asked the committee to identify applied research topics, information, and expertise that can inform action and collaborative priorities within the natural hazard mitigation and resilience fields. The committee, in consultation with the Resilient America Program, selected two large-scale themes within which to identify applied research topics: Equitable and Resilient Infrastructure Investments and Compounding and Cascading Events. This report examines the first theme, and a subsequent report will consider the second theme.

On the theme of Equitable and Resilient Infrastructure Investments, the committee chose three topics as being particularly important for natural hazard mitigation and resilience: (1) partnerships for equitable infrastructure development, (2) systemic change toward resilient and equitable infrastructure investment, and (3) innovations in finance and financial analysis. The committee selected these topics based on information gained from a 1-day public workshop and committee members' backgrounds and experience with hazard mitigation and resilience.

On the first topic, the committee found that more focus is needed on how to build the trust essential for establishing ongoing partnerships between researchers and communities that

would enable two-way knowledge transfer and promote actionable research. Furthermore, building similar trust between communities and those providing essential services (governmental entities, communities of practice) will require not only time but considerable effort to understand how trust is manifest community by community. Listening to and valuing the expertise of community members is a key factor for productive partnerships. Applied research is needed on strategies and tactics for regaining or establishing community trust in institutions, governments, and essential service providers where it has been frayed or new partnerships are formed.

On the second topic, the committee identified six areas with key research questions, including how to (1) catalyze and support systemic change in the institutions involved in infrastructure development; (2) develop effective community resilience hubs; (3) engage in community resilience planning; (4) incorporate integrated multi-benefit solutions into resilient and equitable infrastructure planning; (5) link the built and natural environments to benefit communities; and (6) identify the role minimum code requirements can play in developing resilient and equitable infrastructure.

On the third topic, the workshop pointed to the need to develop innovative approaches to economically assess and finance resilient and equitable infrastructure investment. As part of this effort, the committee noted the importance of modifying benefit-cost analysis to account for the economic realities of disadvantaged populations within communities; better reflect the benefits and costs that future generations will realize or incur over time; reflect the distribution of costs and benefits, particularly in relationship to historically affected and underserved populations; and better reflect indirect benefits, such as equity, public health, and community resilience, that can be difficult to monetize.

In addition, the committee discussed several important underlying themes and enabling factors. These enabling factors included increased data collection and transparency, breaking down both financing and research silos, valuing community input, and ensuring that investments reflect community-specific characteristics.

EQUITABLE AND RESILIENT INFRASTRUCTURE INVESTMENTS

Background

Extreme weather events and shifting climate conditions are more frequently having a devastating effect on communities across the United States. According to the National Oceanic and Atmospheric Administration, there were 20 weather disaster events in 2021 with losses exceeding \$1 billion each, and 323 weather and climate disasters, including wildfires and drought, since 1980 in which overall damage and costs reached or exceeded \$1 billion each. The total cost of these 323 events in 2022 dollars exceeded \$2.2 trillion (NOAA, 2022) (see Box 1 for definitions used in this report).

While media coverage sometimes paints these disasters as affecting rich and poor alike, the reality is that decades of discriminatory policies and practices can contribute to low-income communities, Indigenous people, and communities of color bearing more than their fair share of the social, economic, health, and environmental burdens caused by extreme weather and other natural disasters (Emrich et al., 2022; EPA, 2021; Tate and Emrich, 2021; Domingue and Emrich, 2019; Emrich et al., 2019; Jerolleman, 2019; Rufat et al., 2019; Bakkensen et al., 2017; SAMHSA, 2017; Liu and Li, 2016; Muñoz and Tate, 2016; Tate et al., 2016; Reid, 2013; Smith, 2012; Yoon, 2012; Khunwishit and McEntire, 2012; Tierney and Oliver-Smith, 2012; Schmidlein et al., 2011; Burton, 2010; Finch et al., 2010; Fekete, 2009; Myers et al., 2008; Smith and Wenger, 2007; Kettl, 2006; Enarson, 1998; Nigg, 1995; Berke et al., 1993). Three months after Hurricane Maria struck Puerto Rico, for example, approximately half of its population remained without power (Robles and Bidgood, 2017), and Hurricane Harvey's floods had a disproportionate impact on low-income communities and communities of color in Houston (Coleman et al., 2020).

Current thinking about community resilience—the existence, development, and engagement of community resources by community members to thrive in an environment characterized by change, uncertainty, unpredictability, and surprise (Magis, 2010)—tends to emphasize the potential for individuals and communities to become more adaptable to uncertainty and change through practices such as disaster risk reduction, mitigation, and planning (Uekusa, 2018) (see Box 2). This view, however, fails to account for the fact that marginalized and socially vulnerable communities and communities of color typically lack the knowledge and resources to engage in risk reduction, mitigation, and planning or are neglected in planning by states or other policy makers and decision makers. Any approach that aims to enhance community resilience and adaptability in an equitable manner must include rebalancing public infrastructure investments, addressing fundamental social inequalities starting with the planning phase and recognizing the inequities that have resulted from years of practice (Matin et al., 2018).

BOX 1
Definitions of Terms Used in This Report

COMMUNITY: The members of a collectivity, who share a common territorial area as their base of operation for daily activities. Also, a social group whose members are bound together by the sense of belonging created out of everyday contacts covering the entire range of human activities (NASEM, 2021a).

COMMUNITY RESILIENCE: Community resilience is the ability to prepare for anticipated hazards, adapt to changing conditions, and withstand and recover rapidly from disruptions (NIST, 2016).

DISASTER: A serious disruption of the functioning of a community or a society causing widespread human, material, economic, or environmental losses that exceed the ability of the affected community or society to cope using its own resources (NSTC, 2005).

RESILIENT INFRASTRUCTURE: Infrastructure that is designed, maintained, and/or adapted to support resilience goals, including recovery of functionality within a specified time frame, for a specified scale (e.g., site, network system, community, region).^a

HAZARD: A process, phenomenon, or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption, or environmental degradation (UNDRR, 2020).^b

HAZARD MITIGATION: Steps taken before an event to reduce the exposure of people and property to environmental hazards and to reduce the negative impacts of those hazards. For infrastructure, mitigation often refers to retrofit and renovation of existing infrastructure to improve their future performance (NASEM, 2012).

INFRASTRUCTURE: Physical networks (systems and facilities) that provide functions and services to the community. Infrastructure systems include transportation, energy, communications, water, and wastewater systems. Building clusters (buildings with common functions) and supporting infrastructure systems are organized by functional categories, such as health, economy, education, or housing, for planning purposes (NIST 2016, 2020).

RESILIENCE: The ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events (NASEM, 2012).

SOCIAL EQUITY: Impartiality, fairness, and justice for all people in social policy. Social equity accounts for systemic inequalities to ensure everyone in a community has access to the same opportunities and outcomes.^c

SUSTAINABLE: Sustainable practices support ecological, human, and economic health and vitality. Sustainability presumes that resources are finite and should be used conservatively and wisely with a view to long-term priorities and consequences of the ways in which they are used.^d

SUSTAINABLE CRITICAL INFRASTRUCTURE: Equipment and systems that are designed to meet the population’s essential service needs—including roads, bridges, telephone pylons, hydroelectric power stations, and so forth—based on all-round sustainable principles.^e

^a See <https://www.govpilot.com/blog/what-is-disaster-resilient-infrastructure-why-is-it-needed>.

^b This definition is adopted by the UN General Assembly.

^c See <https://unitedwaynca.org/blog/what-is-social-equity>.

^d See <https://www.sustain.ucla.edu/what-is-sustainability/>.

^e See <https://www.iberdrola.com/sustainability/sustainable-infrastructure>.

BOX 2

Climate Changes, Extreme Weather, and Associated Disasters

According to the U.S. National Climate Assessment, “The United States is observing the impacts of climate change in every region and across economic sectors. Farmers and ranchers across the Great Plains battle drought, transportation planners consider how floods might affect roads and bridges, and utility managers try to keep the electricity flowing during heat waves.” Further, the latest National Climate Assessment indicates “more frequent and intense extreme weather and climate-related events, as well as changes in average climate conditions, are expected to continue to damage infrastructure, ecosystems, and social systems that provide essential benefits to communities” (USGCRP, 2018).

The impacts of climate change are expected to disrupt our lives in the future even more, worsening many challenges that we have been facing and damaging prosperity due to aging and declining infrastructure, stressed ecosystems, and economic inequality. Different regions will experience climate change varying levels. People who are already most vulnerable to climate change, such as low-income and marginalized communities, have less capacity to prepare for and deal with extreme weather events. Therefore, these communities are more likely to suffer from climate change consequences (Cuyahoga County Climate Change Action Plan, 2019).

From 2001 to 2021, Earth experienced 21 of the 22 hottest years since 1880^a and saw record-breaking heatwaves around the globe.^b Exposure to extreme heat is associated with heat stroke, heat stress, increased mortality, cardiovascular strain, and adverse birth outcomes, among other public health impacts. The elderly, children, and those with underlying health conditions such as cardiovascular and respiratory disease are particularly vulnerable to the impacts of extreme heat (Kristie et al., 2021). Heat also poses an elevated risk to outdoor workers, those living in urban heat islands, and households without access to air conditioning, and heat can contribute to the accelerated formation of ozone, further exacerbating respiratory conditions.

As the U.S. Geological Survey noted, “With increasing global surface temperatures the possibility of more droughts and storms with increased intensity of storms will likely occur. As more water vapor is evaporated into the atmosphere it becomes fuel for more powerful storms to develop. More heat in the atmosphere and warmer ocean surface temperatures can lead to increased wind speeds in tropical storms. Rising sea levels expose higher locations not usually subjected to the power of the sea and to the erosive forces of waves and currents” (USGS, 2022). Given this possible future, the Fourth National Climate Assessment stated that “prioritizing

adaptation actions for the most vulnerable populations would contribute to a more equitable future within and across communities” (USGCRP, 2018).

^a See <https://climate.nasa.gov/vital-signs/global-temperature/>.

^b See <https://www.ncei.noaa.gov/access/monitoring/cei/graph/us/01-12/1>.

Goals of the Committee

As part of its efforts to reduce the immense human and financial toll of extreme events, the Federal Emergency Management Agency (FEMA) in 2020 asked the Resilient America Program of the National Academies of Sciences, Engineering, and Medicine to convene the Committee on Applied Research Topics for Hazard Mitigation and Resilience (see Box 3 for further information on the Resilient America Program). FEMA charged the committee with identifying “applied research topics, information, and expertise that can inform action and collaborative opportunities within the natural hazard mitigation and resilience fields.” In 2021, the first committee held two workshops on applied research topics—Social Capital and Social Connectedness for Resilience, and Motivating Local Climate Action—and prepared two brief consensus reports (NASEM, 2021a, 2021b) that identified and summarized key research topics for the applied research community in the specific areas discussed at the workshop and in open discussions of the Resilient America Roundtable.

In 2022, the second committee selected two additional themes—Equitable and Resilient Infrastructure Investments, and Compounding and Cascading Events—and held 1-day public workshops to explore each of these themes. This report examines the first theme, focusing on strategies that enable equitable and resilient infrastructure capable of providing services tailored to local community conditions, needs, and priorities; a subsequent report will consider the second theme. As was true for the two reports issued in 2021, this report contains findings but no recommendations and is limited to the topics covered in the public workshops and in open discussions with the Resilient America Roundtable. The full Statement of Task is as follows:

A committee of the National Academies of Sciences, Engineering, and Medicine will identify applied research topics, information, and expertise that can inform action and collaborative opportunities within the natural hazard mitigation and resilience fields. The committee will convene two public workshops as the primary source of information for its work, supplemented by background materials collected for the workshops and discussions at public sessions of the Resilient America Roundtable.

Each workshop will focus on distinct hazard mitigation and resilience issues and research questions, such as compound and cascading hazard incidents; risk communication and decision making in a changing risk landscape; nature-based solutions, buyouts, and managed retreat options for coastal risks; and equity and social vulnerability considerations in risk and decision metrics. Following each workshop, the committee will prepare a brief consensus study report that identifies and summarizes key research topics for the applied research community in the specific areas discussed at the workshop. Each report will contain findings

but no recommendations and will be limited to the topics covered at that workshop.

To meet this charge for the first theme—Equitable and Resilient Infrastructure Investments—the committee organized a public, 1-day workshop featuring diverse voices and expertise on this topic to survey existing knowledge and practice. Based on information the committee gained at this workshop and committee members’ backgrounds and experience with hazard mitigation and resilience, the committee chose three topics as being particularly important for making equitable and resilient infrastructure investments as part of the nation’s work on natural hazard mitigation and resilience. The three topics are (1) partnerships for equitable infrastructure development, (2) systemic change toward resilient and equitable infrastructure investment, and (3) innovations in finance and financial analysis.

This report’s primary audience is the applied research community in the fields of hazards, vulnerability, risk reduction, and resilience. The community includes hazard-specific and general resilience research centers as well as cooperative institutions engaged with states, tribes, and local communities on related challenges. Broader audiences include public, private, nongovernmental, philanthropic, and academic organizations at the local, regional, state, tribal, and federal levels seeking to reduce the impacts, losses, and suffering across the United States from disasters as a result of natural or technological hazards, public health emergencies, and other significant threats to communities and the nation. The aim of the committee’s activities is to inform applied research programs that will strengthen capacities for hazard mitigation and resilience across the nation and around the world.

BOX 3

The Program on Risk, Resilience, and Extreme Events

Since its creation following the release of the 2012 report *Disaster Resilience: The National Imperative*,^a the Program on Risk, Resilience, and Extreme Events at the National Academies of Sciences, Engineering, and Medicine, known more generally as Resilient America, has sought to harness the power of science, information, and community experience and knowledge to create a more adaptive and resilient nation.^b To achieve this aim, Resilient America engages with the academic, public, and private sectors at the national and local levels to:

- Increase understanding of complex risks and extreme events in a changing environment, and the exposure of communities, infrastructure, and natural systems to these threats.
- Investigate and strengthen attributes of equitable, resilient systems and communities, including their interconnections and interdependencies.
- Test, communicate, and strengthen implementation of equitable strategies for adapting to changing risks and robust recovery from disruptions.
- Share accessible science and data for strengthening resilience and adaptive action, including policies, tools, best practices, and metrics.
- Connect and facilitate partnerships among scientists, data providers, practitioners, and decision makers.

Resilient America pursues these objectives through two main activities. The first is the Resilient America Program, which seeks to implement recommendations from the 2012 report to strengthen community resilience and adaptation. The second is the Resilient America Roundtable, which convenes experts to discuss and catalyze activities that build resilience to extreme events at the community, regional, national, and international levels. Together, these activities seek to promote innovative research to inform strategies for resilience and adaptation; incubate ideas and projects; and conduct education, outreach, and community exchange that advance resilient systems and adaptive capacities.

^a National Research Council. 2012. *Disaster Resilience: A National Imperative*. Washington, DC: The National Academies Press.

^b Resilient America Program. About. <https://www.nationalacademies.org/resilient-america/about>.

Public Workshop

On March 17, 2022, the committee held a 1-day workshop on the theme of *Equitable and Resilient Infrastructure Investments*. The agenda for the workshop, developed in part based on input the committee received during an open session of the Resilient America Roundtable on January 28, 2022, appears in Appendix B, and biographical sketches for the workshop presenters are in Appendix C. Workshop panelists included individuals from the public and private sectors; organizations involved in various resilience and social justice activities across the United States; community-based organizations; and the research, community engagement, infrastructure, transportation, housing, and policy communities. The committee asked workshop panelists to consider and address the questions listed in Appendix D to help determine unmet applied research needs within the workshop theme.

Workshop presentations and discussions focused on two broad areas, equitable community development and equitable physical infrastructure, followed by three deep-dive topic areas to provide examples of how to direct infrastructure investment to support resilience and equity and to reflect specific community requirements. The equitable community development panel explored how infrastructure supports the delivery of equitable services and functions to the entire community, as well as the social impacts of infrastructure damage and loss of community resilience. The equitable physical infrastructure panel explored how infrastructure investments increase the capacity of communities to recover their services and functions and the challenges and opportunities with some of planning and investment strategies.

The first deep dive explored the collaborative development, design, and operation of community resilience hubs and how these concepts can be expanded to strengthen adaptive capacity and provide services that enhance community resilience year-round and in spite of a changing climate and changing technologies. The second deep dive focused on housing infrastructure, and how such investments influence both household and community resilience. The final deep dive examined transportation infrastructure. The panelists addressed infrastructure investments in these three areas as a means of exploring their potential to provide resilience for hazard and other disruptive events, as well as their role in increasing everyday community resilience, particularly for vulnerable populations. The workshop also explored the interplay between physical infrastructure and social infrastructure; examined how infrastructure investments based on codes, standards, and best practices and prioritized community needs can reduce damage and losses from extreme events when damage and disruption occur; and discussed equitable recovery in the context of historical inequities and existing social, economic,

and environmental disparities that may limit community resilience. Full videos of the individual panelists' contributions are available on the web page for the event.¹

APPLIED RESEARCH PRIORITIES

Based on input from the workshop and committee members' knowledge and experiences with natural hazard mitigation and resilience, the committee chose three applied research topics as priorities in motivating local action to address climate impacts and build resilience: (1) partnerships for equitable infrastructure development, (2) systemic change toward resilient and equitable infrastructure, and (3) innovations in finance and financial analysis. The following sections discuss each of these applied research priorities in detail. At the end of each section, the committee includes specific applied research topics and research questions that it considered important for advancing these priorities.

1. PARTNERSHIPS FOR EQUITABLE INFRASTRUCTURE DEVELOPMENT

Targeted equitable public infrastructure investments can generate enormous community benefits in terms of reducing disparities in the quality of and access to services before and after hazard events. Improved equity can increase community resilience and further mitigate the uneven distribution of damage and losses stemming from extreme events. However, ensuring that investments for social, economic, and cultural community functions benefit all community members requires that equity be a focal planning goal and that all community stakeholders be included when identifying needs and prioritizing these investments. The committee identified two areas of research that would improve equitable community involvement: (1) effective partnerships for knowledge transfer and promoting *action research* and (2) building trust to enable productive and equitable community participation.

Partnerships for Knowledge Transfer and Promoting Action Research

Applied research has historically taken two approaches to community participation and inclusion: research *on* communities and research *for* communities. However, capitalizing on the fact that community members hold detailed and often insightful knowledge of local values, needs, constraints, and opportunities that would inform applied researchers requires a more inclusive research strategy—one that enables community stakeholders to drive and direct scientific inquiry. Action research, which seeks both to understand and to alter the problems generated by current social systems, is an approach for generating research about a social system while simultaneously attempting to change that system (Troppe, 1994). Although not a new concept, community-based participatory action research centered on equitable infrastructure would create a unique opportunity to include the community in the knowledge production process (see Box 4). Action research should be collaborative *with* and *inclusive of* the

¹ See <https://www.nationalacademies.org/event/03-17-2022/hazard-mitigation-and-resilience-applied-research-topics-workshop-1-equitable-and-resilient-infrastructure-investments>.

community being studied, and it should strive to achieve social justice through participatory action and social change (Miles, 2018).

Ideally, action research aspires to engage the public at all levels. In practice, however, the process of engagement requires time and interest that community members may not want to devote to that process because they may feel that their input will not be valued or that they do not have adequate time or resources for the requested commitments. Identifying the factors that inhibit community participation can enhance understanding of key barriers to broadening public participation in discourse and decision-making.

Based on the presentations, examples, and research opportunities discussed in the workshop, as well as on discussions with the Resilient America Roundtable and among the committee members, the committee identified the following applied research questions regarding partnerships for knowledge transfer and promoting action research for equitable infrastructure services and access:

- How can applied research on resilient and equitable infrastructure services and access be advanced using participatory action research concepts and principles where the process begins and ends with local communities?
- What are compensation models that value local expertise and how can they be modified to enable greater community participation by those affected by inequitable infrastructure services and access so as not to create additional undue burden on marginalized community members?
- How can community-to-community knowledge transfer of resilience and equity assessment and planning processes for infrastructure services be facilitated?
- What institutional processes would better enable community members to participate in action research?
- What mechanisms would ensure that community input and public participation in action research is actively reflected in equitable and resilient infrastructure planning and development rather than just “heard” and how can we verify/validate the success of such processes and mechanisms?”

In addition, the committee noted the following 3 factors that would enable partnerships for knowledge transfer and promoting action research:

- Provide sustained funding directed to the community to support long-term relationships, ongoing community engagement, and capacity building.
- Require research to be undertaken *with* or *by* the community rather than *for* or *on* the community.
- Develop institutional processes that enable community members to participate.

BOX 4

The CommuniVax Coalition

The CommuniVax Coalition is an ongoing action-oriented equity-focused collaboration among community advocates, social scientists, and health professionals to directly address the “tragic and disproportionate adverse effects on Black, Indigenous, and People of Color (BIPOC) communities across the United States.” The coalition addresses equitable access to

immunizations considering long-standing disparities and community-voiced priorities. The coalition released a plan (Equity in Vaccination) that seeks to “lay the foundation for unbiased health care delivery and enable broader social change and durable community-level opportunities” (Schoch-Spana et al., 2021b).

The coalition’s plan identified 5 key principles that may interest applied researchers investigating equitable and resilient infrastructure investments:

1. Iteration: The coalition suggests repeated engagement with BIPOC communities by organizing “listen-and-plan” sessions to earn their trust and develop authentic co-partnerships geared toward action and actionable “wins” to be shared with elected and appointed officials.

2. Involvement: BIPOC communities must become active partners building on self-determination and self-reliance initiatives enabled by BIPOC individuals.

3. Information: It is important to tailor communications to specific concerns voiced by BIPOC communities and engage trusted BIPOC individuals and organizations to apply lessons learned from the listen-and-plan sessions. To counter misinformation, allies should be enlisted to repeatedly share accurate information.

4. Investment: Equitable outcomes require major and authentic investments in time, attention, and funding to enable economic revitalization and community development, support for the most marginalized individuals in the community, and transactions with local BIPOC nonprofit and for-profit entities.

5. Integration: The coalition advocates a “whole person” approach to recovery from COVID-19—one that meets BIPOC communities’ self-identified needs and ensures durable community benefits such as gains in food security, affordable housing, living wages, and leadership opportunities.

For applied researchers’ intent on addressing topics on equitable infrastructure investments, the coalition advises using rapid ethnography and community engagement techniques (Schoch-Spana et al., 2021a):

- Accelerate translation of knowledge to action by providing interactive efforts and peer-to-peer mentoring between a central work group and local study teams.
- Build trust as a foundation for community partnerships that is cemented with meaningful interactions from the past and genuine follow-through to the future.
- Offer essential social sciences capabilities for timely data and empirically based advice to improve community services.
- Apply ethnography and community engagement methods.
- Play an all-of-society role during crises to leverage community connections, access to decision makers, and supportive infrastructure and media skills.

Building Trust to Enable Productive and Equitable Community Participation

Individuals and communities develop trust over time through observation of consistent behaviors such as clear and unbiased communications, inclusion of and interactions with stakeholders, and ownership of outcomes. In times of stress, the absence of trust can lead to inefficiencies or lack of timely actions that may lead to unintended community impacts. Once trust is lost, it is extremely difficult and time-consuming to restore. Ongoing legacies of inequitable treatment degrade trust and opportunities to identify infrastructure investments that improve resilience and equity of infrastructure services. Unwelcome change can also affect trust levels. Change in communities can be related to improvements before, during, or after disruptive events, where the pace of change and acceptance of its necessity often vary by the degree that individuals or groups are affected.

Research has linked trust within communities to stronger volunteerism, healthier residents, and economic prosperity (Putnam et al., 2004), and it is an essential ingredient in any successful community-based participatory research partnership (Christopher et al., 2008). The workshop informing this report identified four areas where trust is essential to engaging communities effectively: trust in government programs and decisions, trust in institutions, trust in information and data, and trust built with community members.

Transparency is important for building trust. Community plans and efforts should be clear and well understood by all stakeholders, devoid of hidden or alternative agendas, and honest about the role and influence citizens will have in either the decision-making or implementation of solutions (see Box 5). Part of being transparent is sharing information widely between all stakeholders as a means of ensuring that everyone is working from a common understanding of the issue and each other's perspectives.

Based on the presentations, examples, and research opportunities discussed in this workshop, the committee identified the following applied research questions pertaining to trust as it related to equitable and resilient infrastructure development:

- What role does trust play in the development and provision of resilient and equitable infrastructure?
- What role does trust play in the recovery of functions and services of resilient and equitable infrastructure?
- What strategies and tactics can be deployed at the institutional level to regain and grow trust where it has been frayed, especially during times of change resulting from stressors and acute disruptive events?

In addition, the committee noted the following 3 factors that would enable trust:

- Understand the current status of infrastructure services and performance as a baseline or background information for state of trust between stakeholders.
- Cross-reference and coordinate plans and goals for related topics between multiple stakeholders, such as community plans and infrastructure owners and operators.
- Consider the roles and interests of infrastructure ownership, such as public versus private institutions and organizations, and renter versus owner.

BOX 5

Trust and Community Resilience Planning for Affordable Housing

In California, Enterprise Community Partners launched a community-powered resilience initiative offering community organizations and local governments resources and actions to implement for equitable resilience planning and recovery. Community-led resilience is about investing in communities based on their issues, listening to their solutions, and redirecting resources. Nationally, Enterprise includes materials, training, and manuals in their resilience academies and assessment tools to help affordable housing owners engage with a property's residents. That engagement is crucial to build trust and a relationship, avoid unintended consequences, and build a community's motivation to steward their own resilience and recovery efforts. Enterprise Community Partners focuses on meaningful trust building and engagement with residents when completing retrofit and rehabilitation of existing properties. Without resident engagement, building owners will not necessarily make the best decisions about which buildings to prioritize and how to incorporate the unique needs of the residents as they improve properties for resilience.

2. SYSTEMIC CHANGE TOWARD RESILIENT AND EQUITABLE INFRASTRUCTURE INVESTMENT

Inequity can be hard-wired into mature and stable institutions, such as federal and state agencies, city officials, public planners, and the entities that develop infrastructure. Too often, however, institutions do not recognize they have a problem, and even when they do, they may have difficulty bridging the gap between awareness of inequity and substantive change, which in turn can contribute to failed outcomes in building resilient and equitable infrastructure. While resistance to change can be a strength during times of stability or minor turbulence, it can lead to a crisis of confidence in the institution as increasingly unbearable outcomes continue to afflict populations these systems should serve.

Assumptions, norms, processes, and procedures that evolve over long, stable periods may no longer serve when political, social, or ecological baseline conditions shift. Under pressure to change, mature institutions often resist wholesale change, though they may establish limited-scope programs or implement pilot projects to evaluate and demonstrate new ways of thinking or new approaches to solving problems. These pilot projects, while an important first step, are insufficient to stimulate the systemic change required to address the complex challenges of social injustice and inequitable provision of infrastructure introduced by climate change.

During the process of reaching consensus, the committee identified six areas of research that would inform institutional efforts to put equity at the center of their infrastructure investments: systemic change, resilience hubs, community resilience planning, integrated multi-benefit solutions, interdependence of built and natural environments, and minimum code requirements.

Systemic Change

Inequity in infrastructure investments can become visible when access to infrastructure services and post-disaster recovery timelines disproportionately impact some communities more than others. Good intentions to change, even when desired, can be difficult to accommodate in mature and stable organizations, utilities, corporations, and governments. More established organizations can resist change even as baseline conditions shift. Complex natural and human systems do change, however, when profound shocks (e.g., acute disruptive or damaging events such as hurricanes, earthquakes, or floods) and stressors (e.g., chronic conditions such as drought or sea level rise) can force these systems to adapt and or transform (Westley et al., 2013; Gunderson and Hollings, 2002; Hollings, 1986;). Times of stress and shock create opportunities for organizations to undergo systemic change, and pilot projects that model new patterns and relationships can often find broader applicability following a disruption (Westley et al., 2013).

It is during these times of disruption that once-stable systems are most open to innovation and opportunities for change (Dorado, 2005; Snowden and Boone, 2007; Westley et al., 2013). Change agents outside of the system and institutional entrepreneurs within the system can forge new collaborations and new alliances that may redeploy resources to novel endeavors (Snowden and Boone, 2007). These new combinations and alliances can seek to guide their institutions toward new stable states with adapted norms, processes, procedures, and outcomes (Plowman et al., 2007; Westley et al., 2013).

Based on the presentations, examples, and research opportunities discussed in this workshop, the committee identified the following applied research questions regarding systemic change and equitable infrastructure investments:

- What models of system change are most useful for institutions to achieve equitable infrastructure investments? For example, what can applied researchers in equitable and resilient infrastructure investment learn and apply from the CommuniVax Coalition's process and plan? (see Box 4)
- How can equity-focused change agents and institutional entrepreneurs—individuals with an interest in particular institutional arrangements and who leverage resources to create new institutions or to transform existing ones (Maguire et al., 2004, p. 657)—be identified and supported?
- How can successful pilot projects be rapidly scaled to reliably deliver equitable outcomes?
- How can infrastructure providers and investors stimulate their institutions into meaningful and lasting change to address inequitable outcomes? How can these institutions make equity an explicit goal and hold themselves accountable for achieving or advancing equity.

In addition, the committee noted factors that would enable systemic change in infrastructure investments including:

- Provide access to relevant data, such as results from previous pilot projects, with the requirement for pilots to be documented and reviewed prior to systematic investments.
- Develop ways to apply adoption of equity-focused innovations.

- Conduct pilot validation prior to system implementation.

Resilience Hubs

Community resilience hubs provide holistic support to communities during disaster and recovery periods, as well as throughout the year. Resilience hubs should be community-serving facilities that are designed in collaboration with communities and augmented to support residents and coordinate communication, distribute resources, and increase the community’s adaptive capacity while enhancing quality of life (Baja, 2019). They provide the opportunity to work at the intersection of community resilience, emergency management, climate mitigation, and social equity while also helping communities to become more self-determining, socially connected, and successful before, during, and after disruptions. Strong relationships and communication built throughout everyday operations can both strengthen community capacity to face disasters and ensure that resilience hubs are trusted resources in times of emergency.

Resilience hubs have the potential to support historically underinvested and vulnerable communities (such as those facing increasing climate risks) during and after disaster events as well as throughout the year, but siloed funding—such as funding dedicated for emergency operations only—and limited data access and transparency limit the effective design, deployment, and operation of community resilience hubs. To be effective, resilience hub designs must reflect local needs, priorities, and the unique characteristics of their surrounding communities and account for historic inequities and vulnerabilities. A top-down, one-size-fits-all approach does not work, but funding and research often fails to support the design of centers reflecting community-based priorities and needs and fails to provide the kinds of holistic services required to serve the community. Needed services include resilient services and programs to increase human adaptive capacity and enhance the development of strong relationships and trust with the community; resilient communications both during a disaster event and with the community throughout the year; resilient landscape and buildings inclusive of green design and reflective of the natural environment; resilient power systems such as solar energy plus energy storage capacity; and resilient operations and maintenance supported by consistent and reliable funding. These holistic approaches can contribute to strengthening relationships and trust required for effective year-round, disaster, and recovery modes.

Based on the presentations, examples, and research opportunities discussed in this workshop, the committee identified the following applied research questions on the topic of resilience hubs:

- What are the policy and regulatory barriers in different states and jurisdictions that limit resilience hub deployment, and how may these be overcome? Examples may include the following:
 - Utility-level requirements, such as prohibitions to linking together multiple buildings with different electric meters
 - Grid interconnection standards limiting optimal system design or posing challenges to islanding systems
 - Poorly designed incentives for solar + storage, such as those based on narrowly-defined benefit-cost calculations and omitting the value of resilience

- What are effective financing strategies to support resilience hub facilities and operations during emergency events, recovery, and all year? Specific examples include the following:
 - How can siloed funding streams be combined? How should financing and funding streams be better targeted to historically marginalized populations and communities?
 - How should financing and funding streams be better targeted to historically marginalized populations and communities, and how have historic equity goals been successful or fallen short? How should these communities be identified?
 - How can multi-year and other long-term investments support ongoing operations, maintenance, services, and other hub activities?
 - How can benefit-cost frameworks be modified to reflect the broad scope of potential resilience hub services to the community, and analyze factors that are historically omitted, such as continuity of operations, or strengthening of human adaptive capacity?
- What strategies and platforms can enable knowledge transfer between communities and between practitioners? Focus areas may include, for example:
 - Historically underinvested areas
 - Rural areas and tribal communities
 - Places with limited clean energy
- How do we create replicable community engagement strategies for resilience hub design and shift decision-making to those most affected by disasters?

Many of the applied research questions addressed in other subsections of this report—including, for example, trust and benefit-cost analyses—could be framed to address resilience hubs, and the findings from resilience hubs research can be used to help inform broader analyses in these topic areas.

In addition to the research questions identified, the committee noted several factors that would enable establishing resilience hubs:

- Provide sustained financing for communities to engage with researchers in a continuous way (see section on Partnerships for Equitable Infrastructure Investment).
- Consider communities to be full partners in research, with government agencies or other funders helping facilitate these relationships.
- Create options for co-ownership or community ownership of research projects.
- Provide local data on community demographics, climate, carbon life-cycle analysis, energy, and other dimensions and partner with communities to effectively use these data to make effective risk-informed decisions on resilience hub design and operation.
- Provide funding focused on systemic change, not just pilot projects.
- Prioritize resources for historically underinvested communities to help achieve a basic standard of infrastructure access.
- Ensure relevant organizations, including community-based partners, are engaged to continuously help inform state, regional, and local funding and decision-making strategy on resilience.
- Incorporate traditional ecological science and local expertise and knowledge about population concerns, needs, and priorities.

Community Resilience Planning

Communities can prosper only if they have operational and hazard-resilient buildings and infrastructure systems. Damaged buildings and infrastructure systems interrupt social services, produce soaring economic losses, and require resource reallocation to repair and rebuild the systems. When damage is extensive, the recovery process can be a significant drain on the community and may draw on its resources for years (NIST, 2016). Negative outcomes can compound as communities reallocate resources for maintenance and improvements to repairs and reconstruction, stunting the recovery process, which, if it takes too long, can lead to permanent economic decline and population relocation, as in the case of New Orleans following Hurricane Katrina.

Activities such as prevention, protection, mitigation, response, and recovery are key components of resilience, where resilience is an umbrella concept for these actions and the desired outcome of maintaining and improving restoration of functions and services. While response and recovery activities occur post-event, communities should plan these activities prior to hazard events, including pre-positioning assets to be used once the disaster strikes (Rose, 2017) (see Box 6). Communities may need to adjust pre-event plans for response and recovery, as unique or unexpected events may occur, and it is much easier to adjust existing plans than to create them during the turmoil following a disaster. As climate-sensitive hazards continue affecting lives and livelihoods, neglecting to plan in advance will result in planned failures, with many of these failures occurring in historically disadvantaged and socially vulnerable areas.

BOX 6

Indicators and Metrics to Help with Planning

Indicators and metrics can help identify vulnerabilities and track community resilience over time. For example, a 2016 study reviewed 27 resilience assessment tools, indexes, and scorecards and identified four parameters that researchers have used to distinguish between them—focus (on assets baseline conditions), spatial orientation (local to global), methodology (top down or bottom up), and domain area (characteristics to capacities). The most common elements in all the assessment approaches can be split into “attributes and assets (economic, social, environmental, infrastructure) and capacities (social capital, community functions, connectivity, planning)” (Cutter, 2016).

Researchers have also developed frameworks to connect concepts of resilience to measurable indicators and measures to operationalize the concept of resilience. These frameworks have emerged both as a methodology to study community resilience and as a decision support tool for disaster and adaptation planning. However, reviews by the National Institute of Standards and Technology (NIST) Community Resilience Program and others (Loerzel and Dillard, 2021; Walpole et al., 2021; Cutter, 2016) have shown that there is a lack of consensus in terms of the theoretical approaches taken, indicators and measures used, data requirements, and spatial scales among the frameworks. To better understand these disparities, NIST constructed an inventory of resilience frameworks (Loerzel and Dillard, 2021; Walpole et al., 2021).

Figure 1 depicts resilience in terms of infrastructure disruption losses over time in relation to the “loss triangle,” the area between system function or output in the absence of disaster compared with the system function or output when a disaster occurs (the entire gray area between the horizontal) “without-disaster” line and the “with-disaster” curve. In the absence of any risk-reduction efforts prior to a disaster, the system will drop to the lowest vertical point in the loss triangle. Robustness is the ability of the system to withstand the shock and avoid total failure. Pre-disaster actions (ex ante), commonly referred to as mitigation, reduce the initial shock in terms of both property damage and business interruption and reduces time to recovery. Actions taken once the disaster strikes (ex post) cannot reduce property damage, but they can reduce business interruption. Such actions are sometimes referred to in the literature according to a narrower definition of resilience, based on the Latin root of the term, meaning to “bounce back.” However, it is important to note that most analysts view resilience as a process, whereby post-disaster resilience capacity can be built up ahead of time by such actions as purchasing backup electricity generators, stockpiling critical materials, or practicing emergency drills, though these resilience “tactics” are not actually implemented until the disaster strikes (Rose, 2017).

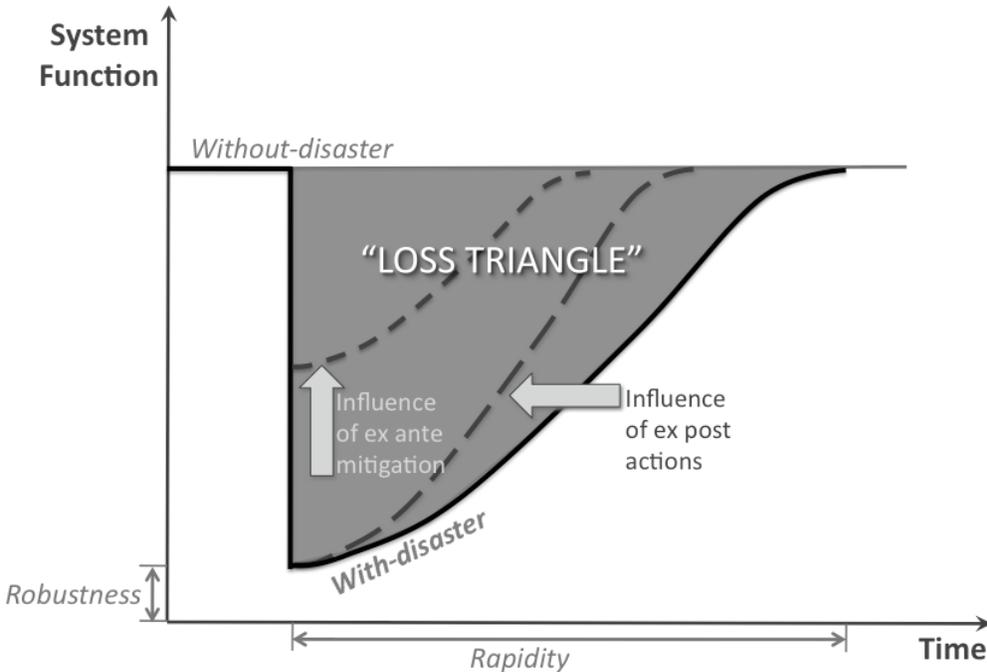


FIGURE 1 Measuring resilience using the “loss triangle” concept.
SOURCE: NRC, 2011.

Figure 2 provides further insight into important aspects of infrastructure resilience. Case A illustrates how pre-event activities, such as mitigation and recovery planning, can lead to a shorter recovery time for infrastructure system functionality and recovery when there is increased capacity to resist or avoid damage. When infrastructure systems age through inadequate maintenance and continued degradation, as shown for Case B, the damage, loss of functionality, and time to recovery of system functions can be much greater. Additionally, as depicted by the shaded area between the dashed lines, there is likely to be a relative increase in uncertainty for the recovery of functionality, due to greater damage and disruptions.

Therefore, for infrastructure services and operations, the most effective approach is to take mitigation and planning actions before a hazard event to minimize the need for emergency response and recovery. For example, retrofitting facilities, improving land use and zoning regulations, adopting and enforcing building codes, and installing flood barriers can improve infrastructure performance and reduce damage and losses. Additionally, as indicated by Case A in Figure 2, immediate and targeted response actions following a hazard event can substantially reduce the recovery time and accelerate recovery (Xie et al., 2018; Zobel, 2014).

Improved infrastructure performance also leads to reduced business interruption and social impacts. An important consideration regarding mitigation for existing infrastructure is the cost of the improvements relative to the increase in performance they produce. For some facilities, the decision may be to move critical functions to another location to reduce vulnerability despite hazard threats, or to plan on rebuilding elsewhere after a hazard event. Major studies of the benefits of mitigation have found that the benefits exceed the costs by at least a 4-to-1 ratio (MMC, 2005, 2019; Rose et al., 2007).

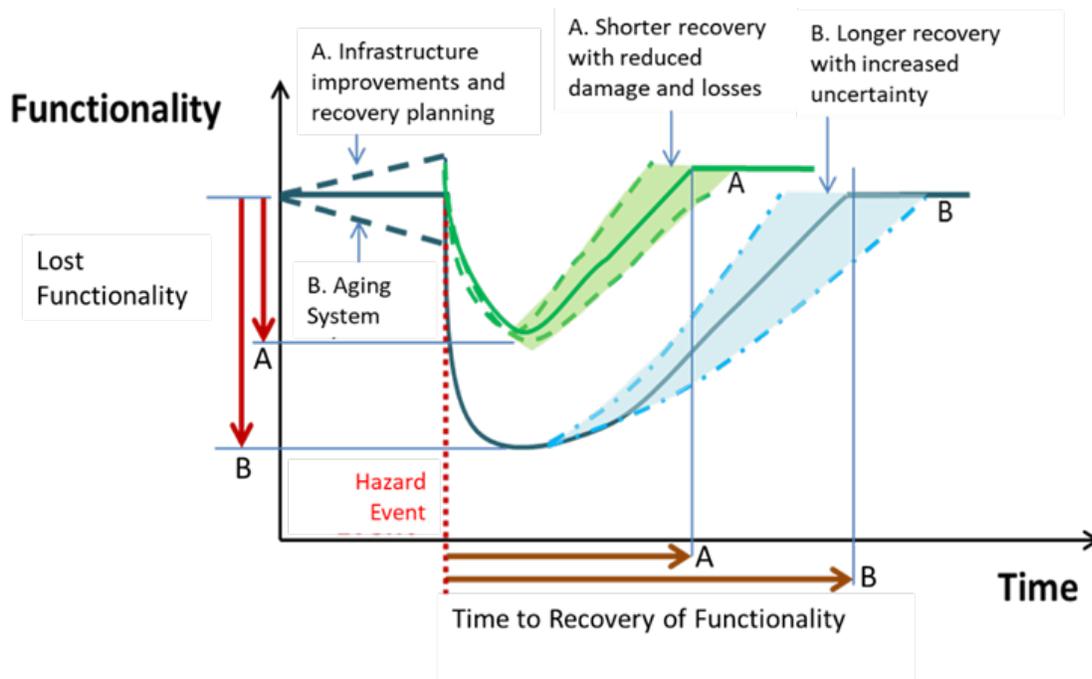


FIGURE 2 Role of pre-event planning and actions to improve recovery of infrastructure functionality.

SOURCE: McAllister, 2013; NIST, 2016.

The community population, businesses, and organizations also need similar resilience activities. Pre-event planning and mitigation activities are essential to accelerating post-event response and recovery. The quality, extent, and timeliness of response activities can greatly increase the recovery of functionality across a community (FEMA, 2011; NIST, 2016). However, policy makers often give precedence to infrastructure because many infrastructure services, especially electricity and water, are considered community lifelines that are needed for survival (FEMA, 2019). Other infrastructure such as transportation and communication are key to emergency response and the recovery process.

As the nation moves forward, it needs better methods to track and measure the impact of infrastructure performance and investments (Preston et al., 2022). Resilient performance of infrastructure should also support equitable access to community services, such as safe housing, transportation, utilities, health care, and education. In addition, mitigation and recovery processes related to hazard threats need to consider underrepresented groups and underserved communities.

Based on the presentations, examples, and research opportunities discussed in this workshop, the committee identified the following applied research questions pertaining to community resilience planning:

- What are the negative compounding outcomes that stunt the recovery process and require resource reallocation by communities? When do they lead to permanent economic decline and population relocation?
- What federal standards are needed to ensure accountability?
- What measures and indicators are needed to help communities track progress toward improving resilience and equity and prioritize infrastructure plans and investments?
- How have pre- and post-event resilience strategies, such as mitigation, redundancy, and relocation, as well as government policies, improved outcomes for individuals, communities, and regions? And which individuals and communities are left out of these benefits?
- Does improved resilience at one scale (e.g., neighborhood, community, region) adversely affect resilience at another scale?
- What has been the performance record of mitigation and other resilience activities in terms of individual and cross-community benefits? How do expected and actual benefits compare?
- What planning and funding strategies are needed for local, state, and federal stakeholders to ensure that affordable housing is not disproportionately located in neighborhoods or communities at higher risk of damage and loss of services?
- How can renters and tenants be included in the decision process for prioritizing resilience and equity improvements to existing housing and supporting infrastructure/services as well as in post-disaster housing? How do we prevent further housing instability and homelessness following a disaster?
- How can we understand and build resilient infrastructure as integral systems that meet the needs of communities in a comprehensive manner and with decisions based on equitable access?
- What are the effects of transportation and its disruption on neighborhoods and micro-movements of population as revealed by micro-data on individual households, businesses, and institutions? How can transportation systems address mobility as well as safety, accessibility, walkability, drainage, resource conservation, and health benefits in an equitable way?
- As transportation systems become more automated and integrated, what are the effects on housing, employment, commuting, and metropolitan transport choke points regarding the interface (nodes, areas, links, and connectivity) between long-distance (long-haul) freight transport and local (within metro areas) distribution?
- Has the COVID-19 pandemic created a tipping point or will access in urban areas be increasingly dominated by mass transit as it was in the years leading up to the pandemic in some parts of the country, such as the East Coast? Can transportation

- risks be balanced with less expensive post-disaster coping mechanisms such as telework and shifting business locations?
- How can we rethink redundancy as a major strategy for coping with risks to infrastructure performance in spite of improvements in efficiency?
 - How can we understand and build resilient transportation infrastructure as integral systems that meet the needs of communities in a comprehensive manner and with decisions based on not only mobility but also safety, accessibility, walkability, drainage, resource conservation, and health benefit?

In addition, the committee noted several factors that would enable community resilience:

- Provide communities with examples of successful community resilience planning and recovery, especially those that encourage public participation and inclusiveness, including accessibility; resilience planning should be co-created with communities.
- Provide communities with quantitative community resilience planning tools that support informed decision-making.
- Incorporate emergency response and functional recovery in infrastructure planning investments to become resilient and to effectively address the current and future challenges resulting from climate change, aging infrastructure, land use, and so forth.
- Develop a better understanding of resilience and equity gaps and related problems using data that are consistently available for analysis and metrics to track progress (or lack thereof).
- Consider mitigation and preparation strategies that are focused on the most vulnerable communities.
- Plan for the higher cost of recovery in vulnerable areas of communities that are expected to have greater levels of damage and losses due to past planning and funding actions as well as due to lack of planning and funding investments.
- Improve preparedness and emergency response logistics to minimize the loss of community functions after a disruptive event. Improve recovery times to reduce adverse impacts on various components of communities (households, businesses, institutions).

Integrated Multi-Benefit Solutions

Silos of expertise, training, and project delivery lead to highly competent solutions that may discount impact and opportunities adjacent to and outside of that silo. This leads to single-problem, single-fix approaches that do not capture broader community benefits that could maximize the value of infrastructure investments to local communities. Achieving smart integrated solutions needs to be done at the pre-design phase of infrastructure development before narrow-focus solutions are designed and funded. Infrastructure providers can find this challenging when they have single-purpose funding streams. Yet when equity and maximizing community value is the intent, then new norms need to be enabled to break down silos. Additionally, having a convener or moderator, who knows and understands the community, during and before the pre-design phase may increase the benefits of the infrastructure development and investments and achieve multi-benefit solutions.

Based on the presentations, examples, and research opportunities discussed in this workshop, the committee identified the following applied research questions pertaining to integrated multi-benefit solutions:

- How can communities use broad-based and inclusive planning to maximize economic, environmental, and social value by working together at the pre-design phase to make infrastructure investments address historic disinvestment in BIPOC (Black, Indigenous, and People of Color) communities?
- What systems-based models can be integrated into infrastructure investments to better understand local values, map assets, and identify alternatives?
- How do we broaden project-funding streams to ensure that they can provide multiple community benefits?
- How do we redesign funding structures to include the resilience component?
- What are the barriers to integrated funding and regulatory solutions?

Some of these concepts will be discussed further in the upcoming section on benefit-cost analyses.

In addition to the above research questions, the committee noted factors that would enable the development of integrated multi-benefit solutions including:

- Condition federal funding to encourage and prioritize broad-based and inclusive approaches to community investments that help communities find fair, equitable, and inclusive solutions for large infrastructure projects.
- Require the design phase of infrastructure solutions to be measured against equitable outcomes and include community stakeholders prior to disaster or in the mitigation phase of resilience.
- Include community stakeholders in the post-disaster recovery phase.

Interdependence of the Built and Natural Environments

The built and natural environments are connected to the health of communities. Focusing on good practices for communities that disastrous events devastate disproportionately could lead to better long-term community benefits. Examples of these benefits include health-related outcomes from physical activities, social engagement, mental health, perceptions of crime, and road traffic collisions. Research has associated these benefits with built environment planning activities such as enhanced walkability, compact neighborhood design, enhanced connectivity, and a safe and efficient infrastructure (Bird et al., 2018).

Exposure to natural environments and even vegetation in cities can enhance physical and emotional health. One study, for example, found that a 20-minute natural experience caused physiological biomarkers of stress to fall by more than 20 percent (Hunter et al., 2019). Other research has shown that tree cover for elders in care facilities was associated with fewer depressive symptoms (Browning et al., 2019). Several studies, however, found significant race-based inequity in urban forest cover (Lin et al., 2021; Locke et al., 2021; Watkins and Gerrish, 2018; Watkins et al., 2017).

Natural watersheds provide potable water and provide soils and habitats that support food and fiber for human uses. Functioning natural systems provide protection for the built

environment. For example, coastal salt marshes function as natural buffer zones and provide protection for coastal communities by attenuating storm surge and wave action. Mountain forests with healthy soils can protect against downstream floods through water storage, erosion control, and increased surface area evaporation (Markart et al., 2021).

Based on the presentations, examples, and research opportunities discussed in this workshop, the committee identified the following applied research questions pertaining to the interdependence of the built and natural environments as they relate to equitable and resilient infrastructure investments:

- How can we investigate, understand, and apply function and design relationships between neighborhood housing and access to natural areas and open space?
- What performance measures could we apply broadly to quantify and accelerate adoption of urban greening programs that link energy conservation, urban heat islands, and equity?
- How can we measure interrelationships between the built and natural environments to foster investment that brings about optimal and equitable conditions for underserved communities?
- How can we integrate the concept of disaster mitigation (pre-disaster) versus post-disaster (resilience) with equity community voices to support investment decisions in the built environments?
- What are successful case studies where urban areas have enhanced and restored natural environments that provide food, fibers, and water and serve as a barrier to mitigate natural hazard risk?

In addition, the committee noted two factors that would enable better connections between the built and natural environments:

- Integrate community stakeholders that represent voices from the community who will push for designs and planning that will support equitable outcomes.
- Understand the spillover effects on investments in communities with planned dividends to the community and to the environment. Investments can have unintended consequences and, if planned accordingly, could benefit and support equitable communities.

Minimum Code Requirements

Communities consist of buildings and infrastructure that can range from new construction based on modern codes to construction that is more than 100 years old. In addition, some hazards, such as floods and earthquakes, vary over the geography of communities. This range in construction quality, standards, and exposure to hazards leads to uneven performance and damage levels across communities, and community resilience and equity planning can address this uneven performance.

National building codes and standards have been developed to ensure minimum requirements for life safety and public welfare. The minimum requirements allow flexibility for designers and communities to tailor additional requirements for local purposes and issues. At the same time, minimum standards set by best practices may not reflect a community's expectation

for resilience. In addition, to be effective, states and communities need to adopt the national codes and standards. However, approximately 60 percent of local jurisdictions have not adopted building codes (FEMA, 2022). Failure to adopt and implement current codes and standards exposes communities to disproportionate impacts, as substantial damage may occur for hazard events that would normally cause minor, if any, damage with proper design and construction.

For existing construction, retrofits and renovations are more challenging to address. The International Existing Building Code addresses requirements for modifications to existing buildings. Depending on the condition of an existing facility, it may or may not be possible to meet current code requirements for new buildings. Mitigation measures that can significantly reduce vulnerabilities to damage need to be evaluated for effectiveness relative to their costs. For example, housing retrofits and renovations can raise costs that disproportionately impact low-income communities, Indigenous people, and communities of color, particularly for tenants.

Model codes and associated standards are prescriptive in nature, where compliance with specified requirements infer a minimum level of acceptable performance. When code requirements do not meet the needs of a project, building officials can approve alternative methods. Alternative methods, such as performance-based design, can use specified performance objectives to explicitly address project requirements. A key aspect of resilient infrastructure, though, is compliance with national regulations, codes, standards, and best practices (McAllister et al., 2022; Wang et al., 2022). Given the lack of code adoption and the effects of aging and lack of maintenance across the nation (ASCE, 2021), simply meeting or exceeding minimum requirements would improve infrastructure performance. A 2019 study (NIBS, 2019) examined five sets of mitigation strategies and found that society could obtain a benefit-cost ratio of 11 to 1 by adopting the 2018 International Residential Code and International Building Code, the model building codes developed by the International Code Council (also known as the I-Codes), versus codes represented by 1990-era design.

Based on the presentations, examples, and research opportunities discussed in this workshop, the committee identified the following applied research questions pertaining to minimum building codes as they related to equitable and resilient infrastructure investment:

- What do states and communities need to understand the value of adopting and administering code and standards as a foundational aspect of short- and long-term economic benefits and resilient infrastructure with reduced damage and losses?
- What incentives exist to encourage communities to specify requirements beyond code -minimum performance?
- How do codes and standards for new construction and upgrades to existing facilities affect community equity and resilience?
- What are the disparate effects of updating existing buildings on landlords and tenants regarding safety, health, and affordable housing?
- What are the impacts on community equity and resilience of failing to adopt codes and standards on resilience?
- What is the role of performance standards versus prescriptive code requirements for achieving resilient and equitable outcomes?
- What data and analyses are needed to address functional recovery in infrastructure design practice?

In addition, the committee noted the following 3 factors that would enable better use of building codes to enhance community resilience:

- Provide access to local infrastructure data, such as codes and history, flood maps, appraisals, records, and drawings.
- Develop codes and standards that support resilient performance and equitable services for new and existing infrastructure.
- Build stakeholder understanding of local resilience goals/needs relative to those achieved by meeting minimum code requirements.

3. INNOVATIONS IN ECONOMIC AND FINANCIAL ANALYSIS

Traditionally, public funds finance infrastructure investments, but public deficits, the inability of the public sector to deliver efficient investment spending, and a lack of political will have in many communities led to governments reducing the level of public funds they allocate to infrastructure. Discussions at the workshop made it clear that research needs to develop new analytical tools that can demonstrate the benefits of public investment in resilient and equitable infrastructure development and that would lead to developing new mechanisms for financing resilient and equitable infrastructure.

Innovative Financing for Equitable Infrastructure Development

As a key driver for sustainable growth, infrastructure constitutes a vital pillar of fiscal stimulus to provide economic recovery, particularly in a post-COVID-19 period. It will also serve as a crucial component of the transition to a low-carbon economy (Gaspar et al., 2020). As such, there is an opportunity to increase the magnitude of investment in infrastructure. However, efforts to expand infrastructure investments must complement, in equal measure, considerations to improve the quality of these investments, including by ensuring that infrastructure is equitable and does not inadvertently exacerbate inequality.

Promoting quality infrastructure²—infrastructure that is well planned, efficiently implemented, resilient, equitable, and sustainable—is an essential enabler for achieving sustainable growth, and more globally, achieving the United Nation’s Sustainable Development Goals and national greenhouse gas mitigation contributions under the Paris Agreement. The focus on quality has taken on greater resonance during the COVID-19 crisis, highlighting the need to “build back better” by maximizing the quality of infrastructure assets at the earliest stages of the project life cycle to improve resilience to, and reduce the costs of, future shocks, including climate change (Rozenberg and Fay, 2019).

Economic stimulus will serve as a critical lever to ensure infrastructure investments are of a high quality, sustainable, and equitable. Increased climate-resilient infrastructure

² Quality infrastructure is a concept embodied by the G20 Principles for Quality Infrastructure Investment to raise awareness of the quality dimensions of infrastructure in emerging markets, but it is equally relevant in the United States.

development can also reduce the risk of physical stranded assets, diminish disruptions in services, and create opportunities to meet infrastructure service needs for all communities, particularly the most vulnerable, in a more efficient way. As global markets recover from the COVID-19 pandemic, there will be an increased need to spend public funds intelligently³ and quickly, which can work at cross-purposes, and incentivize private investments.

Public funding can play an important and sometimes driving role in ensuring infrastructure is both climate resilient and equitable. Thus, public financing is a particularly attractive source of capital whose value simply exceeds the investment dollars from the public balance sheet. Innovation in not only how these funds are invested but also how these funds drive equitable and climate-resilient outcomes will be critical.

Based on the presentations, examples, and research opportunities discussed in this workshop, the committee identified the following applied research questions pertaining to innovative financing for equitable infrastructure development.

- What is the range of public finance for climate-resilient infrastructure that includes mechanisms, incentives, or other measures, including equity requirements, to ensure that projects it supports are equitable?
 - Where they exist, how do these measures ensure that such projects are equitably developed? Which stakeholders were engaged, and what was the process to ensure that the end users defined equity?
- What are the range of public finance options for community equity and resilience that also focus on climate-resilient infrastructure?
- How are these public financing programs supporting climate objectives in addition to equity and community resilience, if defined more broadly than climate resilience?
 - Where they exist, how are measures that ensure climate resilience developed?
 - What assessments were done to understand climate vulnerability, and were these assessments considerate of equity aspects?
- What are the specific financial mechanisms for equitable infrastructure development, such as grants, loans (concessional or commercial), guarantees (concessional or commercial), and equity/financial equity of public financing programs?
 - What are the terms and conditions of such financing? Are these terms and conditions equitable in a way that does not disproportionately disadvantage vulnerable and historically underinvested communities?
 - Do the terms and conditions allow for greater access to financing or less access to finance?
 - How effective are these mechanisms in the context of equitable outcomes?
 - What is the relative cost to accessing these funds for equitable and climate-resilient outcomes, as measured in time spent to apply for funding, the volume of financial support provided, and the ability of communities to leverage funding?
 - How innovative are these financial mechanisms, as measured by (1) the uniqueness of the terms and conditions, (2) the connections to nonfinancial impacts and co-benefits (e.g., measures of improved equity or improved “resilience”), and (3) their complexity.

³ Inefficiencies in public infrastructure investment processes have shown to waste an average of 30 percent of public resources (Schwartz et al., 2020).

- What is the role of wrap-around funding—a collaborative, team-based funding approach to service and support planning—and financing in mitigation, recovery, and other aspects of risk reduction?

In addition, the committee noted the following 3 factors that would enable innovative financing for equitable infrastructure development:

- Map federal, state, and local public funding sources for both climate-resilient infrastructure and equity goals, including the processes that these sources undertook to ensure equity issues are well developed.
- Provide localized data and information about vulnerability beyond climate vulnerability.
- Ensure broad representation in research and in interpreting and assessing the research outcomes before developing recommendations about whether and how innovative financing sources can better enable climate-resilient, equitable outcomes.

Benefit-Cost Analysis

Benefit-cost analysis is a decision-making tool that policy makers use primarily for evaluating certain public-sector investments, such as infrastructure construction when ordinary markets do not exist, or where markets cannot achieve efficient outcomes, or, increasingly, where desired outcomes extend beyond economic efficiency (Boardman et al., 2018).⁴ Policy makers also use benefit-cost analysis to evaluate investment infrastructure protection against disasters (mitigation), coping with ramifications of infrastructure damage and loss (resilience), and decisions regarding reconstruction alternatives (including “building back better”). Increasingly, decision makers are evaluating infrastructure investment as a major strategy to cope with climate change impacts, as in the construction of barriers or elevating structures to protect against sea level rise. In fact, benefit-cost analysis studies have found that mitigation against disasters yields a benefit-cost ratio of at least 4 to 1 for historical cases (MMC, 2005, 2019; Rose et al., 2007) and as much as 11 to 1 for advanced building codes (MMC, 2019). Moreover, a survey-based study that examined resilience responses by businesses to input supply disruptions in the aftermath of Hurricane Harvey found an average 4.5-to-1 benefit-cost ratio in reducing potential lost revenue (Dormady et al., 2022). As applied to infrastructure funding, benefit-cost analysis can on occasion lead to inequitable outcomes, which can include discounting future generations and inappropriately valuing or omitting non-monetizable community values, such as public health, community ownership, or resilience when that is not the primary objective (see Box 7). Benefit-cost analysis also omits equity considerations, such as failing to account for historic disinvestment in low-income communities, Indigenous communities, and communities of color. The tendency to assess the cumulative benefits and costs of projects, rather than the distribution of these benefits and costs, frequently limits these

⁴ This is in contrast to private companies making capital investments or decisions on investments in financial instruments, where considerations such as profits or rates of return represent the “benefits.” In benefit-cost analysis, benefits are interpreted broadly to include all benefits to society, even beyond those that accrue to the individual investor. This is also the case for the cost side of the ledger. Nongovernmental organizations and philanthropic organizations typically use broader concepts of benefits and costs as well.

analyses. In addition, benefit-cost analysis is often used for siloed analyses, and outcomes that depend on how the user selects inclusion and exclusion criteria. For example, the multi-benefit solutions discussed in an earlier section of this report would require a more inclusive benefit-cost framework than is frequently used for investment decisions.

Based on the presentations, examples, and research opportunities discussed in this workshop, the committee identified the following applied research questions pertaining to benefit-cost analysis as applied to resilient and equitable infrastructure development:

- How can we include distributional considerations in benefit-cost analysis to analyze equity, social justice, and other broad societal goals?
- How can we adapt benefit-cost analysis to account for difficult-to-monetize outcomes, such as resilience, public health, and equity?
- Are there alternative decision analysis approaches to benefit-cost analysis to evaluate resilient infrastructure investments?
- What adjustment to benefit-cost analysis would better incorporate benefits to future generations?

In addition, the committee noted factors that could improve benefit-cost analysis as applied to resilient and equitable infrastructure development including:

- Further explore equity considerations during recovery from disasters.
- Enhance public participation of all stakeholders in risk-reduction decisions.
- Improve decision support tools, such as FEMA’s benefit-cost analysis toolkit, to include equity considerations.

BOX 7

Approaches to Measuring Intangibles in Benefit-Cost Analysis

One approach that broadens the scope of benefit-cost analysis is the “triple-dividend” of disaster risk reduction (Surminski and Tanner, 2016). This approach emphasizes that the direct intended benefits of hazard mitigation may never be realized if no disaster occurs, a condition that often biases decision makers against mitigation. To address that shortcoming, this approach adds two additional categories to ordinary direct benefits. One is the reduction in uncertainty that comes from investment in mitigation, which promotes an improved business environment and further investment more generally. The other refers to joint product effects, which can be extensive if properly devised. For example, green stormwater infrastructure serves mobility, safety, drainage, and water conservation needs.

Incorporating emergency response and disaster recovery in transportation planning investment is critical for all communities to become resilient and effectively address the current and future challenges resulting from climate change, other disasters, and aging infrastructure in general. Broader joint products in relation to equity and social justice fit into the triple-dividend framework as well.

Another issue with benefit-cost analysis is that it values the benefits of resilient infrastructure investments for future generations much less than current ones because it accounts for the time value of money. For example, a \$1 million investment today, even at a low discount rate of 3 percent, is only worth \$52,000 in present value terms according to the traditional methodology. There are several alternative approaches to the inappropriate alternative of using a zero-discount rate, such as channeling some of the current benefits of a project in its early years

to invest in other projects that will benefit future generations, such as investments in research and development of clean technologies. Another approach is to establish a set-aside fund for the explicit use of future generations (Hartwick, 1977).

CONCLUSION

Hazard events caused by extreme weather events and other large-scale emergencies continue to devastate communities in the United States. As stated in numerous studies, while nature does not discriminate, the reality is that decades of inadequate adoption and enforcement of codes and standards and discriminatory policy and practices have resulted in low-income communities, Indigenous communities, and communities of color bearing a disproportionate share of the social, economic, health, and environmental burdens caused by extreme weather and other natural disasters (Cutter et al., 2008; Cutter and Finch, 2008; Belkhir and Charlemaine, 2007). In addition, the current thinking about community resilience fails to account for the fact that many communities often lack the resources to engage in risk reduction, mitigation, and planning, and disadvantaged communities lack even more. There are never enough funds to do the level of resilience planning that is desired, but communities can address their needs incrementally, similar to all other community needs. To reduce the equity gap in community resilience, efforts to enhance community resilience and adaptability must include funds and resources for planning and construction, as well as rebalancing public infrastructure investments and addressing fundamental social inequalities.

Recognizing the importance of directing investments in infrastructure to opportunities that will increase community resilience and reduce the equity gap that affects disadvantaged communities, the Committee on Hazard Mitigation and Resilience Applied Research Topics focused on identifying applied research needs and opportunities to better create and capitalize on such opportunities. To inform this work, the committee organized a 1-day workshop to gather information and applied research topic insights from researchers, advocates, and policy makers knowledgeable about resilient and equitable infrastructure. The workshop's panels addressed the following topics:

- Equitable community development
- Equitable physical infrastructure
- Deep dive: resilience hubs
- Deep dive: housing
- Deep dive: transportation

Based on the presentations, examples, and research opportunities discussed in this workshop, the committee identified three applied research priorities with several underlying topics regarding equitable and resilient infrastructure investments:

1. Partnerships for equitable infrastructure development
 - Partnerships for knowledge transfer and promoting action research
 - Building trust with the community to enable productive and equitable community participation
2. Systemic change toward resilient and equitable infrastructure investment
 - Catalyzing and supporting systemic change in the institutions

- Developing effective community resilience hubs
 - Engaging in community resilience planning
 - Incorporating integrated multi-benefit solutions
 - Interdependence of the built and natural environments
 - Identifying the role of minimum code requirements
3. Innovations in economic and financial analysis
- Innovative financing for equitable infrastructure development
 - Modifying benefit-cost analysis

This report identifies activities in each of the applied research topics that are indicated. It also includes specific questions to consider when undertaking this research. The committee took a broad view of applied research and those involved in that research, ranging from researchers in academia to small community groups exploring and testing approaches for addressing climate impacts. The three primary applied research topics the committee identified frame three important components of resilient and equitable infrastructure investments. Tying the three together is the fact that equitable, inclusive, and trusted processes and leaders are essential for accepted and sustainable decisions, which are particularly important for challenges such as climate impacts that do not have short-term solutions.

The workshop presentations and discussions demonstrated an existing base in the academic literature, as well as experience in resilient and equitable infrastructure investment, and they presented important lessons from work developing resilience hubs and dealing with housing needs and transportation infrastructure and services. Academic and applied research is needed to collect and expand this knowledge to better inform equitable and resilient infrastructure investments and motivate further local action on resilience.

The committee hopes to inspire researchers and communities with this report. Research findings from these topics should bolster and extend attention and activities that strengthen capacities for community resilience through inclusive work at the local, regional, national, and global levels for robust and equitable action.

References

- ASCE (American Society of Civil Engineers). 2021. *Report card for America's infrastructure*. Reston, VA: American Society of Civil Engineers.
- Baja, K. 2019. *Resilience hubs: Shifting power to communities and increasing community capacity*. Baltimore, MD: Urban Sustainability Directors Network.
- Bakkensen, L. A., C. Fox-Lent, L. K. Read, and I. Linkov. 2017. Validating resilience and vulnerability indices in the context of natural disasters. *Risk Analysis* 37(5):982–1004. <https://doi.org/10.1111/risa.12677>.
- Belkhir, J. A., and C. Charlemaine. 2007. Race, gender and class: Lessons from Hurricane Katrina. *Race, Gender, and Class* 14(1/2):120–152.
- Berke, P. R., J. Kartez, and D. Wenger. 1993. Recovery after disaster: Achieving sustainable development, mitigation and equity. *Disasters* 17:93–109. <https://doi.org/10.1111/j.1467-7717.1993.tb01137.x>.
- Bird, E. L., J. O. Ige, P. Pilkington, A. Pinto, C. Petrokofsky, and J. Burgess-Allen. 2018. Built and natural environment planning principles for promoting health: An umbrella review. *BMC Public Health* 18(1):930.
- Boardman, A. D., A. Greenberg, A. Vining, and D. Weimer. 2018. *Cost-benefit analysis in theory and practice*. New York: Cambridge University Press.
- Browning, M. H. E. M., K. Lee, and K. L. Wolf. 2019. Tree cover shows an inverse relationship with depressive symptoms in elderly residents living in U.S. nursing homes. *Urban Forestry & Urban Greening* 41:23–32.
- Burton, C. G. 2010. Social vulnerability and hurricane impact modeling. *Natural Hazards Review* 11(2):58–68.
- Christopher, S., V. Watts, A. K. H. G. McCormick, and S. Young. 2008. Building and maintaining trust in a community-based participatory research partnership. *American Journal of Public Health* 98(8):1398–1406.
- Coleman, N., A. Esmalian, and A. Mostafavi. 2020. Equitable resilience in infrastructure systems: Empirical assessment of disparities in hardship experiences of vulnerable populations during service disruptions. *Natural Hazards Review* 21(4):04020034.
- Cutter, S. L. 2016. The landscape of disaster resilience indicators in the USA. *Natural Hazards* 80(2):741–758.
- Cutter, S. L., L. R. Barnes, M. Berry, C. G. Burton, E. Evans, E. Tate, and J. J. Webb. 2008. A place-based model for understanding community resilience to natural disasters. *Global Environmental Change: Human and Policy Dimensions* 18:598–606.
- Cutter, S. L., and C. Finch. 2008. Temporal and spatial changes in social vulnerability to natural hazards. *Proceedings of the National Academy of Sciences* 105(7):2301–2306.
- Cuyahoga County. 2019. *Cuyahoga County Climate Change Action Plan*. https://www.countyplanning.us/wp-content/uploads/2019/05/Final_CCCCAP-1.pdf.
- Domingue, S. J., and C. T. Emrich. 2019. Social vulnerability and procedural equity: Exploring the distribution of disaster aid across counties in the United States. *The American Review of Public Administration* 49(8):897–913. doi:10.1177/0275074019856122.
- Dorado, S. 2005. Institutional entrepreneurship, partaking, and convening. *Organization Studies* 26(3):385–414.

- Dormady, N., A. Rose, C. B. Morin, and A. Roa-Henriquez. 2022. The cost-effectiveness of economic resilience. *International Journal of Production Economics* 244:108371. doi.org/10.1016/j.ijpe.2021.108371.
- Emrich, C. T., S. A. Aksha, and Y. Zhou. 2022. Assessing distributive inequities in FEMA's disaster recovery assistance fund allocation. *International Journal of Disaster Risk Reduction* 74:102855. https://doi.org/10.1016/j.ijdrr.2022.102855.
- Emrich, C. T., E. Tate, S. E. Larson, and Y. Zhou. 2019. Measuring social equity in flood recovery funding. *Environmental Hazards* 19(3):228–250. https://doi.org/10.1080/17477891.2019.1675578.
- Enarson, E. 1998. Through women's eyes: A gendered research agenda for disaster social science. *Disasters* 22:157–173. https://doi.org/10.1111/1467-7717.00083.
- EPA (Environmental Protection Agency). 2021. *Climate Change and Social Vulnerability in the United States: A Focus on Six Impacts*. Washington, DC: U.S. Environmental Protection Agency.
- Fekete, A. 2009. Validation of a social vulnerability index in context to river-floods in Germany. *Natural Hazards and Earth System Sciences* 9(2):393–403. https://doi.org/10.5194/nhess-9-393-2009.
- FEMA (Federal Emergency Management Agency). 2011. *National disaster recovery framework: Strengthening disaster recovery for the nation*. Washington, DC: Federal Emergency Management Agency.
- FEMA. 2019. *National response framework*, fourth edition, Washington DC: Federal Emergency Management Agency.
- FEMA. 2022. 2022 Building Code Adoption Tracking Overview. Washington, DC: Federal Emergency Management Agency.
- Finch, C., C. T. Emrich, and S. L. Cutter. 2010. Disaster disparities and differential recovery in New Orleans. *Population and Environment* 31:179–202. https://doi.org/10.1007/s11111-009-0099-8.
- Gaspar, V., P. Mauro, C. Pattillo, and R. Espinoza. 2020. Public investment for the recovery. International Monetary Fund, *IMF Blog* (posted October 5, 2020). https://blogs.imf.org/2020/10/05/public-investment-for-the-recovery/.
- Gunderson, L. H., and C. S. Hollings. 2002. *Panarchy: Understanding transformations in human and natural systems*. Washington, DC: Island Press.
- Hartwick, J. M. 1977. Intergenerational equity and the investment of rents from exhaustible resources. *American Economic Review* 67(5):972–974.
- Hollings, C. S. 1986. The resilience of terrestrial ecosystems: Local surprise and global change. In *Sustainable development of the biosphere*, edited by W. C. Clark and R. E. Munn. Cambridge, UK: Cambridge University Press. Pp. 292–317.
- Hunter, M. R., B. W. Gillespie, and S. Y.-P. Chen. 2019. Urban nature experiences reduce stress in the context of daily life based on salivary biomarkers. *Frontiers in Psychology* 10.
- IPCC (Intergovernmental Panel on Climate Change). Forthcoming. 2022: Summary for policymakers, edited by H.-O. Pörtner, D. C. Roberts, E. S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, and A. Okem. In *Climate change 2022: Impacts, adaptation, and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K.

- Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama. Cambridge, UK: Cambridge University Press.
- Jerolleman, A. 2019. *Disaster recovery through the lens of justice*. New York: Springer International Publishing. <https://doi.org/10.1007/978-3-030-04795-5>.
- Kettl, D. F. 2006. Is the worst yet to come? *Annals of the American Academy of Political and Social Science* 604(1):273–287. doi:10.1177/0002716205285981.
- Khunwishit, S., and D. McEntire. 2012. Testing social vulnerability theory: A quantitative study of Hurricane Katrina’s perceived impact on residents living in FEMA designated disaster areas. *Journal of Homeland Security and Emergency Management* 9(1). <https://doi.org/10.1515/1547-7355.1950>.
- Kristie, L. E., A. Capon, P. Berry, C. Broderick, R. de Dear, G. Havenith, Y. Honda, R. S. Kovats, W. Ma, A. Malik, N. B. Morris, L. Nybo, S. I. Seneviratne, J. Vanos, and O. Jay. 2021. Hot weather and heat extremes: Health risks. *Heat and Health* 398(10301):698–708. [https://doi.org/10.1016/S0140-6736\(21\)01208-3](https://doi.org/10.1016/S0140-6736(21)01208-3).
- Lin, J., Q. Wang, and X. Li. 2021. Socioeconomic and spatial inequalities of street tree abundance, species diversity, and size structure in New York City. *Landscape and Urban Planning* 206:103992.
- Liu, D., and Y. Li. 2016. Social vulnerability of rural households to flood hazards in western mountainous regions of Henan province, China. *Natural Hazards and Earth System Sciences* 16(5):1123–1134. <https://doi.org/10.5194/nhess-16-1123-2016>.
- Locke, D. H., B. Hall, J. M. Grove, S. T. A. Pickett, L. A. Ogden, C. Aoki, C. G. Boone, and J. P. M. O’Neil-Dunne. 2021. Residential housing segregation and urban tree canopy in 37 US cities. *NPJ Urban Sustainability* 1(1):15.
- Loerzel, J., and M. Dillard. 2021. An analysis of an inventory of community resilience frameworks. *Journal of Research of the National Institute of Standards and Technology* 126(Article No. 126031).
- Magis, K. 2010. Community resilience: An indicator of social sustainability. *Society & Natural Resources* 23(5):401–416.
- Maguire, S., C. Hardy, and T. Lawrence. 2004. Institutional entrepreneurship in emerging fields: HIV/AIDS treatment advocacy in Canada. *Academy of Management Journal* 47(5):657–679. 10.2307/20159610.
- Markart, G., M. Teich, C. Scheidl, and B. Kohl. 2021. Flood protection by forests in alpine watersheds: Lessons learned from Austrian case studies. In *Protective forests as ecosystem-based solution for disaster risk reduction (ECO-DRR)*, edited by M. Teich, C. Accastello, F. Perzl, and K. Kleemayr. London: IntechOpen. doi:10.5772/intechopen.99507.
- Matin, N., J. Forrester, and J. Ensor. 2018. What is equitable resilience? *World Development* 109:197–205.
- McAllister, T. 2013. *Developing guidelines and standards for disaster resilience of the built environment: A research needs assessment*. NIST Technical Note 1795. Gaithersburg, MD: National Institute of Standards and Technology. <https://nvlpubs.nist.gov/nistpubs/TechnicalNotes/NIST.TN.1795.pdf>.
- McAllister, T. P., R. F. Walker, and A. Baker. 2022. *Assessment of resilience in codes, standards, regulations, and best practices for buildings and infrastructure systems*. NIST Technical Note 2209. Gaithersburg, MD: National Institute of Standards and Technology. https://www.nibs.org/files/pdfs/NIBS_MMC_MitigationSaves_2019.pdf.

- Miles, S. B. 2018. Participatory disaster recovery simulation modeling for community resilience planning. *International Journal of Disaster Risk Science* 9(4):519–529.
- MMC (Multi-Hazard Mitigation Council). 2005. *Natural hazard mitigation saves: An independent study to assess the future savings from mitigation activities*. Washington, DC: National Institute of Building Sciences.
- MMC. 2019. *Natural hazard mitigation saves 2: Interim report*. Washington, DC: National Institute of Building Sciences.
- MMC. 2020. *A roadmap to resilience incentivization*. Porter, K.A. and Yuan, J.Q., eds. Washington, DC: National Institute of Building Sciences.
- Muñoz, C. E., and E. Tate. 2016. Unequal recovery? Federal resource distribution after a midwest flood disaster. *International Journal of Environmental Research and Public Health* 13(5):507. doi:10.3390/ijerph13050507.
- Myers, C. A., T. Slack, and J. Singelmann. 2008. Social vulnerability and migration in the wake of disaster: The case of Hurricanes Katrina and Rita. *Population and Environment: A Journal of Interdisciplinary Studies* 29(6):271–291. <https://doi.org/10.1007/s11111-008-0072-y>.
- NASEM (National Academies of Sciences, Engineering, and Medicine). 2012. *Disaster resilience: A national imperative*. Washington, DC: The National Academies Press. <https://doi.org/10.17226/13457>.
- NASEM. 2021a. *Enhancing community resilience through social capital and connectedness: Stronger together!* Washington, DC: The National Academies Press. <https://doi.org/10.17226/26123>.
- NASEM. 2021b. *Motivating local climate adaptation and strengthening resilience: Making local data trusted, useful, and used*. Washington, DC: The National Academies Press. <https://doi.org/10.17226/26261>.
- NIBS (National Institute of Building Sciences). 2019. *Natural hazard mitigation saves: 2019 report*. Washington, DC: National Institute of Building Sciences.
- Nigg, J. M. 1995. *Disaster recovery as a social process*. Newark, DE: Disaster Research Center.
- NIST (National Institute of Standards and Technology). 2016. *Community resilience planning guide for buildings and infrastructure systems*, volumes 1 and 2. Gaithersburg, MD: National Institute of Standards and Technology.
- NIST. 2020. *Community resilience planning guide for buildings and infrastructure systems: A playbook*, NIST SP 1190GB-16, Gaithersburg, MD: National Institute of Standards and Technology. <https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1190GB-16.pdf>.
- NOAA (National Oceanic and Atmospheric Administration) National Centers for Environmental Information. 2022. *U.S. Billion-dollar weather and climate disasters*. <https://www.ncei.noaa.gov/access/monitoring/billions/>.
- NRC (National Research Council). Committee on National Earthquake Resilience—Research, Implementation, and Outreach 2011. *National earthquake resilience: research, implementation, and outreach*. Washington, DC: The National Academies Press.
- NSTC (National Science and Technology Council). 2005. *Tsunami Risk Reduction for the United States: A Framework for Action*. https://nws.weather.gov/nthmp/documents/A_Framework_for_Action-2005-12-22.pdf.
- Plowman, D. A., S. Solansky, T. E. Beck, L. Baker, M. Kulkarni, and D. V. Travis. 2007. The role of leadership in emergent self-organization. *Leadership Quarterly* 18(4):341-356.

- Preston, B. L., M. E. Miro, and A. Lauland. 2022. New thinking to translate infrastructure dollars into resilience. RAND Corporation, *The RAND Blog* (posted June 2, 2021). <https://www.rand.org/blog/2021/06/new-thinking-to-translate-infrastructure-dollars-into.html>.
- Putnam, R.D., L. Feldstein, and D.J. Cohen. 2004. *Better Together: Restoring the American Community*. New York: Simon and Schuster.
- Reid, M. 2013. Disasters and social inequalities. *Sociology Compass* 7(11):984–997.
- Reina, D. S., and M. L. Reina. 2007. Building sustainable trust. *OD Practitioner* 39(1):36.
- Robles, F., and J. Bidgood. 2017. Three months after Maria, roughly half of Puerto Ricans still without power. *The New York Times*, December 29, 2017.
- Rose, A. 2017. *Defining and measuring economic resilience from a societal, environmental and security perspective*. Singapore: Springer.
- Rose, A., K. Porter, N. Dash, J. Bouabid, C. Huyck, J. Whitehead, D. Shaw, R. Eguchi, C. Taylor, T. McLane, L. T. Tobin, P. T. Ganderton, D. Godschalk, A. S. Kiremidjian, K. Tierney, and C. T. West. 2007. Benefit-cost analysis of FEMA hazard mitigation grants. *Natural Hazards Review* 8(4):97–111.
- Rozenberg, J., and M. Fay. 2019. *Beyond the gap: How countries can afford the infrastructure they need while protecting the planet*. Washington, DC: World Bank Group.
- Rufat, S., E. Tate, C. T. Emrich, and F. Antolini. 2019. How valid are social vulnerability models? *Annals of the American Association of Geographers* 109:1131–1153. <https://doi.org/10.1080/24694452.2018.1535887>.
- SAMHSA (Substance Abuse and Mental Health Services Administration). 2017. *Greater impact: How disasters affect people of low socioeconomic status*. Rockville, MD: Substance Abuse and Mental Health Services Administration.
- Schmidtlein, M., J. Shafer, M. Berry, and S. Cutter. 2011. Modeled earthquake losses and social vulnerability in Charleston, South Carolina. *Applied Geography* 31(1):269–281. [10.1016/j.apgeog.2010.06.001](https://doi.org/10.1016/j.apgeog.2010.06.001).
- Schoch-Spana, M., E. Brunson, D. Hosangadi, R. Long, S. Ravi, M. Taylor, M. Trotochaud, T. G. Veenema, and on behalf of the CommuniVax Coalition. 2021a. *A waypoint on the path to health equity: COVID-19 vaccination at month 11*. Baltimore, MD: The Johns Hopkins Center for Health Security.
- Schoch-Spana, M., E. Brunson, D. Hosangadi, R. Long, S. Ravi, M. Taylor, M. Trotochaud, T. G. Veenema, and on behalf of the Working Group on Equity in COVID-19. 2021b. *Equity in vaccination: A plan to work with communities of color toward COVID-19 recovery and beyond*. Baltimore, MD: The Johns Hopkins Center for Health Security.
- Schwartz, G., M. Fouad, T. Hansen, and G. Verdier. 2020. *Well spent: How strong infrastructure governance can end waste in public investment*. Washington, DC: International Monetary Fund.
- Smith, G. 2012. *Planning for post-disaster recovery: A review of the United States Disaster Assistance Framework*. Washington, DC: Island Press.
- Smith, G. P., and D. Wenger, D. 2007. Sustainable disaster recovery: Operationalizing an existing agenda. In *Handbook of disaster research. Handbooks of sociology and social research*. New York: Springer. https://doi.org/10.1007/978-0-387-32353-4_14.
- Snowden, D.J., and M.E. Boone. 2007. A Leader's Framework for Decision Making. *Harvard Business Review* 85(11): 68-149.

- Surminski, S., and T. Tanner. 2016. *Realising the triple resilience dividend: A new business case for disaster risk management*. Heidelberg: Springer.
- Tate, E., and C. Emrich. 2021. Assessing social equity in disasters, *Eos* 102. <https://doi.org/10.1029/2021EO154548>.
- Tate, E., A. Strong, T. Kraus, and H. Xiong. 2016. Flood recovery and property acquisition in Cedar Rapids, Iowa. *Natural Hazards* 80(3):2055–2079.
- Tierney, K., and A. Oliver-Smith. 2012. Social dimensions of disaster recovery. *International Journal of Mass Emergencies and Disasters* 30(2):123–146.
- Troppe, M. 1994. *Participatory action research: Merging the community and scholarly agenda*. Denver, CO: Education Commission of the States.
- Uekusa, S. 2018. Rethinking resilience: Bourdieu’s contribution to disaster research. *Resilience* 6(3):181–195.
- UNDRR (United Nations Office for Disaster Risk Reduction). 2020. Hazard definition and classification review technical report. Geneva, Switzerland: United Nations Office for Disaster Risk Reduction. <https://www.undrr.org/publication/hazard-definition-and-classification-review>.
- USGCRP (U.S. Global Change Research Program). 2018. *Fourth national climate assessment: Volume II – impacts, risks, and adaptation in the United States*. <https://purl.fdlp.gov/GPO/gpo112011>.
- USGS (U.S. Geological Survey). 2022. How can climate change affect natural disasters? Frequently Asked Questions: Climate and Land Use Change. <https://www.usgs.gov/faqs/how-can-climate-change-affect-natural-disasters>.
- Walpole, E. H., J. Loerzel, and M. Dillard. 2021. *A review of community resilience frameworks and assessment tools: An annotated bibliography*. Gaithersburg, MD: National Institute of Standards and Technology.
- Wang, W. L., J. W. van de Lindt, B. Hartman, H. Cutler, J. L. Kruse, T. P. McAllister, and S. Hamideh. 2022. Determination of individual building performance targets to achieve community-level social and economic resilience metrics. *Journal of Structural Engineering* 148(5):04022045.
- Watkins, S. L., and E. Gerrish. 2018. The relationship between urban forests and race: A meta-analysis. *Journal of Environmental Management* 209:152–168.
- Watkins, S. L., S. K. Mincey, J. Vogt, and S. P. Sweeney. 2017. Is planting equitable? An examination of the spatial distribution of nonprofit urban tree-planting programs by canopy cover, income, race, and ethnicity. *Environment and Behavior* 49(4):452–482.
- Westley, F. R., O. Tjornbo, L. Schultz, P. Olsson, C. Folke, B. Crona, and Ö. Bodin. 2013. A theory of transformative agency in linked social-ecological systems. *Ecology and Society* 18(3).
- Xie, W., A. Rose, S. Li, J. He., N. Li, T. Ali, T., and W. Wei. 2018. Dynamic economic resilience and economic recovery from disasters: A quantitative assessment. *Risk Analysis* 38(6): 1306-18. doi.org/10.1111/risa.12948.
- Yoon, D. K. 2012. Assessment of social vulnerability to natural disasters: A comparative study. *Natural Hazards* 63(2):823–843.
- Zobel, C.W. 2014. Quantitatively representing nonlinear disaster recovery. *Decision Sciences* 45(6):1053-1082. Decision Sciences Institute. <https://doi.org/10.1111/dec.1210.3>.

Appendix A

Committee Member Biographical Sketches

Steve Moddemeyer (*Chair*)

Steve Moddemeyer is a principal of CollinsWoerman with more than 30 years' experience leading governments, land owners, and project teams toward increased sustainability and resilience. He creates tools, policies, and programs that empower communities to implement resilience principles into planning for land use and urban infrastructure. He works on climate change adaptation, sustainability strategies for large urban redevelopments, and advanced sustainability strategies for land owners, cities, counties, and utilities. He is a past member of the National Academies of Sciences, Engineering, and Medicine's Resilient America Roundtable (two terms). He serves as an advisor to the University of Washington Masters in Infrastructure Management and Planning, member of the International Union for the Conservation of Nature: Resilience Theme Group, and founding member of The Little Think Tank, a group of academic and policy experts that focus on resilient recovery actions for American communities. Trained as a landscape architect, Mr. Moddemeyer creates multi-benefit implementation strategies that bring together natural and human systems by applying socio-ecological principles to system design, urban design, policy design, and industrial symbiosis development.

Christopher Todd Emrich

Christopher Emrich is the Boardman Endowed Associate Professor of Environmental Science and Public Administration within University of Central Florida's School of Public Administration and director of research in UCF's newly formed National Center for Integrated Coastal Research (UCF Coastal). His research/practical service includes applying geospatial technologies to emergency management planning and practice, long-term disaster recovery analysis, and the intersection of social vulnerability and community resilience in the face of catastrophe. From 2004 to 2008, he provided geospatial support for response and long-term recovery to the states of Florida, Louisiana, and Mississippi and has since been actively involved in understanding how differential recoveries manifest across disaster-stricken areas. Dr. Emrich is actively working at pinpointing challenges to equity in disaster recovery and mitigation and where he has most recently assisted in building empirically based and result-oriented impacts assessments to inform recovery programs in several states and U.S. territories. He has remained at the vanguard of theory, data, metrics, methods, applications, and spatial analytical model development for understanding in the field of hazard vulnerability science and the often very inequitable and disproportionate pattern of disaster loss and recovery across communities.

Erick C. Jones Sr.

Erick C. Jones, Sr., is a George and Elizabeth Pickett Endowed Professor in Industrial, Manufacturing, and Systems Engineering at the University of Texas at Arlington. He is a noted engineer, researcher, and leader whose career has spanned industry, government, and academia.

He joined the U.S. State Department as a senior advisor (expert) in the Office of the Chief Economist through the National Academies of Sciences, Engineering, and Medicine, Jefferson Science Fellowship, focusing on resilient supply chains. His industry background spanned working as an engineer to an executive at Fortune 500 companies leading projects including ERP (enterprise resource planning) implementations, business process re-engineering, and corporate merger and acquisitions. His industry experiences facilitated his success in academia with supply chain engineering and led to 4 academic textbooks, more than 200 publications, 17 Ph.D.'s (7 from underrepresented groups), funding from national agencies including NASA, the Department of Transportation, and the National Science Foundation (NSF), and tenured professorships from two Tier 1 universities. His fundamental theories on automated inventory control, quality, and supply chain economics and logistics engineering have impacted the fields of artificial intelligence, manufacturing, and supply chain management.

Dr. Jones' leadership and administrative activities include leading government-funded public/private multi-university research centers, funding large-scale programs at the NSF as a director, initiating academic programs as a chair and dean, and fundraising as a board member on public and private foundation boards. He represents and is an advocate for diverse and equitable conditions for all. Dr. Jones is an alum of Texas A&M University and Distinguished Engineering Alumni of the University of Houston, a scholar of William J. Fulbright and Alfred P. Sloan programs, and a fellow of American Association for the Advancement of Science and the Institute of Industrial and Systems Engineering.

Elena Marie Krieger

Elena Krieger is the director of research at the energy science and policy research institute Physicians, Scientists, and Engineers for Healthy Energy (PSE). She joined PSE in 2013 to launch the organization's clean energy practice area, and now oversees its scientific research efforts. Her current work focuses on accelerating the transition to clean energy resources, and developing transition pathways that realize non-energy co-benefits. She serves as principal investigator on numerous research projects, and simultaneously works closely with community organizations, nonprofits, policy makers, and other stakeholders to use science to inform energy and climate policy. Her current research areas include designing solar+storage resilience hubs and deployment strategies, and integration of resilience, health, equity, and environmental metrics into state-level deep decarbonization efforts. She is a member of the Disadvantaged Communities Advisory Group to the California Energy Commission and the California Public Utilities Commission, a member of the National Academies' New Voices in Sciences, Engineering, and Medicine Program 2021 Cohort, and a science advisor to the American Resilience Project. She received her Ph.D. in mechanical and aerospace engineering from Princeton University, where her research focused on optimizing energy storage in renewable systems, and she holds an A.B. in physics and astronomy and astrophysics from Harvard University.

Therese P. McAllister

Therese McAllister is the community resilience group leader and program manager in the Engineering Laboratory (EL) at the National Institute of Standards and Technology (NIST). She

is also the NIST liaison for the NIST-funded Center of Excellence, Center for Risk-Based Community Resilience Planning that is led by Colorado State University. Dr. McAllister conducts research on community resilience, with a focus on the integrated performance of physical infrastructure and social and economic systems. She has expertise in structural reliability, risk assessment, failure analysis of buildings and infrastructure systems, and the performance of structures in fire. She co-led detailed structural analyses of the World Trade Center (WTC) towers and WTC 7 for the NIST WTC Investigation, conducted reliability studies of levee systems for the U.S. Army Corps of Engineers following Hurricane Katrina flooding in New Orleans, and evaluated Hurricane Sandy flood effects on infrastructure systems as part of the Federal Emergency Management Agency Mitigation Assessment Team. She recently was recognized with the 2021 American Society of Civil Engineers (ASCE) Walter P Moore, Jr. Award and 2018 ASCE Ernest E Howard Award for her research on structural codes and standards and on resilience. Dr. McAllister is an ASCE Structural Engineering Institute fellow and serves on the ASCE Structural Engineering Institute seven standard committee, Infrastructure Resilience Division, the Technical Council on Life-Cycle Performance, Safety, Reliability and Risk of Structural Systems, and the SEI Board Level Resilience Committee. She previously served on the International Code Council Structural Committee. She is an advisory panel member for the National Institute of Building Sciences, Department of Homeland Security, and Department of Housing and Urban Development resilience activities. She has a Ph.D. and an M.S. in civil/structural engineering from Johns Hopkins University, an M.S. in civil/ocean engineering from Oregon State University, and a B.S. in ocean engineering from Florida Atlantic University.

Adam Z. Rose

Adam Rose is a research professor in the University of Southern California (USC) Sol Price School of Public Policy, and senior research fellow in USC's Center for Risk and Economic Analysis of Threats and Emergencies (CREATE). He obtained his Ph.D. in economics from Cornell University. Professor Rose's primary research interest is the economics of disasters. He has spearheaded the development of CREATE's comprehensive economic consequence analysis framework and has done pioneering research on resilience at the level of the individual business/household, market/industry, and regional/national economy. He is currently the principal investigator on a National Science Foundation grant on advanced computational methods to improve reliability and resilience of interdependent systems and a contract with the Critical Infrastructure Resilience Institute to measure the cost-effectiveness of individual resilience tactics. Dr. Rose is the author of several books and more than 250 refereed professional papers. He has served as the American Economic Association representative to the American Association for the Advancement of Science and as a member of the Board of Directors of the National Institute of Building Sciences Multi-hazard Mitigation Council. He is the recipient of several honors and awards, including, among others, the Distinguished Research Award from the International Society for Integrated Risk Management, Woodrow Wilson Fellowship, East-West Center Fellowship, American Planning Association Outstanding Program Planning Honor Award, and Applied Technology Council Outstanding Achievement Award. He is also an elected fellow of the Regional Science Association International. Dr. Rose has served on the National Academy of Sciences panels on Earthquake Resilience and Seismic Warning.

Stacy Swann

Stacy Swann is the CEO and founding partner of Climate Finance Advisors, a benefit LLC based in Washington, D.C., with expertise in banking, development finance, and climate change. During her career, Ms. Swann has held senior positions with the International Finance Corporation, as well as with the U.S. Department of Treasury, Enron Corporation, and other organizations. For more than 25 years, she has worked with investors, financial institutions, and policy makers on mainstreaming climate considerations across both investment and policy and has particular expertise in blended finance, climate finance, climate-smart fiscal policies, and approaches to identify, assess, and manage climate risk.

In addition to leading Climate Finance Advisors, Ms. Swann is currently the chair of the Export-Import Bank of the United States Chair's Council on Climate Change, a subcommittee of its Advisory Board. She also sits on the Board for the Montgomery County Green Bank, the United States' first county-level green bank and is chair of its Investment Committee. She is a member of the Steering Committee/Board of the Global Water Partnership, a global action network of more than 3,000 partner bodies in 179 countries focused on building sustainable water systems globally. Ms. Swann holds an M.B.A. in finance and development economics from American University, a master's degree from Harvard University, and a bachelor's degree from City University of New York–Hunter College.

Appendix B

Workshop Agenda

Committee on Hazard Mitigation and Resilience Applied Research Topics
Workshop 1: Equitable and Resilient Infrastructure Investments
Thursday, March 17, 2022
11:00AM – 6:00PM Eastern Time

Objectives: Determine **unmet applied research needs** of equitable and resilient infrastructure investments informed by community social and economic factors. Panelists will be asked to address the topics, below, with consideration to:

- Strategies and investments to improve services, functions, access, and equity across infrastructures for resiliency to hazards and extreme events.
- Challenges and opportunities within these strategies and investments that may benefit from further investigation and research to facilitate better outcomes.

11:00AM – 11:15AM	Welcome
	Negin Sobhani, Resilient America Program, National Academies of Sciences, Engineering, and Medicine
	Steve Moddemeyer, Principal for Planning, Sustainability, and Resilience/CollinsWoerman Architects; Committee Chair
11:15AM – 12:30PM	Panel 1: Equitable Community Development
	Nnenia Campbell, Deputy Director, Bill Anderson Fund
	Manal J. Aboelata, Deputy Executive Director, Prevention Institute
	Marissa Ramirez, Director, Community Strategies, Equity, Environment, and Justice Center, Natural Resources Defense Council
	Joyce Coffee, President, Climate Resilience Consulting
	<i>Moderator:</i> Stacy Swann, CEO, Climate Finance Advisors
12:30PM – 1:00PM	Break: Solicit attendee input on shared values
1:00PM – 1:15PM	Results of attendee input

1:15PM – 2:15PM

Panel 2: Equitable Physical Infrastructure

Rae Zimmerman, Research Professor and Professor Emerita of Planning and Public Administration; Director, Institute for Civil Infrastructure Systems, Robert F. Wagner Graduate School of Public Service, New York University

Kelly Kibler, Associate Professor, University of Central Florida

Carol Friedland, LaHouse Director and Associate Professor, Louisiana State University AgCenter

Moderator: Chris Emrich, Boardman Endowed Associate Professor of Environmental Science and Public Administration, University of Central Florida

2:15PM – 2:45PM

Break

2:45PM – 3:45PM

Panel 3: Deep Dive-Resilience Hubs

Kristin Baja, Director of Direct Support & Innovation, Urban Sustainability Directors Network

Jana Ganion, Sustainability and Government Affairs Director, Blue Lake Rancheria

Shina Robinson, Policy Coordinator, Asian Pacific Environmental Network

Moderator: Elena Krieger, Director of Research, Physicians, Scientists, and Engineers for Healthy Energy

3:45PM – 4:35PM

Panel 4: Deep Dive-Housing

Emily Alvarado, Vice President, Pacific Northwest, Enterprise Community Partners

Anne Cope, Chief Engineer, Insurance Institute for Business & Home Safety

Sarah Saadian, Senior Vice President of Public Policy, National Low Income Housing Coalition

Moderator: Therese McAllister, Community Resilience Group Leader and Program Manager, National Institute of Standards and Technology

4:35PM – 4:55PM

Break

4:55PM – 5:45PM

Panel 5: Deep Dive-Transportation

Genevieve Giuliano, Professor, Margaret and John Ferraro Chair in Effective Local Government, Director, METRANS Transportation Center

Johana Clark, Senior Assistant Director, Stormwater Operations, Houston Public Works

Kingsley Haynes, Ruth D. Hazel and John T. Hazel, M.D. Faculty Chair in Public Policy; Eminent Scholar, University Professor Emeritus, Schar School of Policy and Government, George Mason University

Moderator: Adam Rose, Research Professor, Department of Public Policy
Senior Research Fellow, Center for Risk and Economic Analysis of Threats and Emergencies, University of Southern California

5:45PM – 6:00PM

Recap and Closing

Steve Moddemeyer, Principal for Planning, Sustainability, and Resilience/CollinsWoerman Architects; Committee Chair

Appendix C

Panelist Biographical Sketches

Panel 1: Equitable Community Development

Manal J. Aboelata

Manal J. Aboelata is deputy executive director at Prevention Institute, a national nonprofit dedicated to advancing effective strategies to achieve health equity, prevent illness and injury, and ensure safe and healthy communities. An epidemiologist by training, Dr. Aboelata advocates for health equity and racial justice. She writes and speaks on many issues, especially those pertaining to health equity and the built environment. She coauthored a chapter in the first and second editions of *Making Healthy Places* and wrote the foreword for *Schools that Heal: Design with Mental Health in Mind*. In the form of original articles, op-eds, and policy briefs, she has written extensively on timely, relevant public health justice issues. She has served on numerous health advisory boards, review panels, and expert councils. She is currently serving her third and final term as an appointee of Supervisory District 2 (South Los Angeles) to Los Angeles County's Community Prevention and Population Health Taskforce. Dr. Aboelata graduated from UCLA, with a master's degree in epidemiology (2001) and from the University of California, Berkeley, with a bachelor of arts (1998). She was inducted into the UCLA Hall of Fame (2009) and was a Stanton Fellow of the Durfee Foundation from 2018 to 2020.

Nnenia Campbell

Nnenia Campbell is deputy director at the Bill Anderson Fund and a research associate with the Natural Hazards Center at the University of Colorado Boulder. Dr. Campbell's work with the Bill Anderson Fund supports leadership, professional development, and research training among historically underrepresented minority doctoral students studying hazards and disasters. Her work with the Natural Hazards Center translates empirical research on the social aspects of disasters into tools and information products designed for practitioners and decision makers, with an emphasis on inclusive engagement. Dr. Campbell's research interests center on the intersections between disaster vulnerability and resilience within marginalized communities and on the role that community-based organizations play in disaster preparedness, response, and recovery. Her current research collaborations include projects related to disaster planning and response capacity among food banks and other community-based organizations, linkages between disaster scenarios and hazard mitigation efforts, risk communication in the context of concurrent and successive disasters, and the impacts of the COVID-19 pandemic on youth and older adults.

Joyce Coffee

Joyce Coffee is founder and president of Climate Resilience Consulting, a social enterprise that works with clients to create practical and equitable strategies that enhance markets and communities through adaptation to climate change. Ms. Coffee has 25 years of leadership experience in government, private, nonprofit, philanthropic, and academic sectors. She has

worked with more than 200 institutions to create and implement climate-related resilience initiatives. Specific areas of emphasis include resilience strategy, resilience finance, resilience measurement, and social equity. She is an appointed director or chair of 25 nonprofit boards and initiatives. She received a B.S. in biology, environmental studies, and Asian studies from Tufts University and a master's degree in city planning from the Massachusetts Institute of Technology.

Marissa Ramirez

Marissa Ramirez is the director of community strategies for the Equity, Environment, and Justice Center at the Natural Resources Defense Council (NRDC). She believes that meaningful change happens locally. Since coming to NRDC in 2010, Ms. Ramirez has worked with neighbors and local leaders primarily in underserved communities of color on revitalizing communities by providing best practices and tools for a more equitable and sustainable future. She is a coauthor of *4-Steps to a Climate Savvy Community*, which is designed for communities to find solutions to climate, health, and racial equity issues where they live. She is also author and coauthor, respectively, of *Green Neighborhoods: Advancing Strategies that Create Strong, Just, and Resilient Communities* and *The Sustainable Square Mile Handbook: Cultivate Your Green Village with Community-Based Principles and Practices*. She has led new research to uncover the links between climate change, displacement, and gentrification in U.S. cities. Ms. Ramirez has a master of environmental management from the Yale School of Forestry and Environmental Studies, where she focused on urban environmental economics. She also holds a bachelor of science degree in biology from Yale University. She continues to bring her passion for both human and environmental health to her professional work in communities.

Panel 2: Equitable Physical Infrastructure

Carol Friedland

Carol Friedland is LaHouse director and associate professor of biological agricultural engineering at Louisiana State University AgCenter. Her research focuses on resilient and sustainable housing, disaster loss estimation, post-disaster damage assessment, hazard mitigation planning and mitigation decision-making. Her areas of expertise include hazard-resistant construction and mitigation, performance of housing and other built infrastructure subjected to natural hazards, combined wind and flood interactions on structures, post-event data acquisition, remote sensing of building damage, hazard-resistant and sustainable construction, integration of Geographic Information Systems in hazards research, hazard mitigation planning and mitigation decision-making, and loss estimation. She is a member of the American Association of Wind Engineers, American Society of Civil Engineers, and Association of State Floodplain Managers. Dr. Friedland holds a bachelor's degree from the University of Wyoming and master's and doctorate degrees from Louisiana State University.

Kelly Kibler

Kelly Kibler is an associate professor of water resources engineering in the Department of Civil, Environmental and Construction Engineering at the University of Central Florida (UCF). She is faculty of UCF's National Center for Integrated Coastal Research and a faculty fellow of UCF's Center for Global Economic and Environmental Opportunity. Dr. Kibler obtained her Ph.D. in

water resources engineering from Oregon State University and worked with the United Nations Environmental, Scientific and Cultural Organization, or UNESCO, before joining UCF faculty. Her Ecohydraulics Laboratory targets coupled biological and physical variables in river and estuarine systems. Research topics include flow-biota interaction and its influence on hydrodynamics and sediment transport at multiple scales. Applications for Dr. Kibler's research include development pathways and infrastructure that minimize ecosystem disruption and promote the restoration or engineering of aquatic ecosystem services, including those related to climate adaptation. Her research has been supported by the National Science Foundation, U.S. Defense Advanced Research Projects Agency, U.S. Environmental Protection Agency, National Oceanic and Atmospheric Administration, Florida Department of Environmental Protection, and Florida Department of Transportation.

Rae Zimmerman

Rae Zimmerman is research professor and professor emerita of planning and public administration at New York University's Wagner Graduate School of Public Service, following a full-time tenured professorship for many years, and she currently directs NYU-Wagner's Institute for Civil Infrastructure Systems. She is a fellow of the American Association for the Advancement of Science, past president and fellow of the international Society for Risk Analysis (SRA), and recipient of SRA's 2019 Distinguished Achievement Award and 2015 Outstanding Service Award. She has authored or coedited a half dozen books, including *Transport, the Environment and Security*, and almost 200 other publications encompassing social and economic dimensions of infrastructure systems and their vulnerability to natural hazards, climate change, and accidents. She has had more than four dozen research grants funded by the National Science Foundation and other agencies through university centers, currently focusing on infrastructure interdependencies and sustainability, COVID-19-related food consumption patterns, risk communication, and behaviors that shape and are shaped by infrastructure services. Dr. Zimmerman holds a B.A. in chemistry from the University of California, Berkeley, an M.C.P. from the University of Pennsylvania, and a Ph.D. in planning from Columbia University.

Panel 3: Deep Dive – Resilience Hubs

Kristin Baja

Kristin Baja is Urban Sustainability Directors Network's (USDN) director of direct support and innovation. Ms. Baja is responsible for identifying, leading, and supporting innovative projects and trainings that actively transform local government processes and lead to proactive, respect-based change. She actively works to identify and compost archaic and discriminatory practices and to provide pathways for change rooted in courage, equity, and justice. She works across scales and actively helps facilitate deeper connectivity and collaboration between local government practitioners and their stakeholders while helping to shift to more transformational systems-level change. Prior to USDN, Ms. Baja served as the climate and resilience planner with the City of Baltimore where she led the city's climate and equity work. She holds an M.U.P. and an M.S. from the University of Michigan and is actively working on a master's in biomimicry from Arizona State University. She is an EPIC-N board member and serves on several local and international advisory committees. In 2016, Ms. Baja was recognized by the Obama administration as a Champion of Change for her work on climate and equity.

Jana Ganion

Jana Ganion is the sustainability and government affairs director for the Blue Lake Rancheria, a federally recognized Native American tribal government. She has established the tribe's strategy for zero-carbon resilience. Her development experience includes low-carbon community-scale and facility-scale microgrids, electric vehicle infrastructure, strategic planning in sustainability, climate action (pairing mitigation with adaptation), emergency preparedness, and economic enterprise development. She is an appointee to and current (2021) co-chair of the U.S. Department of Energy's Indian Country Energy and Infrastructure Working Group, the U.S. Bureau of Ocean Energy Management California Intergovernmental Task Force, California's Integrated Climate Adaptation and Resilience Program Technical Advisory Committee, the California SB 350 Disadvantaged Communities Advisory Group for the California Public Utilities Commission and California Energy Commission, among other roles. She works on policy, programs, and investments to achieve rapid, cost-effective transition to decarbonized and resilient communities for the resulting social, environmental, and economic co-benefits.

Shina Robinson

Shina Robinson, policy coordinator at the Asian Pacific Environmental Network (APEN), is a bridge builder between passing transformative climate, energy, and housing policies, and implementing state policy through local models of Just Transition and Energy Democracy, rooted in local design and decision-making of APEN's immigrant and refugee leaders. She leads policy and political education trainings, community engagement processes, joint advocacy, and coordination with local and state coalitions to advance these projects and collective vision. Her current focus is on implementation of policies, accessing investments, and engaging APEN communities as decision makers to build community-based climate resilience hubs in Oakland and Richmond. Ms. Robinson has served in many roles at APEN since 2012, but her deep commitment to environmental justice at the intersection of human rights, health, and equity started from a young age between visiting family in the Philippines and growing up in the shadow of a Los Angeles area oil refinery. She took on human rights and climate disaster relief campaigns while pursuing undergraduate degrees in international studies and political science at California State University, Long Beach.

Panel 4: Deep Dive – Housing

Emily Alvarado

Emily Alvarado is vice president and Pacific Northwest market leader for Enterprise Community Partners. In that role, she oversees Enterprise's work in Washington and Oregon to create and preserve affordable homes and brings programmatic solutions to scale through policy advocacy. Her work includes directing Enterprise's Washington Early Learning Loan Fund and the Puget Sound Taxpayer Accountability Account Early Learning Facilities Fund. Before joining Enterprise, Ms. Alvarado worked at Seattle's Office of Housing, which she joined in 2014 and was named director in 2019. During her tenure, she stewarded more than \$275 million in investments that supported affordable rental housing and homeownership opportunities for more than 3,600 families. She worked to implement community preference as a way to counter displacement, paved the way for new approaches to community-driven affordable housing connected to light rail and accelerated production of Permanent Supportive Housing. She also

forged partnerships with stakeholders across the city to advance housing production and preservation programs. She has extensive policy advocacy experience including leadership positions in nonprofits such as Pittsburgh UNITED, a coalition of community, labor, faith, and environmental organizations, and the Housing Consortium of Seattle-King County. She was named to the Puget Sound Business Journal’s “40 Under 40” list in 2020. Ms. Alvarado also serves as a board member for the Washington Low Income Housing Alliance and the Washington Housing Alliance Action Fund. She holds a bachelor’s degree from Scripps College and a juris doctor from the University of Washington School of Law.

Anne Cope

Anne Cope, chief engineer at the Insurance Institute for Business & Home Safety (IBHS) joined IBHS in 2009 just a few months before the groundbreaking for the construction of the IBHS Research Center in Richburg, South Carolina. As the chief engineer, she leads the development of research programs to improve the performance of structures in hurricanes, wildfires, severe thunderstorms, and hailstorms as well as the team of engineers, scientists, and skilled craftsman who conduct research on full-scale homes and commercial buildings. She is responsible for the team’s implementation of research findings into building codes and standards. Prior to joining IBHS, Dr. Cope was a project manager and structural engineer with Reynolds, Smith & Hills, Inc., designing projects for NASA, the U.S. Department of Defense, and commercial launch operations. Her research encompasses topics ranging from the full-scale simulation of wind effects on buildings to detailed studies of the vulnerabilities of buildings to natural hazards and the development of damage prediction models. She is also a proud veteran of the United States Army. She earned her bachelor’s and master’s degrees in civil engineering from Clemson University and her doctorate from the University of Florida. She is a registered professional engineer in Florida and South Carolina.

Sarah Saadian

As senior vice president of public policy at the National Low Income Housing Coalition, Sarah Saadian oversees NLIHC’s broad congressional portfolio and policy team. Ms. Saadian has over a decade of experience working on affordable housing and community development. She has been quoted in major media outlets, and she has testified before Congress. She graduated from the University of Connecticut School of Law in 2009 after receiving her bachelor’s degree from the University of Virginia in 2005. She has also been a member of the Virginia State Bar since 2009.

Panel 5: Deep Dive – Transportation

Genevieve Giuliano

Genevieve Giuliano is professor of urban planning, Margaret and John Ferraro Chair in Effective Local Government, and director of the METRANS Transportation Center at the University of Southern California. Dr. Giuliano’s research areas include relationships between land use and transportation, transportation policy analysis, travel behavior, and information technology applications in transportation. Current research includes examination of relationships between urban form, online shopping behavior, and local freight demand; market potential for zero-emission trucks; reducing local impacts of truck traffic; and applications for transportation

system analysis using archived real-time data. She has published more than 170 papers and given invited lectures around the world. Dr. Giuliano is a past chair of the Executive Committee of the Transportation Research Board, and of the Council of University Transportation Centers. She has received numerous distinguished scholarship and service awards including the Transportation Research Board (TRB) Distinguished Service Award (2006), the Thomas B. Deen Distinguished Lectureship Award (2007), the Transportation Research Forum Outstanding Researcher Award (2012), the Council of University Transportation Centers Distinguished Contribution award (2013), and the Walter Isard Award for Distinguished Scholarship in Regional Science (2017). She is a former member of the Intelligent Transportations Systems Joint Program Advisory Committee and the National Freight Advisory Committee. She has participated in many TRB policy studies; most recently on the Committee on the Future of the Interstate Highway System. At the state level, she is working with Caltrans and the California Air Resources Board on the implementation of the California Sustainable Freight Action Plan.

Johana Clark

Johana Clark has a 19-year professional career with the public sector. She is currently the senior assistant director with Houston Public Works managing the Stormwater Operations Branch with Transportation and Drainage Operations. She is responsible for overseeing the daily operation of the city's critical storm drainage system infrastructure with a team of more than 300 employees, including field and professional staff. She has previously managed the Traffic Operations Branch and supervised the signal timing and operations team with the city. Ms. Clark has a bachelor's degree in civil engineering from the National University of Colombia and a master of engineering from the University of Texas at Arlington. She is a licensed professional engineer, a professional traffic operations engineer, and an Envision sustainability professional. She is an active member of the Institute of Transportation Engineers and the American Society of Civil Engineers.

Kingsley Haynes

Kingsley Haynes, the Ruth D. Hazel and John T. Hazel, M.D. Faculty Chair in Public Policy, Eminent Scholar, University Professor Emeritus, and Schar School of Policy and Government at George Mason University, has been building academic programs for 50 years. After starting an Urban Institute at McGill University, he was a founding faculty member and played a central role in the development of the Lyndon B. Johnson School of Public Affairs at the University of Texas at Austin. He was a faculty chair and major contributor to the School of Public and Environmental Affairs at Indiana University and its third place national ranking. At George Mason University, Dr. Haynes served as graduate dean. He is active in the academic fields of regional science, geography and public administration. His research focuses on regional economic development, transportation, and infrastructure investment. He has authored more than 250 articles, 150 professional reports, and 10 books. He has been an active participant in economic development activities in Texas; the U.S. Midwest; and internationally in Malaysia, Brazil, Southeast Asia, and the Middle East. Dr. Haynes was awarded prizes for his Ford Foundation work on the Nile River. From 1995 to 1997, he was president of the 50-nation Regional Science Association International. He was executive secretary to the International Geographical Union's Commission on Applied Geography (2010–2012). At The Hague, he was honored to present the UNESCO Megacities Foundation Lecture on his book *Infrastructure: The Glue of Megacities* in 2007. Also in 2007, he was awarded the Grosvenor Gold Medal for his

work in geographic education. He was elected to the National Academy of Public Administration in 2002. Dr. Haynes has served as visiting professor at the School of Geography, Planning and Environment, University of Queensland (2010) and at the Institute for Sustainability Studies, University of Melbourne (2011). He has been a senior scholar and visiting professor at the Institute for Advanced Studies and the Institute for Public Policy, Hong Kong University of Science and Technology. From 2015 to 2019, he served as the inaugural president of Clarewood University in Reston, Virginia.

Appendix D

Discussion Questions for Panelists

Panel 1: Equitable Community Development

1. What are emerging strategies that can better serve community services and functions in light of existing social/economic equity disparities in infrastructure investment?
2. What are the challenges and opportunities with these equitable infrastructure strategies?
3. Where are the gaps? Where can new applied research facilitate better outcomes?

Panel 2: Equitable Physical Infrastructure

1. How can investments in essential lifeline infrastructure increase the capacity of diverse communities to recover their distinct services and functions from shocks and stresses?
2. What are the challenges and opportunities with these strategies?
3. Where are the gaps? Where can new applied research facilitate better outcomes?

Panel 3: Deep Dive – Resilience Hubs

1. What are resilience hubs? Are they buildings with specific capabilities or can they transform the entire public realm including streets and utilities?
2. What are the challenges and opportunities with implementing resilience hub strategies?
3. Where are the gaps? Where can new applied research facilitate better outcomes?

Panel 4: Deep Dive – Housing

1. What are some initial steps that federal and state agencies can take to better address equity?
2. Are there promising strategies that address equity, belonging, and resilience in housing retrofits and new construction including financing, affordability, and design?
3. What are the challenges and opportunities with these strategies?
4. Where are the gaps? Where can new applied research facilitate better outcomes?

Panel 5: Deep Dive – Transportation

1. How can investments in transportation renewal, connectivity, and technology support community services and functions despite disaster threats for communities facing disparities in access, safety, and resilience?
2. What are the challenges and opportunities with these strategies?
3. Where are the gaps? Where can new applied research facilitate better outcomes?

