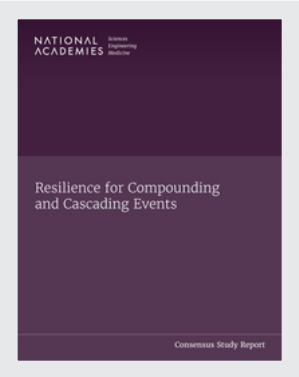

Resilience for Compounding and Cascading Events (2022)

DETAILS

68 pages | 8.5 x 11 | PDF

ISBN 978-0-309-69183-3 | DOI 10.17226/26659

CONTRIBUTORS

Steve Moddemeyer, Negin Sobhani, and Berna Oztekin-Gunaydin, Editors; Committee on Hazard Mitigation and Resilience Applied Research Topics; Policy and Global Affairs; National Academies of Sciences, Engineering, and Medicine

SUGGESTED CITATION

National Academies of Sciences, Engineering, and Medicine. 2022. *Resilience for Compounding and Cascading Events*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26659.

NATIONAL ACADEMIES Sciences Engineering Medicine

NATIONAL ACADEMIES PRESS
Washington, DC

Resilience for Compounding and Cascading Events

Steve Moddemeyer, Negin Sobhani, and Berna Oztekin-Gunaydin, *Editors*

Committee on Hazard Mitigation and Resilience Applied Research Topics

Policy and Global Affairs

Consensus Study Report

NATIONAL ACADEMIES PRESS 500 Fifth Street, NW, Washington, DC 20001

This activity was supported by contracts between the National Academy of Sciences and the Federal Emergency Management Agency (Contract No. 10005604). Any opinions, findings, conclusions, or recommendations expressed in this publication do not necessarily reflect the views of any organization or agency that provided support for the project.

International Standard Book Number-13: 978-0-309-69183-3
International Standard Book Number-10: 0-309-69183-4
Digital Object Identifier: https://doi.org/10.17226/26659

This publication is available from the National Academies Press, 500 Fifth Street, NW, Keck 360, Washington, DC 20001; (800) 624-6242 or (202) 334-3313; http://www.nap.edu.

Printed in the United States of America.

Suggested citation: National Academies of Sciences, Engineering, and Medicine. 2022. *Resilience for Compounding and Cascading Events*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26659.

The **National Academy of Sciences** was established in 1863 by an Act of Congress, signed by President Lincoln, as a private, nongovernmental institution to advise the nation on issues related to science and technology. Members are elected by their peers for outstanding contributions to research. Dr. Marcia McNutt is president.

The **National Academy of Engineering** was established in 1964 under the charter of the National Academy of Sciences to bring the practices of engineering to advising the nation. Members are elected by their peers for extraordinary contributions to engineering. Dr. John L. Anderson is president.

The **National Academy of Medicine** (formerly the Institute of Medicine) was established in 1970 under the charter of the National Academy of Sciences to advise the nation on medical and health issues. Members are elected by their peers for distinguished contributions to medicine and health. Dr. Victor J. Dzau is president.

The three Academies work together as the **National Academies of Sciences, Engineering, and Medicine** to provide independent, objective analysis and advice to the nation and conduct other activities to solve complex problems and inform public policy decisions. The National Academies also encourage education and research, recognize outstanding contributions to knowledge, and increase public understanding in matters of science, engineering, and medicine.

Learn more about the National Academies of Sciences, Engineering, and Medicine at **www.nationalacademies.org**.

Consensus Study Reports published by the National Academies of Sciences, Engineering, and Medicine document the evidence-based consensus on the study's statement of task by an authoring committee of experts. Reports typically include findings, conclusions, and recommendations based on information gathered by the committee and the committee's deliberations. Each report has been subjected to a rigorous and independent peer-review process and it represents the position of the National Academies on the statement of task.

Proceedings published by the National Academies of Sciences, Engineering, and Medicine chronicle the presentations and discussions at a workshop, symposium, or other event convened by the National Academies. The statements and opinions contained in proceedings are those of the participants and are not endorsed by other participants, the planning committee, or the National Academies.

Rapid Expert Consultations published by the National Academies of Sciences, Engineering, and Medicine are authored by subject-matter experts on narrowly focused topics that can be supported by a body of evidence. The discussions contained in rapid expert consultations are considered those of the authors and do not contain policy recommendations. Rapid expert consultations are reviewed by the institution before release.

For information about other products and activities of the National Academies, please visit www.nationalacademies.org/about/whatwedo.

COMMITTEE ON HAZARD MITIGATION AND RESILIENCE APPLIED RESEARCH TOPICS

STEVE MODDEMEYER (*Chair*), Principal for Planning, Sustainability, and Resilience, CollinsWoerman Architects
CHRISTOPHER EMRICH, Boardman Endowed Associate Professor of Environmental Science and Public Administration, School of Public Administration, University of Central Florida
ERICK C. JONES SR., Dean, College of Engineering, University of Nevada, Reno; and Jefferson Science Fellow, Office of the Chief Economist, U.S. Department of State
ELENA KRIEGER, Director of Research, Physicians, Scientists, and Engineers for Healthy Energy
THERESE MCALLISTER, Community Resilience Group Leader and Program Manager, National Institute of Standards and Technology
ADAM Z. ROSE, Research Professor, Department of Public Policy and Senior Research Fellow, Center for Risk and Economic Analysis of Threats and Emergencies, University of Southern California
STACY SWANN, Chief Executive Officer, Climate Finance Advisors, BLLC

Project Staff
NEGIN SOBHANI, Study Director
BERNA OZTEKIN-GUNAYDIN, Program Officer (*from April 2022*)
DANIELLE GOLDSMITH, Senior Program Assistant
OLIVIA TORBERT, Senior Program Assistant (*until March 2022*)
HOPE HARE, Administrative Assistant (*until March 2022*)

Consultant
JOE ALPER, Consulting Writer

Acknowledgments

The committee would like to acknowledge the Federal Emergency Management Agency for their generous support of this study. The committee also acknowledges the input it received from the Resilient America Roundtable and from those individuals who attended the April 11, 2022 planning meeting for the workshop that informed the committee's work. In addition, the committee acknowledges the valuable contributions made by the speakers at the May 31, 2022 workshop.

Acknowledgements of Reviewers

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.

We thank the following individuals for their review of this report: **Anita Chandra**, RAND Corporation; **Lisa Churchill**, Climate Advisory, LLC; **Felicia Jefferson**, Fort Valley State University; **Alessandra Jerolleman**, Jacksonville State University; **Steward Pickett**, Cary Institute of Ecosystem Studies.

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 **Gerald Galloway**, University of Maryland. 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.

Contents

Summary

Key Findings

- Applied research is needed to determine whether there are distinctive signatures to recurring acute disasters and their impacts on human ecosystems.
- Long-term observations of disaster hot spots are needed to develop lessons learned based on empirical evidence and to determine how impoverished and rural communities either recover or do not from successive events.
- New models are needed regarding the impact of compounding and cascading events on infrastructure.
- Applied research is needed to characterize readiness for multiple hazards that can strike at any time.
- Applied research is needed to assess the extent to which government policy promotes or inhibits private-sector initiatives for improving resilience.
- Applied research is needed to inform more effective collaboration among the entities that respond to disasters and to consider issues related to both local capacity and social equity.

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 in the fields of natural hazard mitigation and resilience. 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 second theme; a prior report considered the first.[1]

The committee organized a 1-day public workshop to inform this report, where four foundational themes for future research were identified: (1) compounding and cascading disasters are the new normal; (2) legacy conditions need to be assessed, evaluated, and addressed; (3) researchers need to practice codesign with communities, starting with pain points and impacts and working backward to solutions; and (4) relentless resilience, or the ability to function throughout a series of disruptive events, is critical for a future marked by compounding and cascading events.

From the workshop discussions, the committee chose three approaches to addressing applied research priorities that are particularly germane to natural hazard mitigation and

[1] The prior report can be accessed at https://nap.nationalacademies.org/catalog/26633/equitable-and-resilient-infrastructure-investments.

resilience: (1) defining the problem—diagnosing drivers, systems, and relationships that impact understanding of compounding and cascading disasters; (2) mitigating impacts—developing solutions and avoiding unintended consequences; and (3) effectively implementing solutions and strategies, and governance for those solutions and strategies. The committee selected these approaches based on information gained at the workshop, input from the Resilient America Roundtable, and committee members' backgrounds and experience with hazard mitigation and resilience.

On defining the problem (first approach), more investigation is needed to determine if there are distinctive signatures to recurring acute disasters and their impacts on human ecosystems. In addition, the committee identified a need for long-term observations of disaster hot spots to develop lessons learned based on empirical evidence and to determine, in particular, how impoverished and rural communities recover or do not from successive events.

On mitigating impacts (second approach), the committee identified a number of applied research questions pertaining to developing solutions and avoiding unintended consequences associated with mitigation and adaptation for the built environment, systems, and populations. Additionally, the committee described questions regarding benefit-cost analysis, incentives, and social equity considerations. Among them were such questions as how to better model the impact of compounding and cascading events on infrastructure, characterizing readiness for multiple hazards that can strike at any time, and assessing the extent to which government policy promotes or inhibits private-sector initiatives to improve resilience.

On effective implementation and governance (third approach), workshop discussions pointed to the need for applied research that would improve institutional operations, enable communities to better leverage federal disaster preparedness and relief funds, expand governance perspectives and strategies, and identify governance knowledge and tools needed for implementing solutions and strategies. Taken together, these research questions aim to inform more effective collaboration among entities that respond to disasters and to consider issues related to both local capacity and social equity—such as lack of trust, the need for two-way knowledge transfer, and modifying benefit-cost analysis to account for perpetuation of inequitable investments in historically affected and underserved populations.

1

Resilience for Compounding and Cascading Events

INTRODUCTION

Not long ago, disasters would strike one at a time. The disaster would occur, and the disaster relief assembly line would kick into high gear: first responders would help stabilize the local situation, and local community members, people from surrounding areas, and even volunteers from around the nation—second responders—would pitch in to start the recovery process. The disaster would be named and declared, and Congress would pass funding for the next several years. Eventually, the affected communities would reassemble their broken pieces, and America would move on.

Today, there is a new normal—most disasters do not occur as isolated events and instead seem to pile on one another, disaster after disaster, often unleashing new devastation on a community before it has had a chance to recover from the prior disaster. Furthermore, acute events can be compounded by chronic deteriorating conditions, such as an acute, intense rain event causing mudslides and flash flooding in an area that had been experiencing extreme drought. Compound disasters—two or more extreme events occurring simultaneously—are typically the outcome of multiple causes and can generate multiplicative damage and losses. Because of climate change, compound disasters are increasingly likely. According to the Intergovernmental Panel on Climate Change's 2021 report, examples include "concurrent heatwaves and droughts, compound flooding (e.g., a storm surge in combination with extreme rainfall and/or river flow), compound fire weather conditions (i.e., a combination of hot, dry and windy conditions), or concurrent extremes at different locations" (IPCC, 2021, p. 9). Additionally, long-term pandemics, such as COVID-19, further compound the situation.

A cascading hazard refers to a primary event (trigger), such as heavy rainfall, seismic activity, or rapid snowmelt, followed by a chain of consequences that may range from modest (lesser than the original event) to substantial. Also, the type of cascading damage and losses may be more severe than if they had occurred separately. A classic example is the major earthquake that struck Japan in 2011, which triggered a tsunami that led to failure of the Fukushima nuclear reactor. More recently, the war in Ukraine during the COVID-19 pandemic highlighted the importance of supply chain problems, which are cascading by their very nature as they represent the ripple effects of an initial bottleneck across sectors and regions over time.

Currently, research on disasters has focused largely on those triggered by natural hazards interacting with vulnerable human systems (e.g., populations and organizations) and the built environment. This report has taken a broader view of possible disaster scenarios. Recent events have highlighted how compounding and cascading natural hazards, whether acute or chronic in nature, can be further amplified by other events, such as public health outbreaks, supply chain

disruptions, and cyberattacks. For example, an increasing number of possible disaster scenarios involve "bad actors" who leverage an emergent or existing disaster context to cause additional harm through a cyberattack on a hospital, banking system, port, or other critical facility.

Regardless of the cause of a disaster, the nation's disaster mitigation, response, and recovery system in its present form can no longer keep pace. "Cascading disasters are the new normal," said Susan Cutter, the Carolina distinguished professor and director of the Hazards Vulnerability & Resilience Institute at the University of South Carolina, in her keynote address at the workshop designed to inform this report.[1] The nation has two options for addressing what is becoming an untenable situation: The first is to make the disaster system as it currently exists work faster and harder. The second is to take a step back and rethink and redesign the system so that it has the capability and capacity to work on multiple disasters that are interconnected in multiple physical and social ways, at multiple locations, and on multiple scales, all at the same time (Moddemeyer, 2022).

While pondering which of these two options to pursue, the nation should consider the real possibility that the way communities have designed and built their infrastructure, including building codes and land use regulations, contributes or even amplifies the effects of cascading disasters on those communities. In that regard, the nation needs greater understanding of the dense entanglement between natural disasters, vulnerability, land ownership, and property rights with the legacies of racism, redlining, and disinvestment that can cause social disasters (NASEM, 2022; van Straalen et al., 2018). Recovery requires more than getting back to normal, especially when what is considered normal may be a major contributor to a community's vulnerability to cascading disasters. How can communities recover from disasters when the normal they have lost was a major contributor to the disaster itself (Haggerty, 2020)? How can recovery efforts acknowledge a changing climate, shifting economic and cultural expectations for social equity, and the imperative for climate-smart economic development?

Answering these questions requires rethinking what is appropriate today and going forward in terms of disaster preparedness, emergency response, and recovery actions (Román, 2022). Fostering resilience and the governance of recovery appears to require integrated capabilities and skills that the nation has yet to deploy (Román, 2022). Specifically, the nation has yet to stand up the networks, measures, and tools that can help communities navigate their biophysical, political, and cultural crosscurrents so that they can recover and reduce their vulnerability to avoid cascading disaster upon disaster.

While humans have the capacity to adapt, that capacity is not unlimited in the face of compounding and cascading events. Human adaptive capacity contributes to resilience, and while there is a proliferation of methods to assess human adaptive capacity, there has been no definitive assessment of the best approach(es). Better understanding of human adaptive capacity can help improve the design of equitable policies and ensure that policies can be targeted to support those with less capacity to prepare for and respond to hazard events. Codevelopment of

[1] The workshop agenda, video, and slides are available at https://www.nationalacademies.org/event/05-31-2022/hazard-mitigation-and-resilience-applied-research-topics-workshop-2-compounding-and-cascading-events.

solutions focused on governance, land use planning, and decisions about relocating infrastructure has been shown to be effective for addressing the growing number of compounding and cascading events and for building community resilience (Schoch-Spana et al., 2019a,b).

GOALS OF THE COMMITTEE

As part of its efforts to reduce the immense human and financial toll of extreme events, in 2020, the Federal Emergency Management Agency (FEMA) asked the Resilient America Program of the National Academies of Sciences, Engineering, and Medicine to convene the Committee on Hazard Mitigation and Resilience Applied Research Topics (see Box 1-1 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 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, a second committee selected two additional themes—Equitable and Resilient Infrastructure Investments, and Compounding and Cascading Events—and held public workshops to explore each of these themes. This report examines the second theme, focusing on strategies that would enable the nation to be better prepared for and respond to compounding and cascading disasters so that affected communities can not only rebuild, but do so in a manner that increases their resilience to future disasters. As was true for the previous three reports produced by this project, 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 second theme—compounding and cascading events—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 focused on (1) drivers, systems, and relationships that impact understanding of compounding and cascading disasters; (2) solutions and avoiding unintended consequences; and (3) effective implementation of and governance for solutions and strategies.

This report's primary audience is the applied research community in the fields of hazards, vulnerability, risk reduction, and resilience. This community includes hazard-specific and general resilience research centers, as well as cooperative institutions engaged with states 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 that seek to reduce the impacts, losses, and suffering from disasters as a result of natural or technological hazards, public health emergencies, and other significant threats to communities and the nation. The committee's activities intend to inform applied research programs that will strengthen capacities for hazard mitigation and resilience.

BOX 1-1

The Program on Risk, Resilience, and Extreme Events (Resilient America)

Since its creation following the release of the 2012 report *Disaster Resilience: A National Imperative* (NRC, 2012), 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.[a] To achieve this aim, Resilient America engages with the academic, public, and private sectors at national and local levels for the following purposes:

- 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] See https://www.nationalacademies.org/resilient-america/about.

PUBLIC WORKSHOP

On May 31, 2022, the committee held a workshop on the theme of compounding and cascading events. The agenda for the workshop, developed in part based on input the committee received during an open session of the Resilient America Roundtable on April 11, 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. While the voices included in the workshop were not exhaustive, and additional voices and inputs would continue to educate and bring attention to equity issues, the workshop panelists were diverse in their perspectives and orientations, and they reinforced the need for continued research on equity in resilience. The workshop highlighted the urgency of the current moment that requires rethinking disaster preparedness, emergency response, and recovery actions. As Miguel Román noted in his keynote address, "The choice before us is clear: We can either accept the status quo and allow this unique moment to bring equity, transparency, and accountability to pass, or we can promote transformative ideas around disaster science and fund them and implement them in a responsible manner so that we can serve and protect all Americans. This is the choice before us, and the stakes have never been higher" (Román, 2022).

The workshop presentations and discussions following the keynote address focused on answering the following questions:

- How can the nation build the ability of its communities, states, tribes, and territories to recover and thrive given increased likelihood, severity, and complexity of disasters in the midst of all the types of more general change coming in their direction?

- How can the resilience, mitigation, and disaster recovery communities step back and reframe the governance for recovery and resilience efforts, to take off the regulatory blinders and look clearly at the complex interplay of "acts of humans" that expose, situate, and perpetuate losses from compound and cascading disasters?
- What is an emergent applied research agenda that can help the nation and the disaster recovery community step up, respect, and re-envision the challenge the nation is facing regarding compound and cascading disasters?

The committee acknowledges that challenges this broad and complex defy easy answers. Nonetheless, the thought leaders tasked with addressing these challenges at the workshop provided the committee with four themes to guide its work, as noted in the statement of task, on identifying and summarizing key research topics for applied research. Several terms used in this report are defined in Box 1-2.

BOX 1-2

Definitions of Terms Used in This Report

Cascading disaster: A primary event (trigger), such as heavy rainfall, seismic activity, or rapid snowmelt, followed by a chain of other events that may range from modest (lesser than the original event) to significant intensity or magnitude; the combined impacts over time (damage, losses, disruption) are more severe than if they had occurred separately (Jones et al., 2014; Kunreuther et al., 2014; Lawrence et al., 2020).

Codesign: A participatory approach to designing solutions, in which community members are treated as equal collaborators in the design process. Codesign goes beyond consultation by building and deepening equal collaboration between citizens affected by, or attempting to resolve, a particular challenge. A key tenet of codesign is that users, as "experts" of their own experience, become central to the design process.

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, 2021).

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, 2020).

Compounding disaster: A combination of events that occur at the same time and lead to impacts that exceed the sum of the individual contributing events (Jones et al., 2014; Kunreuther et al., 2014).

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 (Subcommittee on Disaster Reduction, 2005).

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).[a]

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 its future performance (NRC, 2012).

Infrastructure: Physical networks (systems and facilities) that provide functions and services to the community, including 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 (NRC, 2012). In addition to this definition, which addresses the capacity of systems to recover from events, the term *resilience* may be used to focus on post event activities of response and recovery.

Social equity: Social equity accounts for systemic inequalities to ensure everyone in a community has access to the same opportunities and outcomes, and it includes concepts of impartiality, fairness, and justice for all people in social policy, including financial, economic, distributional, procedural, structural, intergenerational, and recognition aspects.[b]

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.[c]

[a] This definition is adopted by the United Nations General Assembly.
[b] See https://unitedwaynca.org/blog/what-is-social-equity.
[c] See https://www.sustain.ucla.edu/what-is-sustainability.

Theme 1—Compounding and Cascading Disasters Are the New Normal

As noted above, recurrent acute disasters are happening with more frequency, intensity, periodicity, and harm (Román, 2022). The COVID-19 pandemic, as an obvious example, compounds with other disasters and complicates recovery efforts. Climate change, an ongoing disaster, increases the likelihood and intensity of extreme weather events and natural hazards including wildfire, extreme heat, drought, and their natural follow-on events, including flooding,

landslides, and ecosystem collapse (Masson-Delmotte et al., 2022; Olsson et al., 2014; Siders, 2022). Heavy rainfall, for example, can lead to lush plant growth, which, if followed by a drought that dries out the ground cover, makes the area more prone to fires, which can then destroy the ground cover that holds the soil together. If another heavy rain falls, the denuded landscape will be vulnerable to mud- and rockslides. Climate change has also added significant uncertainty to future events and has reduced confidence levels in predictions of their frequency and magnitude (Kunreuther et al., 2014). These kinds of cascading events were seen in California when the record-breaking Thomas Fire burned through Santa Barbara County in December 2017, leaving behind barren hillsides that collapsed into mudslides during the subsequent January rainstorms, killing more than 20 people and destroying more than 100 homes.[2]

These cascading disasters affect response and recovery, yet the protocols, governance, regulatory underpinnings, and funding do not yet account for this new normal. For example, hurricane evacuations during the COVID-19 pandemic increase exposure of vulnerable people to infection, and seniors vulnerable to extreme heat must choose between sheltering at home without air conditioning or cooling at a shelter with increased exposure to infection (Zaitchik, 2022).

The United States as a nation has immense capabilities for responding to multiple disasters. However, while the national financial capacity to address losses is high, even a singular event can exceed the local capacity of vulnerable communities to absorb the associated losses (Cutter, 2022). Exacerbating the situation, the current condition of much of the U.S. infrastructure is inadequate to resist increasingly extreme natural hazards, as a result of siloed decision making, inadequate design parameters, poor construction quality, lack of maintenance, or aging effects, leading to avoidable disasters. In most cases, disasters are created by decisions that make a system brittle (ShelterBox, n.d.).

Legacy conditions, extreme hazards, and opaque response and recovery bureaucracy can overwhelm local communities already suffering from an extreme event. Moreover, communities may also have unrecognized cumulative risk when considered across the life expectancy of their infrastructure assets. For example, when engaging in water and climate risk management and planning, many risk managers continue to model risk assuming that they can calculate the statistical likelihood of extreme events by looking at past climate records (Churchill, 2022). This assumption, however, no longer holds as greenhouse gas emissions increase thermal energy and resulting water vapor in the atmosphere makes measurable probabilities of extreme events inadequate for long-range infrastructure design (Milly et al., 2008).

During recovery, cumulative risk compounds when a community replaces the brittle systems that failed in the previous disaster with a similarly brittle system, condemning survivors to continued risks in a time of changing climate. The nation's approach to climate resilience will remain fundamentally flawed if it continues to focus on short-term horizons and singular major events. In fact, treating each event as discrete and short-lived, and without considering

[2] See https://news.caloes.ca.gov/remembering-the-montecito-mudslides-two-years-later.

compounding or cascading impacts, undermines efforts to value and increase resilience (Churchill, 2022).

Theme 2—Legacy Conditions Need to Be Assessed, Evaluated, and Addressed

Legacy conditions are caused by a combination of ongoing stressors (hunger, poverty, etc.), socioeconomic conditions, and impacts from prior and ongoing events. When one disaster follows another in the same locale, the impacts from the first event can be amplified by legacy conditions and continue to affect the outcome of the subsequent disaster. Driven in part by a combination of climate change, population growth in at-risk locations such coastal communities, historic inequities and underinvestment in certain communities, and inadequate disaster preparedness, these compounding and cascading disasters pose an increasing threat to environmental quality, economic activity, public safety, national security, and health. A better understanding of how compounding and cascading disasters interact with and affect critical resources and social systems (see Figure 1-1) has the potential, then, to advance disaster science, improve disaster response, build resilience to future disasters, and save lives (Machlis et al., 2022; Román, 2022).

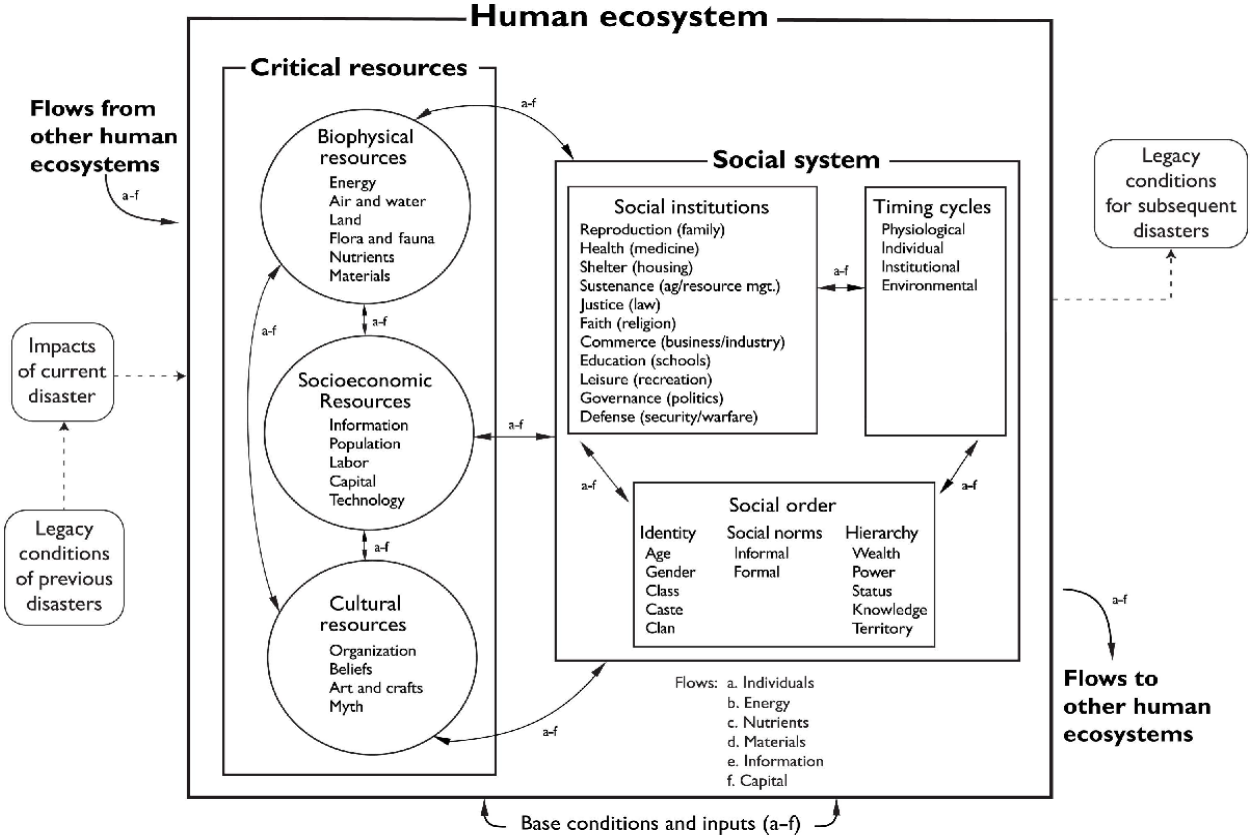

FIGURE 1-1 Compounding and cascading disasters will interact with and affect critical resources and social systems.
SOURCE: Román, 2022.

In fact, many workshop speakers were clear in stating that the current understanding of social, investment, and legacy conditions in communities is poor, and what is known cannot be characterized adequately. One approach to addressing this knowledge deficit would be to establish a long-term resiliency and vulnerability observatory network to gather and share relevant, near-real-time information about response, recovery, and mitigation. This disaggregated network, with standards for data collection, analysis, and archiving, would support applied research, information, and actionable insight for recovery (Cutter, 2022). The data this network generates could enable researchers to develop and validate informative indicators in addition to models for understanding the disparities in impact and recovery for communities affected by compounding and cascading disasters (Averyt, 2022).

An additional challenge is to develop a better understanding of how damage to all infrastructure networks and their interdependencies extend the impact of disaster and incurred losses (Figure 1-2). Addressing this challenge will require a better understanding of the interdependencies between systems and jurisdictions, digital assessment platforms and operations, and natural systems and urban water supply, along with the codependency of each of these with natural ecosystems (DeFlorio, 2022; Elhami-Khorasani, 2022).

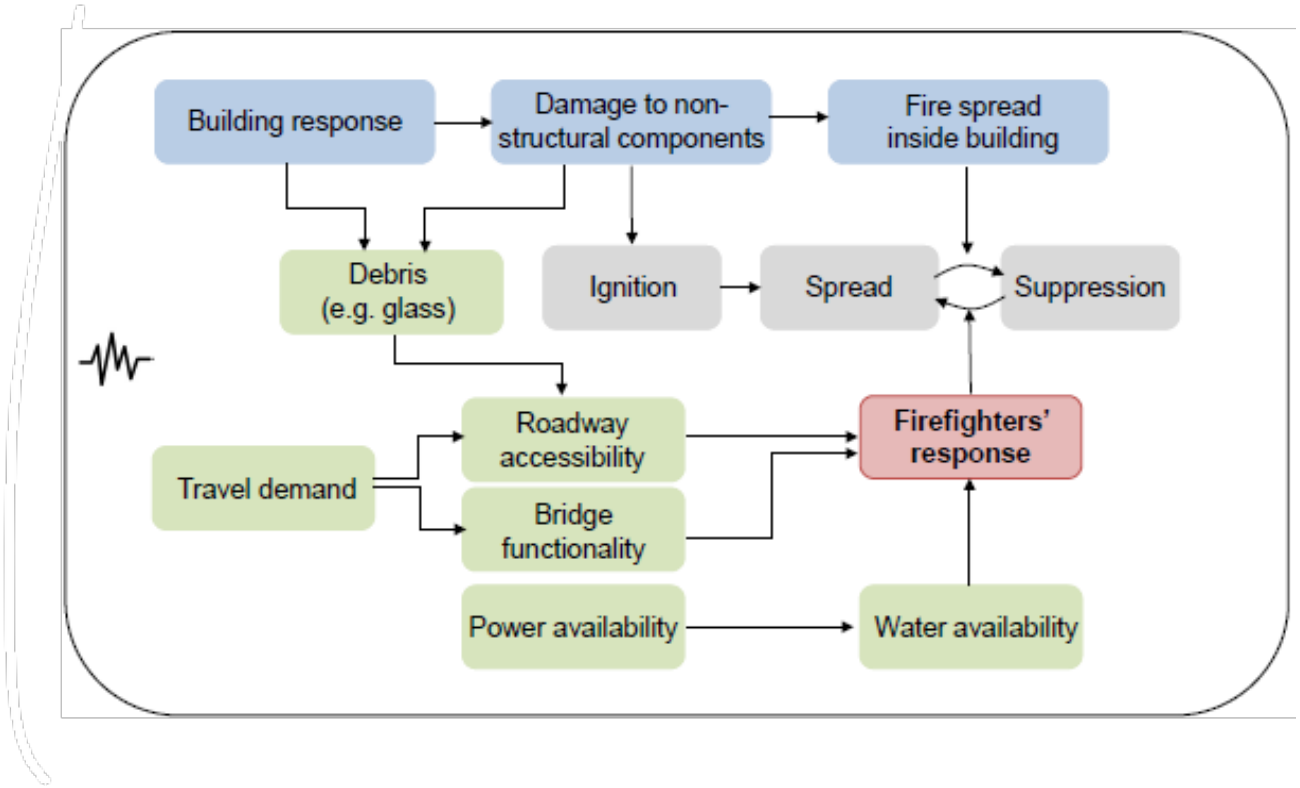

FIGURE 1-2 An illustration of how interdependencies affect the infrastructure network and response to a fire following an earthquake.
SOURCE: Elhami-Khorasani, 2022.

Theme 3—Codesign with Communities: Examine Pain Points and Opportunities, Reverse the Design Process, and Start from the Impacts

There are many pain points in the nation's response to disasters in general and to compounding and cascading disasters specifically. These include a disaster management system designed for singular events, a regulatory and governance model that has yet to adapt to compounding and cascading events, and a lack of meaningful and actionable data for recovery. As is increasingly recognized, failing to address these pain points or to leverage existing community strengths and opportunities can increase a community's vulnerability and fragility. Without seeking out and receiving the views and standpoints of underrepresented minority communities, inequitable outcomes may increase. One approach is to create a modeling system based on current community conditions and capabilities that not only works backward from that point to the disaster, but also engages those potentially affected individuals, including local decision makers, and communities in codesigning pragmatic strategies that eliminate or reduce pain points and leverage a community's strengths and opportunities (Zaitchik, 2022). Although they are normally left out of such conversations, including these voices affected by planning activities is important because they can provide a different perspective and greater local ownership in acceptable trade-offs that might be associated with a solution (Siders, 2022). Many of these historically excluded voices also belong to those who provide the services on which much of the economy is built, such as operating public transit or restocking groceries, and their inclusion can contribute to better outcomes across the economy.

Codesign, or meaningful and collaborative end-user engagement in the design of research, should occur across all stages of the research process. Community member engagement can range in intensity from relatively passive involvement to being highly interactive. For example, a project for extreme weather preparedness codeveloped materials with unhoused community members so that the information accounts for people's life circumstances (Every and Richardson, 2017). The codesign approach resonates with a prior report from this committee on equitable and resilient infrastructure investments (NASEM, 2022), which describes codevelopment as taking into account voices from underserved and underrepresented minority communities that have been ignored previously and works directly with people impacted by disasters and redevelopment. That report documented that consultation and inclusion at the community level can help build trust in the engagement relationships that are essential for place-based disaster recovery.

When codesigning a solution, it is important to consider that most mitigation and recovery funding programs are too complex, and that most states, counties, and municipalities lack the capacity to implement them. These barriers are particularly high in rural areas where the tax base and local government staffing may be limited, as illustrated in Headwater Economics' Rural Capacity Index.[3] As a result, communities may miss the opportunity to make the most of

[3] See https://headwaterseconomics.org/equity/rural-capacity-map.

the significant funding available to repair and improve damaged infrastructure because of a lack of capacity at the federal level to provide technical assistance and at the state and local levels to implement programs (Sprayberry, 2022). Another challenge arises as a result of multiple state and federal agencies having different rules and procedures and varied comfort levels in working across agencies. Addressing that challenge requires creating protocols for combining information about hazards with relevant vulnerability information (Zaitchik, 2022).

The workshop discussions generated four proposals for action (Cutter, 2022):

- Create a long-term resiliency and vulnerability observatory network.
- Fix the current governance bifurcation of recovery by providing a formal legislative or legal structure for disaster recovery and resilience on par with the Stafford Act,[4] which constitutes the statutory authority for most federal disaster response activities, especially as they pertain to FEMA and FEMA programs.
- Reform the National Flood Insurance Program to reflect future climate risks and disproportionate risks to underserved communities.
- Create and fund a FEMA Office of Applied Research to conduct action-oriented research on social and behavioral science as a means of providing the evidentiary basis for disaster mitigation and resilience policy and practice.

Theme 4—The Importance of Relentless Resilience

When a series of earthquakes struck Puerto Rico over 2 days in early January 2020, the resulting devastation compounded difficulties the island was already experiencing: a 9-month drought had ended only 2 months earlier, and hurricanes Irma and Maria had struck 2 weeks apart in September 2017. One individual, Dr. Enid Santos Cintron of Guayanilla, refused to leave her community, even though her home was destroyed, and worked to supply medical care continuously through the resulting crisis. Hailed as a heroine of Puerto Rico, her steadfastness and support for her community demonstrate relentless resilience.

Relentless resilience may become the seed of a deeper antidote to the new normal of cascading events (Román, 2022). This emerging concept can be described as creating cultures, mindsets, tools, and insights that help people, both individually and collectively, to handle the diversity of challenges our country is facing, including the ability to function throughout a series of disruptive events. A bottom-up approach to relentless resilience starts with codesign involving vulnerable community members who face compounding and cascading disasters. The codesign process would examine the ability of legacy programs, existing governance procedures, and available funding streams to enable relentless resilience. Working together, communities would codesign adaptive protective systems, programs, social norms, and mechanisms to reduce suffering and accelerate recovery when design events are exceeded—as they almost always are.

[4] *Robert T. Stafford Disaster Relief and Emergency Assistance Act of 1988,* Public Law 100-707, 100th Congress (November 23, 1988), 42, 68.

Some may worry that the concept of relentless resilience places stress on individuals and communities from a constant need to be resilient in the face of never-ending, and often externally imposed, stressors (Mahdiani and Ungar, 2021). The committee believes that resilience is about more than coping and surviving in the face of negative events. Rather, socioecological resilience is about creating cultures, mindsets, tools, and insights that help people individually and collectively handle the diversity of challenges individuals and communities face (Anderson, 2015; Khalid, 2019).

The false certainty that stationarity has offered for designers of infrastructure needs to be replaced, as it is insufficient and inhumane in a world of changing baseline conditions. Indeed, at a time of climate uncertainty, it is no longer acceptable for infrastructure designers to believe that it is sufficient to resist events up to a certain design event. Instead, the goal should be to pick a design event and then design systems, programs, cultures, and mechanisms to reduce suffering and accelerate recovery when those design events are exceeded.

The workshop discussions identified a series of cross-cutting questions through which applied research could supply important information to drive the codesign process:

- How could we restructure boundaries and organizations to focus funding on people first?
- Can we create a long-term resiliency and vulnerability network with real-time response, recovery, and mitigation?
- How can we create a new formal legal structure for disaster recovery?
- How can we improve monitoring, evaluation, and learning approaches to adapt, learn, and promulgate community resilience?
- How can we make funding simple, synchronized, and integrated?
- How can we account for shifting baseline conditions and stop relying solely on stationarity thinking?

In response to these broadly framed questions, the committee identified a series of specific approaches to prioritizing applied research. These applied research priorities can begin to inform new parameters for governance, mitigation, response, and recovery that embrace a broader, more equitable approach to compounding and cascading disaster management.

2

Approaches to Applied Research Priorities

The statement of task includes a charge to this committee to produce a consensus report identifying the priority applied research approaches, information, and expertise needed to encourage and stimulate emerging opportunities within the fields of natural hazard mitigation and resilience. Based on insights from the Resilient America Roundtable, input from the workshop's keynote speakers and panelists, and the committee members' knowledge and experiences with natural hazard mitigation and resilience, the committee identified the following approaches to addressing applied research priorities for preparing for and responding to compounding and cascading disasters:

1. Defining the problem—drivers, systems, and relationships that impact understanding of compounding and cascading disasters.
2. Mitigating impacts—developing solutions and avoiding unintended consequences.
3. Effectively implementing solutions and strategies, and governance for those solutions and strategies.

The examples presented in Boxes 2-1 and 2-2 illustrate how these three approaches work together as a process to generate solutions that communities can implement to increase their resilience for future events. The sections following the two boxes discuss each of these priority applied research approaches in detail. At the end of the discussion of each approach, the committee includes specific applied research topics and questions that it considers important for advancing related priorities.

BOX 2-1

Rebuilding Puerto Rico's Electric Power Grid

1. Defining the problem—An aged and vulnerable electric infrastructure

Hurricane Maria devastated Puerto Rico's electric power grid when it hit the island on September 20, 2017.[a] The resulting loss of power affected the entire island for months, causing more than 3,000 deaths; adding to the misery was damage to more than 1 million homes—92 percent of the nation's housing stock. Then, in January 2020, while recovery was incomplete and several recovery projects were still in the planning stages, a series of earthquakes struck southwestern Puerto Rico and the municipality of Ponce, the island's second most populous metropolitan area. Though the lines and poles rebuilt after Hurricane Maria survived the earthquake, some aging power plants, including one in Costa Sur that produces more than 40 percent of Puerto Rico's electricity, was damaged extensively, plunging the island into darkness once again. Though power was eventually restored, a fire at the same plant on April 6, 2022, triggered by a faulty breaker, again cut power to much of the island.

2. Mitigating impacts

In 2018, the Resilient Puerto Rico Advisory Commission (RPRAC), with extensive community input, developed an island-wide plan called ReImagina Puerto Rico, based on the Federal Emergency Management Agency's (FEMA's) National Disaster Recovery Framework and The Rockefeller Foundation's City Resilience Framework. ReImagina "identified the need to go beyond pre-existing conditions and seek to promote innovation, ingenuity, and a learning-by-doing approach in all rebuilding and reconstruction initiatives" (CNE, 2018). As the ReImagina report states, "Even in the midst of all this turmoil, Puerto Ricans are clear on one thing: The path forward is not to return the island to its prior state, normality is not the goal" (RPRAC, 2018, p. 22).

ReImagina Puerto Rico divided the work into six broad topic areas: housing; energy; physical infrastructure; health, education, and social services; economic development; and natural infrastructure. To develop actionable recommendations, RPRAC clearly defined the scope and reach of the issues that it intended each of these initiatives to address (RPRAC, 2018). Its goal for the energy initiative is to "address Puerto Rico's energy needs by transforming its electric power infrastructure into an affordable, reliable and innovative system, while reducing adverse impacts on human health and the environment" (RPRAC, 2018, p. 47). To achieve that goal, ReImagina Puerto Rico identified five actionable steps (RPRAC, 2018, p. 53):

- Identify the designation of all critical facilities with the relevant federal and local government departments.
- Organize and implement a full energy redundancy assessment of the identified facilities and individuals.
- Establish an appropriate mechanism to allocate and provide financial access to backup system procurements, purchasing, and installations based on the mix of facility types identified across the region and their different assessed needs.
- Fast-track demonstration projects should be prepared and implemented as early as possible for each of the different types of critical facilities and vulnerable population groups.

- Simultaneously, organize implementation teams for project leads (e.g., hospitals facilities managers, community center facilities managers, nursing home facilities managers, among others.)

3. Effectively implementing solutions and strategies, and governance for those solutions and strategies

As part of the process of developing ReImagina Puerto Rico, RPRAC established a set of principles to guide its work. These principles stated that the process of rebuilding Puerto Rico should maximize social well-being in all investments, establish equity and inclusiveness as a priority, ensure transparency at all levels of policy making, and emphasize and foster coordination and collaboration (RPRAC, 2018). The commission noted that it expects that ensuring transparency and emphasizing and fostering coordination and collaboration in the rebuilding process will "go a long way toward addressing the challenges presented by Puerto Rico's complex governance and decision-making processes" (RPRAC, 2018, p. 39). The ReImagina Puerto Rico plan calls for creating a multisector advisory board to "ensure evidence-based design and prioritization of projects and to enable knowledge transfer between municipalities, nonprofit organizations, community groups, public schools' personnel, academia and the private sector" (RPRAC, 2018, p. 42).

As of June 2022, FEMA has approved more than $107.3 million for 15 projects to modernize and strengthen Puerto Rico's electric generation, transmission, and distribution system. It has also awarded an additional $8.7 million to repair earthquake damage to the Costa Sur facility. That reconstruction effort, according to FEMA, is nearly complete (FEMA, 2022).

[a] Puerto Rico has once again experienced extensive damage and loss of power from Hurricane Fiona in September 2022, after this report was drafted.

BOX 2-2

Storm Surge and Flooding in Jacksonville, Florida

1. Defining the problem—Historical flooding caused by compounding of storm surge and rainfall runoff

The City of Jacksonville, the largest U.S. city in terms of geographic area, spans the entirety of Duval County in northeastern Florida. In September 2017, Hurricane Irma triggered Jacksonville's worst flood event since the late 1800s, when the St. Johns River and its many tributaries overflowed their banks. Though the Category 1 hurricane had passed, a wind-driven storm surge of between 3 and 5 feet flooded the city, whose waterways were already swollen by a nor'easter than had blanketed the area in the days prior to Hurricane Irma making landfall. In fact, the size and counterclockwise rotation of the hurricane pushed the storm surge up the St. John's River at the same time rain-induced flood waters were attempting to exit the city and surrounding areas (the city's storm drains are designed to move water toward the mouth of the river into the Atlantic Ocean). This compound event inundated areas not normally prone to flooding with storm surge or rainwater alone (Juárez et al., 2022). [a]

2. Mitigating impacts

Improved characterization of the response of the built environment, institutions, and communities to multihazard events can help provide guidance on how best to mitigate impacts from events such as Hurricane Irma. For example, modeling of the St. John's River estuary suggests that historic channel deepening likely increased the impact of storm surge but may have decreased the impact of river flooding from Irma (Talke et al., 2021). Understanding flooding risk can subsequently inform infrastructure decisions. Drawing in part on funding from the Federal Emergency Management Agency (FEMA), Jacksonville allocated nearly $10 million to purchase nearly 40 flood-prone homes and restore the land to its natural state, based on the idea that increasing wetland area may help mitigate future storm surge. However, solutions such as these are most effective if codeveloped with affected communities to ensure that attempts to fix one problem mitigate rather than exacerbate historic inequities and do not lead to other cascading problems.

3. Effectively implementing solutions and strategies, and governance for those solutions and strategies

Emergency response in the wake of the historic flooding included search-and-rescue efforts that pulled hundreds of victims to safety. Power was out for more than a quarter-million people, and the debris left behind took months to clear. In March 2020, FEMA approved two federal grants totaling $18 billion for the State of Florida to help the City of Jacksonville defray the costs of debris removal under FEMA's Public Assistance Program (FEMA, 2020). Four years later, Jacksonville's city council completed a resiliency survey and the mayor hired a chief resilience officer (Rivers, 2021).

[a] For additional information on the risk of compound flooding from storm surge and rainfall, see Wahl et al. (2015).

DEFINING THE PROBLEM: DIAGONOSING DRIVERS, SYSTEMS, AND RELATIONSHIPS THAT IMPACT UNDERSTANDING

Creating appropriate solutions for the challenges linked to compounding and cascading disasters requires diagnosing the drivers, systems, and relationships that underlie the vulnerabilities and impacts on lives, livelihoods, and ecosystems. The workshop panelists and participants highlighted the following:

- the need to identify possible distinctive signatures to recurring acute disasters and their impacts upon human use systems and ecosystems (Machlis et al., 2022; Raymond et al., 2020);
- the importance of analyzing past events and their impact on current and future preparedness, response, and recovery (Bourque, 2013; Mishra and Suar, 2007; Sun and Xue, 2020);
- the need to explore if and when future disasters will compound as a result of climate change (Fink and Ajibade, 2022; Zscheischler et al., 2018); and

- the need for effective approaches for preparedness and mitigation that account for legacy stressors, such as those related to economic characteristics and social marginalization (Emrich et al., 2014; Kruczkiewicz et al., 2021).

The workshop speakers and participants also called for efforts to study these events through a different lens, one that focuses on impacts rather than specific events and requires public participation and additional expertise from disciplines such as economics, sociology, communication, biology, and others. Examining the broad impacts of compounding and cascading events from the bottom up (e.g., outcomes from previous events) could generate new perspectives on how to effectively mitigate these growing threats and may also illuminate critical pathways forward. To support addressing these shortcomings, applied research should include research into community stakeholder understanding, socially accepted data for decisions, and defining and building investment options that minimize compounding disasters, which in turn will require applied research in the following areas:

- Measuring, understanding, and enhancing baseline infrastructure resilience and readiness by community. For example, research is needed to anticipate and measure vulnerabilities to cascading global events, such as when the combination of the COVID-19 pandemic and Russia's invasion of Ukraine created supply chain disruptions that affected oil and gas markets, food supply, and computer chip shortages, ultimately creating food insecurity and increased fuel and power costs in rural communities. Though these two events (COVID-19 and the Russian invasion of Ukraine) were not weather-related disasters, their ongoing cascading effects have led to long-term resilience challenges.
- Better understanding how communities accept information and support decisions based on trusted data.
- Understanding how broken supply chains can starve isolated and rural communities of basic necessities.
- Understanding how system-of-systems effects impact community apathy toward preparing for a wide variety of events, including those that do not rise to the level of disaster.
- Identifying more "ready-for-practice" scientific guidance on compound probabilities to establish credible methods and compare against adaptive strategies.

The committee identified the following specific applied research questions:

Applied Research Questions to Help Define Problems Regarding Compounding and Cascading Events

- Are there distinct signatures left by recurring acute disasters and their impact on human ecosystems?

- What additional knowledge would we gain by switching from an event-specific research approach to an impact-specific research approach?
- How can better identification and characterization of cascading events contribute to more effective design of solutions?
- How have smaller historic disasters contributed to subsequent events?
- How do global mitigating events or cascading events create supply chain disruptions that impact oil and gas, food supply, and computer chip shortages, which ultimately create food insecurity and increase fuel and power costs in rural communities?
- What long-term resilience problems do ongoing cascading events generate?
- How can we evaluate the trade-offs between exposure thresholds, such as extreme heat versus poor air quality exposure?
- What information is needed to evaluate the trade-offs between preparation and response?
- How can long-term observation of disaster hot spots provide empirically based evidence that can help develop lessons learned and unlearned?

To help answer the applied research questions listed above, the research community could take the following steps (Wahl, 2018):

- Identify additional key variables and event combinations needing scrutiny.
- Use bottom-up approaches and perform system stress tests to identify vulnerabilities.
- Use appropriate statistical methods to simulate dependence in time (i.e., temporal clustering) and space (i.e., spatial footprints), and across multiple variables.
- Identify data and model requirements for documenting, understanding, simulating, and attributing compound events.
- Incorporate compound events into impact assessments and disaster risk mitigation planning.

As Wahl notes, this can be accomplished only through close collaboration and communication among scientists from various fields in the natural sciences, engineering, and social sciences, as well as stakeholders and policy makers.

MITIGATING IMPACTS: DEVELOPING SOLUTIONS AND AVOIDING UNINTENDED CONSEQUENCES

For the second approach, the committee identified three topics—(1) the built environment, (2) response and recovery of systems, and (3) incentives for disaster risk reduction and equity—that would benefit from new knowledge for advancing efforts to mitigate the impacts of compounding and cascading events.

The Built Environment

Current infrastructure design typically incorporates mitigation and resilience needs based on historical event probabilities and impacts. Infrastructure design considers all potential natural hazards based on design requirements in codes and standards. However, buildings, bridges, roads, and other infrastructure design rarely accounts for multiple compounding hazards or future climate effects. Further research and modeling is needed to better design infrastructure to be less vulnerable and more resilient to multiple hazards, such as natural hazards, climate effects, and pandemics, and in various contexts. Initial studies in this area have produced some promising outcomes, demonstrating for example that optimizing hospital operation in the face of compound wildfires and COVID-19 pandemic stressors can improve resource allocation and patient outcomes (Hassan and Mahmoud, 2021). In addition, since land use and population growth assumptions can significantly affect the outcomes of hazard events (Siders, 2022), there is a need to better understand the interaction of compound events with land use and population growth, as well as the interaction between humans and the built environment.

While new construction can address hazards outside of typical design practice with minimal additional cost, much of the existing infrastructure has been designed to earlier codes and standards, or possibly without codes and standards. This aging infrastructure has highly variable levels of maintenance and often underperforms in the face of extreme events.[1] Opportunities exist to employ individual mitigation tactics and strategies to address cascading events, such as strengthening existing buildings and infrastructure to withstand increased storm surge due to sea level rise or a tsunami following an earthquake event, although the costs can be significant. However, even the best designs and mitigation tactics and strategies will do little if communities do not enforce building codes and standards. Opportunities are also available to improve business continuity by strengthening post-disaster resilience in the face of multiple or compound events, such as by stockpiling critical materials and relocating operations to less vulnerable locations (Dormady et al., 2022).

At present, there is no universal agreement on appropriate metrics for community resilience, although significant work is underway (Cutter et al., 2003; Ellingwood et al., 2019; Loerzel and Dillard, 2021; Sherrieb et al., 2010). There is some general consensus on what factors or aspects should be included among community resilience metrics, such as population impacts (dislocation, housing status, strength of social networks); economics (employment, income); equity (income distribution, poverty); social services (public health, education, commerce); physical services (utilities, transportation); and governance (first responder access, essential services). Further research is needed in this area to develop, estimate, and validate community resilience metrics. Such metrics can help better inform benefit-cost analyses and the design of incentives to support resilience, as discussed further below.

[1] The American Society of Civil Engineers (2022) has estimated an infrastructure funding gap of $10 trillion in gross domestic product by 2039.

Response and Recovery of Systems

There is a lack of understanding and modeling of the interconnectedness of various systems and impacts of multiple events on different components of a system. Often, there is also a lack of clarity regarding who has access to data about how systems and infrastructure are connected. This extends, for example, to international supply chains, where state-of-the-art economic models, such as the Global Trade Analysis Project,[2] are powerful but not yet capable of adequately and accurately estimating the effects of supply chain bottlenecks and supply delays that can lead to both lost production and inflation (Rose et al., 2022). An inability to produce needed goods and services due to property damage or infrastructure disruptions results in canceling orders for inputs from successive chains of suppliers upstream and a failure to provide inputs to successive downstream customers. These suppliers and customers likely extend far beyond the geographic area directly affected by the initial disaster. Moreover, delayed production due to supply chain bottlenecks and other sources of deterioration of synchronicity may extend the disaster.

As a second example, disasters can also have significant impacts on communication systems, damaging their ability to provide early warnings for a subsequent extreme event or to get critical information to the affected populations. For example, if communication systems are inoperable during a flood, people can have a difficult time getting the information they need to weigh the trade-offs between evacuating to a shelter and facing risk of exposure to COVID-19 at that shelter.

Incentives for Disaster Risk Reduction and Equity

In many circumstances, individuals and businesses can be counted on to make decisions that are consistent with both their best interests and the sound allocation of resources. Disasters, however, are major exceptions for reasons that include their infrequency and uncertainty, misperceptions of vulnerability, lack of access to information, inability or unwillingness to take a proper long-term perspective, and the divergence of objectives between parties of interest (Kunreuther and Pauly, 2004). Underresourced populations and communities may also lack access to capital to support resilience investments. Most of these considerations fall into what economists refer to as "market failure," when the ordinary workings of demand and supply fail to allocate resources efficiently (Boardman et al., 2018). Remedies typically fall into two categories: government involvement or market strengthening. The former includes taxes or subsidies to incentivize appropriate behavior, such as carbon taxes or subsidies for rooftop solar systems, or even government provision of the good or service itself, as is the case with flood insurance. Market strengthening includes providing information to improve decision making, such as more accurate weather forecasts, higher-resolution flood and earthquake mapping, or the establishment of an emissions trading ("cap and trade") system for addressing greenhouse gas emissions.

[2] See https://www.gtap.agecon.purdue.edu.

Incentives and programs are frequently designed using benefit-cost analyses to allocate funding and support. While efficiency and benefit-cost analysis are important in evaluating mitigation and resilience tactics and strategies, other considerations, such as broader societal and environmental factors, are often omitted from these analyses. Such analyses should account for historic inequities, such as ensuring that a wealthier home is not preferentially protected over a lower-income home simply because the wealthier home has a higher property value (see Box 2-3). This new form of analysis should consider approaches to including a broader set of benefits, such as in the triple-dividend of resilience (NASEM, 2022; Surminski et al., 2016). In addition, disaster preparation and response strategies have pros and cons, which communities can perceive differently. For example, some communities build seawalls because they feel safer behind them, while other communities prefer open coastlines (Siders, 2022). Comprehensive benefit-cost analyses in these communities may vary based on their local values and priorities.

In parallel, while many extol the virtue of free markets for their ability to promote the efficient allocation of resources, nearly everyone agrees that the market is "blind to equity" in that it cannot ensure equitable outcomes even under the best of circumstances. Moreover, inequities are especially rife in disaster contexts; many studies have shown that members of underrepresented groups bear a disproportionate burden of negative disaster impacts.[3] In such cases, policy can be developed to help reduce these inequities. An example is policy instruments focused on incentives, such as subsidies intended to help those households and businesses that cannot afford to take adequate protective measures or that have difficulty recovering. In addition, where there is a split-incentive issue between property owners, who are relatively more well-to-do, and renters, who are less so, remedies can include providing financial incentives to one or the other party—though a consideration of equity is likely to favor the latter (Kousky and Kunreuther, 2014).

Extensive literature is available on such failures of the market to allocate resources efficiently and equitably, and many studies have explored remedies. Building on existing knowledge, future research should focus on identifying entirely new approaches to addressing new phenomena, such as climate change impacts and compounding and cascading disasters. Such approaches may include both improved mechanisms for incorporating widespread societal benefits and approaches to valuing these benefits—and the distribution of benefits—into the design of various interventions, as well as strategies to use incentives to address market failures. This can serve as the basis for the specification of remedial policy instruments. Prime examples include research on the cost-effectiveness of incentives, such as improved earthquake- and landslide-mapping insurance rates and subsidies. Note that subsidies need not be for the entire cost of the action, but simply set at amounts necessary to close the gap between private and socially desirable outcomes (Rose, 2016). A new type of incentive uses the concept of "nudges" that take the form of suggestions or positive reinforcement to address long-standing issues such

[3] Ironically, a major exception is sea level rise, which is having a disproportionate impact on relatively expensive beachfront property. The burden is not only on individual households and businesses, but also on government at the regional and national level, with regard to commercial seaport operations and naval bases, respectively.

as low uptake of disaster insurance (Thaler and Sunstein, 2009). More research is needed on applying this nonmonetary policy instrument to disaster risk reduction (Karver et al., 2022; Robinson et al., 2021).

Businesses have many options for reducing the impacts of a disaster on employment and economic activity, including implementing a range of cost-effective resilience tactics in response to critical input disruptions caused by damaged infrastructure, such as conserving water and electricity, utilizing backup electricity generators, using stored water, and relocating activity to places where services are available (Dormady et al., 2022). Most of these tactics are applicable to compound and cascading hazard events, though they are likely to be more constrained (e.g., inventories, stockpiles). Many businesses are likely to implement them on their own accord for the purpose of survival, and limited government involvement in the form of inducements is necessary, although the government can help by removing obstacles to implementation. Some minority-owned businesses, small businesses, and microbusinesses[4] may require inducements when they have limited access capital, and the lack of availability of government assistance, in the case of compounding and cascading hazard events because of event severity and duration.

Applied Research Questions to Help Develop Solutions and Avoid Unintended Consequences

Built Environment

- How do we better model the impacts of compounding and cascading events on infrastructure, and how can we increase infrastructure resilience by incorporating these models into engineering and design?
- How do human–infrastructure interactions and decision making affect outcomes in the face of compounding and cascading events?
- How do land use and population growth assumptions influence resilient infrastructure planning decisions to address compounding and cascading events?
- How can we design solutions knowing that all future disasters may be compound because of climate change?

Systems and Populations

- How can community infrastructure stakeholders mitigate compounding and cascading hazards and attract investment?
- How can readiness strategies be adapted to a new normal of multiple compounding hazards?
- How can business continuity and general recovery strategies be improved to cope with this new normal?

[4] Microbusinesses are a subcategory of small businesses that employ fewer than 10 people (see https://ncses.nsf.gov/pubs/nsf22309).

- How can we improve inventory strategies (e.g., "just-in-time") to better smooth out supply chain bottlenecks?
- How do we create a more coherent and collectively agreed-upon understanding of human adaptive capacity and incorporate this into planning?
- What are the tools needed to provide ground truth screening that better characterizes risks and vulnerabilities (inclusive of identifying data and indicators) to evaluate disproportionate impacts and recovery for underresourced communities?
- What tools most effectively map the interdependency of institutions, infrastructure, and systems, and integrate this interdependency into approaches to hazard response (e.g., inclusion in standard Enterprise Asset Management practice)?
- How effective are early warning systems and other communication strategies for reducing injuries and loss of life in the face of multiple hazards?
- What are potential unintended consequences of mitigation and adaptation decisions, such as managed retreat and how do we understand these? Particularly in contexts of low trust in institutions because of historic inequities. Important examples include
  - populations in which family wealth is low because of systemic lack of economic and education opportunities;
  - communities in marginal development areas most impacted by extreme events, in which physical vulnerabilities are hardwired; and
  - Indigenous communities that resist relocation because it obliterates historical legacies.
- How do we account for personal and community crises, such as mental health crises during the pandemic, to better design solutions?
- What tools can be used to better measure disaster recovery time?
- How are underresourced communities that have not fully recovered from previous events able to prepare for or recover from successive events, including not only infrastructure, but also social and emotional damage?
- What are the impacts of land use and population growth on compounding and cascading event preparation and response?

Benefit-Cost Analysis, Other Assessment Methods, Incentives, Metrics, and Equity

- What methods could most efficiently improve or replace benefit-cost analysis—which is currently biased toward evaluating impacts on aggregate property values—to put equity at the forefront by focusing on the distribution of benefits and costs and protecting people in addition to property and income?
- To what extent can and should researchers measure the impacts of prior policy decisions and such factors as home values as a means of accounting for systemic racism?
- To what extent do various market failures take place in the context of disasters; what are the inequitable outcomes of market operation; and how do we design strategies

for closing the gap between typical outcomes and those in the best interest of a climate-resilient society (Rose, 2016)?

- To what extent does government policy promote or interfere with private-sector initiatives (Kousky and Kunreuther, 2014)?
- How do we reach consensus on key metrics, supported by sensitivity and validation studies, to better understand and articulate how to better reduce loss of lives and livelihoods, and how can these metrics be used to better inform government spending, planning, and philanthropy?
- What trade-offs do communities face when preparing for and responding to hazards?
  - How do communities perceive trade-offs and how does that affect adaptation pathways (e.g., seawalls vs. beach access)?
  - What are the trade-offs between exposure thresholds (e.g., extreme heat vs. poor air quality)?
- How do we apply measurement systems for weighing decisions about specific solutions and their trade-offs?

BOX 2-3

A Disaster Deductible/Credit System

A major area concerning incentivization and governance relates to the problem of "moral hazard," in which entities fail to make the right decision because they do not have to take full responsibility for their actions. A classic example in the disaster field is households and businesses not purchasing adequate flood proofing or earthquake insurance, and rebuilding in floodplains or seismically active areas because they believe—and their experience proves—that they will continue to receive federal government compensation.

Recently, the Federal Emergency Management Agency (FEMA) proposed a "disaster deductible" for its Public Assistance Program,[a] which is intended to promote mitigation but could potentially reduce funding to states and subsequently to localities. This approach is analogous to the deductible in automobile insurance policies. However, as in the case of enlightened insurance incentive designs, FEMA's proposal calls for pairing the deductible with a credit system in which community expenditures on hazard mitigation and resilience would reduce the deductible. Public opposition from states and localities to the proposed rule was strong, in part because of misunderstanding of how this policy design would work and in part because the credit system would not totally offset the deductible in most cases in the early years of the program (Rose et al., 2020).

Further examination of this or related policies would be worthwhile. Such research would examine specific design of the deductible/credit system or allocation framework for disaster aid tied to resilience planning and how to improve communication to the public about such a system. Research could also include formal, focused accounting of state and local resilience investment policies and practices that resulted in low-income, Indigenous, people, and communities of color bearing a disproportionate share of social, economic, health, and environmental burdens. Studies in this area could also be part of an analysis to link the deductible/credit system to a broadening of the Public Assistance Program. The program's

current objectives focus on reducing property damage, but more consideration might be given to promoting life safety, as well as immediate recovery to prevent excessive job loss in the aftermath of disasters. Additional analysis is needed on the flow-down of such policies from the federal to the state and local levels, especially with regards to equity concerns of communities consisting of large proportions of underrepresented groups (Domingue and Emrich, 2019). In particular, historically underinvested and low-income communities may lack access to resources and capital for resilience investments, and therefore receive lower funding because of the deductible system, unless this concern is specifically addressed.

[a] See https://www.fema.gov/sites/default/files/documents/fema_pappg-v4-updated-links_policy_6-1-2020.pdf.

EFFECTIVELY IMPLEMENTING SOLUTIONS AND STRATEGIES, AND GOVERNANCE FOR THOSE SOLUTIONS AND STRATEGIES

Great relationships are the foundation for successful interactions in daily business. This is particularly true for emergency response situations, in which sudden needs arise from an unexpected event (see Box 2-4) to interact with many partners that are not part of daily operations. As such, it would likely improve a community's response to an emergency if procedures for collaboration were in place prior to the emergency. The challenge, then, is to develop mechanisms for efficient coordination between government entities, public utilities, private stakeholders, and nongovernmental organizations that improve communication and minimize barriers to coordination.

To understand governance challenges, the following scenario can provide helpful context: For an earthquake event along the Wasatch Fault near Salt Lake City, Utah, an integrated approach to planning, response, and recovery would require coordination across two counties, 49 cities, many municipal service districts, multiple private power companies, state and federal agencies, private stakeholders, and community members. Each entity will have varying goals, economic incentives, time horizons, risk tolerances, and administrative capacities, and each will have distinct roles, priorities, responsibilities, and authorities (French, 2022).

The national emergency management system provides vertical integration among federal, state, and local governments for disaster assistance and funds. However, at the local, regional, and state levels, there is a lack of similar vertical integration of other offices for economic development, land use planning, climate change, and resilience. Moreover, there is often a lack of horizontal integration among these offices at the community, regional, and state levels. Such gaps are made more apparent by compounding and cascading hazard events.

One of the most important elements of effective recovery after a disaster is the availability to access funding to support recovery and advance resilience. In fact, the absence of sufficient financial resources at the individual, community, municipality, and state levels is itself a measure of vulnerability. Effective implementation of both disaster recovery and resilience measures will require coordination among available sources of funding, which are mostly public but sometimes philanthropic. Governance solutions and strategies should integrate these considerations as well.

Well-established methods for building collaboration and improving operations include broad interagency participation in hazard scenario exercises. These exercises also help prepare for compound or cascading events. However, as such exercises tend to focus on emergency response for a single hazard, they may not simulate the combined resilience requirements of single assets, the broader communities, and the systems of services such as health care, water systems, and education, among others. In addition, communities already burdened with patterns of historic disinvestment and abuse may require tailored emergency response and recovery efforts focused on all aspects of community resilience.

Nonetheless, there is much to learn about interagency collaborations and processes from such hazard scenario exercises if they are designed comprehensively. For example, Oregon used the 2018 solar eclipse—when a million people, the equivalent of 25 percent of its population, visited the state—to test preparations for a Cascadia earthquake response as a live exercise. Many response actions easily translate across hazards, and practicing them in a nonemergency situation can foster working together and developing relationships. State and local governments may consider going beyond emergency response situations by simulating recovery scenarios over short (days), intermediate (weeks to months), and long (months to years) terms (FEMA, 2011). For example, exercises that simulate planning and implementing incentives to repair and rebuild after a damaging event would inform emergency response and resilience plans among local and state governments and organizations.

One of the major factors that curbs planning and response activities is the limited bandwidth and staff capacities in many communities and states. The level of coordination and maintenance for preparedness, response, and recovery for hazard events is a huge challenge for many communities and states. Strategies for addressing this challenge include rural counties collaborating to support small, underserved communities, and states helping counties and municipalities as they apply for and manage grants.

The committee identified three topics that would benefit from new knowledge for advancing efforts to effectively implement solutions and strategies, and governance for those solutions and strategies: (1) leveraging funds and creating incentives through financial instruments, (2) expanding governance perspectives and strategies, and (3) obtaining governance knowledge and tools for implementing solutions and strategies.

BOX 2-4

BLACK SWANS AND GRAY RHINOS

A “black swan” event occurs when the gap between what people know and what they think they know becomes dangerously wide (Taleb, 2017). The concept of black swan events dates back to the discovery of black swans in Australia, prior to which it was assumed that all swans were white. The fact that black swans exist highlighted the fragility of existing knowledge on that specific topic. Similarly, the fact that compounding and cascading disasters are becoming more and more prevalent should not come as

a surprise in and of itself. Rather, society should recognize the limitations of currently available knowledge on these emerging hazard phenomena and attempt to close that knowledge gap.

"Gray rhino" events, on the other hand, are high-impact, highly likely threats that are nonetheless largely ignored for one reason or another (Wucker, 2016). They are not surprises, as are black swan events, but occur after a series of warnings and visible evidence. As the originator of this term has noted, "A gray rhino is the two-ton, horny thing that is coming right at you. You've a choice to do something about it or not. It's a metaphor for the fact that so many of the things that go wrong in business, in policy, and in our personal lives are actually avoidable. We don't pay enough attention to the big obvious problems that are in front of us" (Jaye and Wucker, 2017, p. 2).

The concept here is that society can make a choice to deal with the likelihood of extreme events such as compound or cascading disasters or not. Unfortunately, myriad social, economic, environmental, political, or other conditions often complicate society's choices by making it both difficult to make the "right" decision and impossible to make timely decisions.

Leveraging Funds and Creating Incentives Through Financial Instruments

Successful investment in climate adaptation and resilience requires long-term planning, institutional capacity, capital investment, and well-designed financial incentives to accelerate voluntary actions. Investment dollars may come from public sources, including those from federal and state agencies, through public-sector bond issuances (e.g., municipal bonds), or from private sources, such as banks or infrastructure funds, and in some cases from philanthropic sources such as foundations and family offices. Public–private partnerships (PPPs) offer a useful funding model for infrastructure construction or renovation. The National Council for Public-Private Partnerships defines a public-private partnership as

> a contractual agreement between a public agency (federal, state, or local) and a private sector entity. Through this agreement, the skills and assets of each sector (public and private) are shared in delivering a service or facility for the use of the general public. In addition to the sharing of resources, each party shares in the risks and rewards potential in the delivery of the service and/or facility. (quoted in AGC, n.d.)

Each of these funding models has its own benefits and drawbacks. PPPs offer an effective way for both public and private investors to share and bear different types of financial risk within a transaction. However, communities commonly use multiple types of funding sources and mechanisms to achieve their resilience goals.

Federal and state programs that support resilience often contain important incentives, such as tax credits, guarantee mechanisms, rebates, and other financial mechanisms that help to catalyze resilient investment. These can span many sectors, agencies, and departments across federal and state governments. A number of federal programs have funds to help states and communities improve the current state of their infrastructure (ASCE, 2021) and resilience needs (Olszewski et al., 2021). As of December 2021, 20 federal agencies administered 75 funding programs related to climate adaptation and resilience, providing hundreds of millions of dollars

in grants, low-cost loans, and nonmonetary technical assistance (Climate Finance Advisors, 2022). Examples include the Infrastructure Investment and Jobs Act,[5] hazard mitigation grants from the Federal Emergency Management Agency (FEMA), such as the Building Resilient Infrastructure and Communities (BRIC) program,[6] and Department of Housing and Urban Development Community Development Block Disaster Recovery and Mitigation Program grants.[7]

However, there can be a significant gap between available funds and a community's capacity to apply, manage, and implement multiple funding streams with their varying timelines and application and management requirements. Federal mitigation and recovery programs are often too complex and cumbersome for most communities to implement (Sprayberry, 2022). The difficult, time-consuming nature of navigating various websites, understanding specific program priorities, and determining eligibility requirements can be a barrier for applicants—especially those without prior experience accessing federal programs. Communities need to be agile and deft to manage the timing of various grants, which can be received years after the damaging event.

Mandates and incentive programs can be key aspects of implementing solutions that will improve the resilience of communities to all hazards, including compounding and cascading hazards.[8] The FEMA Community Rating System, for example, is a voluntary incentive program for encouraging floodplain management practices that is used by over 1,500 communities (FEMA, 2018). Programs such as this also present an opportunity to improve coordination at all levels to advance preparedness, recovery, and resilience programs.

While local communities best understand their challenges and needs, grant funding applications often have narrowly focused requirements that may not align with local priorities. Models of improved local, regional, and state coordination for better management and leveraging of funds are needed, as is localized expertise across communities whose sole purpose is to identify, understand, and procure federal and state funding for resilience. For example, when North Carolina was responding to challenges following hurricanes Matthew and Irma, it established a grants and incentives program to aid their communities with applying for and managing federal and state funds.[5] In 2022, Maryland passed legislation establishing a statewide Office of Resilience with a chief resilience officer to coordinate state and local efforts to build resilience to risks identified in the Maryland Hazard Mitigation Plan, and to develop a state resilience strategy including an investment plan to fund the strategy.

---

[5] *Infrastructure Investment and Jobs Act of 2021*, Public Law 58, 117th Congress, 1st session (November 15, 2021).
[6] See https://www.fema.gov/grants/mitigation/building-resilient-infrastructure-communities.
[7] See https://www.hud.gov/program_offices/fair_housing_equal_opp/fheo_requirementsfor_community_development_block_grant_%E2%80%93.
[8] The National Institute of Building Sciences has published examples of public and private incentives for building and infrastructure owners (Multi-Hazard Mitigation Council, 2020).
[5] See https://www.nccommerce.com/grants-incentives.

Workshop speakers and participants suggested the following as possible ways to improve governance:

- Simplify funding and incentive programs; many are too complex with their application and management requirements.
- Fund more staff at the local and state levels to help coordinate resilience responses.
- Use clear language that all government officials can understand; for instance, discount rates for benefit-cost analyses are not generally understood.
- Find ways to have academia and private companies assist communities in developing effective approaches for governmental coordination and advancing resilience to future hazard events.
- Use grant funding to plan and exercise scenarios with intergovernmental coordination.
- Incorporate land use planning and more stringent building codes; BRIC requires use of the International Building Code and local Hazard Mitigation Plan.
- More guidance and assistance on how to plan for, compensate, and achieve parity for historically marginalized communities.
- Award funds to states and let states make awards to counties and municipalities.
- Dramatically shorten the time it takes to complete a property buyout; at present it can take up to 5 years.

Expanding Governance Perspectives and Strategies

Local and state governments are facing new challenges regarding how to balance acute hazards and chronic conditions, such as coastal hazard events with sea level rise and wildlife–urban interface fires with drought conditions. These combinations may lead to compounding and cascading hazards—such as landslides following a wildlife–urban interface fire, and earthquake events or wind and flood events that occur in succession before a region recovers from previous events. These new challenges raise issues about the current paradigm of readiness, emergency management, and resilience that are based on a one-event-at-a-time perspective. For example, what does governance look like with multiple event occurrences? What type of implementation and governance changes are needed at the federal, state, and local levels to shift from a single-event condition to multiple events?

Evolving issues, such as equity in the face of pandemics, supply chain disruptions, and climate effects, are pressing needs for government agencies that should be integrated into planning, health, emergency management, resilience, and other activities. Equity issues—including demographics; historical context and legacy conditions; the role of marginalized populations in maintaining infrastructure; and, most notably, what constitutes equity in the context of resilience—all need greater attention. These evolving issues often require immediate actions while the research community is still developing and refining the science and tools that would lead to better decisions. For officials used to working with slowly evolving parameters,

such as building codes and standards, decision making under increased uncertainty can be uncomfortable and stultifying. However, the alternative of doing nothing until science and tools are better established is unacceptable.

Communities need guidance on how to address new risks associated with climate effects and with compounding and cascading events, particularly where communities have a risk-averse approach. It can be uncomfortable to make decisions about resilience, especially when uncertainties about events and outcomes are greater than in the past. Guidance is needed that simply and clearly conveys that the risk of doing nothing is much greater than taking steps to improve resilience, even if corrections are needed along the way. The research literature addresses risk stances (risk averse, risk neutral, or risk tolerant) for businesses and organizations, but public and government decision makers require improved guidance.

Obtaining Governance Knowledge and Tools for Implementing Solutions and Strategies

Decision makers need data-informed information and tools and an understanding of their intended application, including how risk and uncertainty are addressed. A 2018 workshop addressing data, information, and tools needed for community resilience planning and decision making found that: (1) communities seek tools to develop plans, communicate with stakeholders, and track progress; (2) data standards would improve the accessibility of data and tool development; and (3) implementation requires identifying funding opportunities and evaluating the benefits and costs of proposed projects (McAllister et al., 2019).

Examples of useful tools include National Flood Insurance Program flood hazard maps and fire hazard maps for land use planning. Other tools include web-based systems the public can use to obtain flood (Dorman and Banerfee, 2016) or fire alerts.[6] Various research groups are also developing tools to support resilience planning (Olszewski et al., 2021), including

- FEMA's Hazus tool, a geographic information system–based desktop software tool that identifies areas with high risk for natural hazards and estimates physical, economic, and social impacts of earthquakes, hurricanes, floods, and tsunamis[7];
- the Center of Excellence for Risk-Based Community Resilience Planning's Interdependent Networked Community Resilience Modeling Environment (IN-CORE) program, which allows users to run scientific analyses that model the impact of natural hazards and resiliency against the impact on communities[8];
- the Critical Infrastructure Resilience Institute's Business Resilience Calculator (BRC)[9]; and

[6] See https://www.alertwildfire.org.
[7] See https://www.fema.gov/flood-maps/products-tools/hazus.
[8] See https://incore.ncsa.illinois.edu.
[9] See https://resiliencecalculator.com.

- the National Institute of Standards and Technology's Community Resilience Planning Guide[10] and Inventory of Community Resilience Indicators & Assessment Frameworks.[11]

Tools for supporting risk assessment in underserved communities include

- the Environmental Protection Agency's EJScreen, an environmental justice screening and mapping tool that combines environmental and demographic indicators in maps and reports,[12] and
- FEMA's National Risk Index for Natural Hazards, an online mapping application that identifies communities most at risk for 18 natural hazards using county-level data.[13]

Rural communities have a different set of parameters that current data and tools often do not address. For example, community members may not have cell phone access, and the nearest neighbors may be miles away. Workshop speakers and participants noted that many states and communities are developing their own tools either because they did not understand how to apply existing tools or did not know they already existed. One key question that remains for all data and tools is how to verify and validate them.

Applied Research Questions Regarding Effectively Implementing Solutions and Strategies, and Governance Those Solutions and Strategies

Improving Institutional Operations

- How can coordination for mitigation, planning, and recovery from cascading events be streamlined for timely, effective operations among government entities, public utilities, private stakeholders, and nongovernmental organizations?
- How can communications among agencies and community members, both urban and rural, be improved for clarity, timeliness, and understanding, in terms of both providing early warnings and functioning under emergency conditions?
- What is the minimum capacity (staffing, funding, etc.) needed at the local and state levels to appropriately plan for resilience and effectively coordinate disaster recovery (e.g., improve governance)?

Leveraging Funds and Creating Incentives through Financial Instruments

- There is a significant gap between available federal funds and local capacity to apply, manage, and implement multiple funding streams with varying requirements. How

[10] See https://www.nist.gov/community-resilience/planning-guide.
[11] See https://www.nist.gov/community-resilience/assessment-products.
[12] See https://www.epa.gov/ejscreen.
[13] See https://www.fema.gov/flood-maps/products-tools/national-risk-index.

can mitigation and recovery programs be made less complex and cumbersome? How can local and state agencies get the capacity (staffing and funds) needed to navigate the complex system of federal and state funding streams?
- What incentives and metrics can be used to improve coordination at the interagency and public and private levels?
- How effective are federal and state mandates and incentives for encouraging hazard mitigation and response planning?
- How should different funds be used to effectively coordinate among different actors? If the funding comes from one source, how should it be distributed?
- How can communities leverage federal funding more effectively (e.g., through bond issuances, to securitize private investment)?
- How can we better integrate resilience into solutions that are driven by funds, services, and connections provided by industry, government, and civil society?

Expanding Governance Perspectives and Strategies

- How can the federal and state mindset for acute events and emergency management be shifted to include long-term planning for compounding and cascading events?
- Should every state institute chief resilience officers to help coordinate at the local and federal levels?
- How can innovation be introduced and incorporated into risk-averse institutions?
- What evidentiary basis do social and behavioral sciences provide for improving implementation of disaster mitigation and resilience policies and strategies?
- How can consensus on adaptive capacities, especially in the context of compounding and cascading disasters, be developed to inform resilience solutions and strategies?
- How do we balance acute hazard events and chronic conditions, such as drought, from a governance perspective?
- How can governance roles and authorities be assigned more effectively among entities (federal, state, local; public–private)?
- How can government staff be trained to obtain new capabilities for future event resilience planning, response, and recovery?
- What does the governance transition look like when hazard events become so frequent that they have to be managed as status quo? Perhaps these are no longer "emergency" appropriations?

Obtaining Governance Knowledge and Tools for Implementing Solutions and Strategies

- What knowledge (data/information) is needed by decision makers and those that implement resilience solutions and strategies?
- How can this knowledge about implementation status (progress/vulnerabilities) be provided through current data/information and tools (assessments, indexes, indicators/metrics, etc.)?

- In particular, what knowledge and tools are available or needed to address equitable solutions?

3

Conclusion

The present reality is an era of compounding and cascading disasters. In multiple locations across America today, individuals, families, and communities are struggling to move forward from one disaster before the next disaster hits. The time to heal, regroup, and resettle between disasters is limited, and in some cases nonexistent, because of choices society has made; natural systems that society's actions have stressed; and the institutions and bureaucracies that maintain a status quo that perpetuates suffering among individuals, families, and communities, as extreme events and the disasters they produce are becoming the norm.

While the public may marvel at and take satisfaction from the way the nation, communities, families, and individuals respond in the immediate aftermath of a disaster, we as a nation frequently fail to consider the circumstances and prior decisions that made necessary these acts of heroism, altruism, and giving that are so admirable. More important, as it pertains to resilience in the face of compounding and cascading extreme events, we frequently fail to consider what comes after that immediate response to disaster, both in terms of providing continued support for an affected community and its members and taking the needed forward-thinking actions that would increase resilience and mitigate the disastrous effects of future extreme events.

Clearly, urgent and transformative action is required. This report challenges the applied research community and disaster response professionals to apply their analytical skills to begin to address the challenges that perpetuate the status quo. Now is the time to step back, take in the whole picture, and focus on details for analysis while continuing to embody empathy for those who suffer. Given this era of compounding and cascading disasters, there is no time to waste to create new choices, new tools, new collaborations, and new rules and regulations. The question is simple: Will we choose to move forward on a path toward resilience, or will we chose to maintain the status quo and continues to put our communities at ever-increasing risk?

REFERENCES

Anderson B. 2015. What kind of thing is resilience? *Politics* 35(1):60-66. doi:10.1111/1467-9256.12079

Associated General Contractors of America. (n.d.). *Public-private partnership basics.* https://www.agc.org/public-private-partnership-p3-basics (accessed September 23, 2022).

ASCE (American Society of Civil Engineers). 2021. *Report card for America's infrastructure*. https://infrastructurereportcard.org (accessed September 22, 2022).

Averyt, K. 2022. *Emergency management in the context of resilience*. Paper presented at Committee on Hazard Mitigation and Resilience Applied Research Topics Workshop 2: Compounding and Cascading Events, Washington, DC, May 31, 2022.

Boardman, A. E., D. H. Greenberg, A. R. Vining, and D. L. Weimer. 2018. *Cost-benefit analysis: Concepts and practice*, 5th ed. New York: Cambridge University Press.

Bourque, L. 2013. Household preparedness and mitigation. *International Journal of Mass Emergencies and Disasters* 31(3):360-372.

Churchill, L. 2022. *Strategies to effectively apply solutions*. Paper presented at Committee on Hazard Mitigation and Resilience Applied Research Topics Workshop 2: Compounding and Cascading Events, Washington, DC, May 31, 2022.

Climate Finance Advisors. 2022. *U.S. public sources for climate resilient investment, climate finance-IQ brief.* https://climatefinanceadvisors.com/wp-content/uploads/2022/04/310-026-US-CRI-Brief_V5.pdf (accessed September 22, 2022).

CNE (Center for a New Economy). 2018. *Fostering a better and stronger Puerto Rico for all*. https://grupocne.org/reimagina-puerto-rico (accessed July 3, 2022).

Cutter, S. 2022. *What do we do next?* Paper presented at Committee on Hazard Mitigation and Resilience Applied Research Topics Workshop 2: Compounding and Cascading Events, Washington, DC, May 31, 2022.

Cutter, S. L., B. J. Boruff, and W. L. Shirley. 2003. Social vulnerability to environmental hazards. *Social Science Quarterly* 84(2):242-261.

DeFlorio, J. 2022. *The resilience cycle: An iterative approach to building resilience*. Paper presented at Committee on Hazard Mitigation and Resilience Applied Research Topics Workshop 2: Compounding and Cascading Events, Washington, DC, May 31, 2022.

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.

Dormady, N. C., A. Rose, A. Roa-Henriquez, and C. B. Morin. 2022. The cost-effectiveness of economic resilience. *International Journal of Production Economics* 244:108371.

Dorman, J., and N. Banerfee. 2016. A real-time flood warning system. *ArcUser* Winter 2016:16-19.

Elhami-Khorasani, N. 2022. *Characterizing drivers, systems, and relationships*. Paper presented at Committee on Hazard Mitigation and Resilience Applied Research Topics Workshop 2: Compounding and Cascading Events, Washington, DC, May 31, 2022.

Ellingwood, B., J. van de Lindt, and T. McAllister. 2019. A fully integrated model of interdependent physical infrastructure and social systems. *The Bridge* 49(2):43-51.

Emrich, C. T., D. P. Morath, G. C. Bowser, and R. Reeves. 2014. *Climate-sensitive hazards in Florida: Identifying and prioritizing threats to build resilience against climate effects.* Columbia: University of South Carolina Hazards Vulnerability & Resilience Institute.

Every, D., and J. Richardson. 2017. *Building the disaster resilience of the homeless community.* Melbourne: Australian Red Cross and Central Queensland University.

FEMA (Federal Emergency Management Agency). 2011 *National disaster recovery framework.* Washington, DC: FEMA.

FEMA. 2018. *National flood insurance program community rating system: A local official's guide to saving lives, preventing property damage, and reducing the cost of flood insurance.* Washington, DC: FEMA.

FEMA. 2020. *FEMA awards city of Jacksonville nearly $18.2 million for Hurricane Irma expenses*. Orlando, FL: FEMA.

FEMA. 2022. *FEMA announces progress in Puerto Rico's power grid work*. Guaynabo, PR: FEMA.

Fink, J., and I. Ajibade. 2022. Future impacts of climate-induced compound disasters on volcano hazard assessment. *Bulletin of Volcanology* 84(5):42.

French, S. P. 2022. *Wasatch cascading event scenario*. Paper presented at Committee on Hazard Mitigation and Resilience Applied Research Topics Workshop 2: Compounding and Cascading Events, Washington, DC, May 31, 2022.

Haggerty, M. 2020. *Fiscal policy is failing rural America*. Bozeman, MT: Headwaters Economics.

Hassan, E. M., and H. N. Mahmoud. 2021. Orchestrating performance of healthcare networks subjected to the compound events of natural disasters and pandemic. *Nature Communications* 12(1):1338.

IPCC (Intergovernmental Panel on Climate Change (IPCC). 2021. *Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3−32, doi:10.1017/9781009157896.001.

Jaye, N., and M. Wucker. 2017. Do "gray rhinos" pose a greater threat than black swans? *CFA Institute Magazine*, October 23, 2017. https://blogs.cfainstitute.org/investor/2017/10/23/do-gray-rhinos-pose-a-greater-threat-than-black-swans (accessed September 22, 2022).

Jones, R. N., A. Patwardhan, S. J. Cohen, S. Dessai, A. Lammel, R. J. Lempert, M. M. Q. Mirza, and H. von Storch, 2014: Foundations for decision making. In *Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects.* Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. C. B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White. eds. New York: Cambridge University Press. Pp. 195-228.

Juárez, B., S. A. Stockton, K. A. Serafin, and A. Valle-Levinson. 2022. *Compound flooding in a subtropical estuary caused by Hurricane Irma 2017*. Ensenada, MX: Instituto de Investigaciones Oceanológicas.

Karver, J. G., H. Shijaku, and C. T. F. Ungerer. 2022. *Nudging in the time of the coronavirus : Evidence from an experimental tax trial in Albania at the onset of a global pandemic.* Washington, DC: World Bank.

Khalid, H. 2019. Building resilience in chronic trauma through self-regulation. *The European Journal of Educational Sciences*. doi:10.19044/ejes.s.v6a7.

Kousky, C., and H. Kunreuther. 2014. Addressing affordability in the national flood insurance program. *Journal of Extreme Events* 1(1):1450001.

Kruczkiewicz, A., J. Klopp, J. Fisher, S. Mason, S. McClain, N. M. Sheekh, R. Moss, R. M. Parks, and C. Braneon. 2021. Compound risks and complex emergencies require new approaches to preparedness. *Proceedings of the National Academy of Sciences* 118(19):e2106795118.

Kunreuther, H., and M. Pauly. 2004. Neglecting disaster: Why don't people insure against large losses? *Journal of Risk and Uncertainty* 28:5-21.

Kunreuther, H., S. Gupta, V. Bosetti, R. Cooke, V. Dutt, M. Ha-Duong, H. Held, J. Llanes-Regueiro, A. Patt, E. Shittu, and E. Weber. 2014. Integrated risk and uncertainty assessment of climate change response policies. In *Climate change 2014: Mitigation of climate change*. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx, eds. New York: Cambridge University Press.

Lawrence, J., P. Blackett, and N. A. Cradock-Henry. 2020. Cascading climate change impacts and implications *Climate Risk Management* 29:100234.

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* 126:126031.

Machlis, G. E., M. O. Román, and S. T. A. Pickett. 2022. A framework for research on recurrent acute disasters. *Science Advances* 8(10):eabk2458.

Mahdiani, H., and M. Ungar. 2021. The dark side of resilience. *Adversity and Resilience Science* 2(3):147-155. doi:10.1007/s42844-021-00031-z.

Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield. 2022. *Global warming of 1.5°C.* Intergovernmental Panel on Climate Change. https://www.ipcc.ch/sr15 (accessed September 22, 2022).

McAllister, T. P., C. T. Clavin, B. R. Ellingwood, J. van de Lindt, D. Mizzen, and F. Lavelle. 2019. *Data, information, and tools needed for community resilience planning and decision-making.* Gaithersburg, MD: National Institute of Standards and Technology.

Milly, P. C. D., J. Betancourt, and M. Falkenmark. 2008. Stationarity is dead: Whither water management? *Science* 319(5863):573-574.

Mishra, S., and D. Suar. 2007. Do lessons people learn determine disaster cognition and preparedness? *Psychology and Developing Societies* 19(2):143-159.

Moddemeyer, S. 2022. *Welcome remarks*. Paper presented at Committee on Hazard Mitigation and Resilience Applied Research Topics Workshop 2: Compounding and Cascading Events, Washington, DC, May 31, 2022.

Multi-Hazard Mitigation Council. 2020. *A roadmap to resilience incentivization*. K. A. Porter and J. Q. Yuan, eds. Washington, DC: National Institute of Building Sciences.

NASEM (National Academies of Sciences, Engineering, and Medicine). 2021. *Enhancing Community Resilience through Social Capital and Connectedness: Stronger Together!*. Washington, DC: The National Academies Press.

NASEM (National Academies of Sciences, Engineering, and Medicine). 2022. *Equitable and resilient infrastructure investments.* Washington, DC: The National Academies Press.

NIST (National Institute of Standards and Technology). 2016. *Community Resilience Planning Guide for Buildings and Infrastructure Systems*. NIST Special Publication 1190(1). http://dx.doi.org/10.6028/NIST.SP.1190v1.

NIST. 2020. *Community Resilience Planning Guide for Buildings and Infrastructure Systems*. NIST SP 1190GB-16. https://doi.org/10.6028/NIST.SP.1190GB-16.

NRC (National Research Council). 2012. *Disaster resilience: A national imperative*. Washington, DC: The National Academies Press.

Olsson, P., V. Galaz, and W. J. Boonstra. 2014. Sustainability transformations: A resilience perspective. *Ecology and Society* 19(4):1.

Olszewski, T., I. Liu, and A. Cunningham. 2021. *Survey of federal community resilience programs and available resilience planning tools*. Gaithersburg, MD: National Institute of Standards and Technology.

Raymond, C., R. M. Horton, J. Zscheischler, O. Martius, A. AghaKouchak, J. Balch, S. G. Bowen, S. J. Camargo, J. Hess, K. Kornhuber, M. Oppenheimer, A. C. Ruane, T. Wahl, and K. White. 2020. Understanding and managing connected extreme events. *Nature Climate Change* 10(7):611-621.

RPRAC (Resilient Puerto Rico Advisory Commission). 2018. *ReImagina Puerto Rico report.* San Juan, PR: Resilient Puerto Rico Advisory Commission.

Rivers, B. 2021, July 8. *Mayor Curry hires Jacksonville's chief resiliency officer*. News4Jax. https://www.news4jax.com/community/2021/07/08/mayor-curry-hires-jacksonvilles-chief-resiliency-officer (accessed September 22, 2022).

Robinson, P. J., W. J. W. Botzen, S. Duijndam, and A. Molenaar. 2021. Risk communication nudges and flood insurance demand. *Climate Risk Management* 34:100366.

Román, M. O. 2022. *A framework for research on recurrent natural disasters*. Paper presented at Committee on Hazard Mitigation and Resilience Applied Research Topics Workshop 2: Compounding and Cascading Events, Washington, DC, May 31, 2022.

Rose, A. 2016. Capturing the co-benefits of disaster risk management in the private sector. In *Realising the "triple dividend of resilience" a new business case for disaster risk management*. S. Surminski and T. Tanner, eds. Geneva, Switzerland: Springer International Publishing.

Rose, A., P. Ganderton, J. Eyer, D. Wei, R. Bostic, and D. Winterfeldt. 2020. The role of a deductible/credit system for post-disaster public assistance in meeting alternative policy goals. *Journal of Environmental Planning and Management* 63:1-31.

Rose, A., Z. Chen, D. Wei, D. F. Roberts, and A. Tucci. 2022, July 2. *Supply-chain impacts of the war in the Ukraine on world regions*. Paper presented at Annual Meetings of the Western Economic Association, Portland, OR.

Schoch-Spana, M., K. Gill, D. Hosangadi, C. Slemp, R. Burhans, J. Zeis, E. Carbone, and J. Links. 2019a. Top-down and bottom-up measurement to enhance community resilience to disasters. *American Journal of Public Health* 109(S4):S265-S267.

Schoch-Spana, M., K. Gill, D. Hosangadi, C. Slemp, R. Burhans, J. Zeis, E. G. Carbone, and J. Links. 2019b. The Copewell rubric: A self-assessment toolkit to strengthen community resilience to disasters. *International Journal of Environmental Research and Public Health* 16(13):2372.

ShelterBox. n.d. *Why disasters are not natural.* https://reliefweb.int/report/world/why-disasters-are-not-natural (accessed September 29, 2022).

Sherrieb, K., F. H. Norris, and S. Galea. 2010. Measuring capacities for community resilience. *Social Indicators Research* 99(2):227-247.

Siders, A. R. 2022. *Adaptive capacity for communities*. Paper presented at Committee on Hazard Mitigation and Resilience Applied Research Topics Workshop 2: Compounding and Cascading Events, Washington, DC, May 31, 2022.

Sprayberry, M. A. 2022. *Governance through mitigation, resiliency, and recovery programs*. Paper presented at Committee on Hazard Mitigation and Resilience Applied Research Topics Workshop 2: Compounding and Cascading Events, Washington, DC, May 31, 2022.

Subcommittee on Disaster Reduction. 2005. *Grand challenges for disaster reduction*. Washington, DC: National Science and Technology Council.

Sun, L., and L. Xue. 2020. Does non-destructive earthquake experience affect risk perception and motivate preparedness? *Journal of Contingencies and Crisis Management* 28(2):122-130.

Surminski, S., T. Tanner, and S. I. Publishing. 2016. *Realising the "triple dividend of resilience" a new business case for disaster risk management*. Geneva, Switzerland: Springer International Publishing.

Taleb, N. N. 2017. *The black swan: The impact of the highly improbable*. London: Taylor and Francis.

Talke, S. A., R. Familkhalili, and D. A. Jay. 2021. The influence of channel deepening on tides, river discharge effects, and storm surge. *Journal of Geophysical Research: Oceans* 126(5):e2020JC016328.

Thaler, R. H., and C. R. Sunstein. 2009. *Nudge: Improving decisions about health, wealth, and happiness*. New York: Penguin.

UNDRR (United Nations Office for Disaster Risk Reduction). 2020. *Annual report.* New York: United Nations.

van Straalen, F., F., T. Hartmann, and J. Sheehan. 2018. *Property rights and climate change: Land use under changing environmental conditions*. Abingdon-on-Thames, UK: Routledge.

Wahl, T. 2018. *Compound flooding: Examples, methods, and challenges*. Paper presented at SMA Speaker Series, NSI, Inc., Boston, MA, August 14, 2018.

Wahl, T., S. Jain, J. Bender, S. D. Meyers, and M. E. Luther. 2015. Increasing risk of compound flooding from storm surge and rainfall for major US cities. *Nature Climate Change* 5(12):1093-1097.

Wucker, M. 2016. *The gray rhino: How to recognize and act on the obvious dangers we ignore*. New York: St. Martin's Press.

Zaitchik, B. 2022. *Pandemic + [x]: What we've learned*. Paper presented at Committee on Hazard Mitigation and Resilience Applied Research Topics Workshop 2: Compounding and Cascading Events, Washington, DC, May 31, 2022.

Zscheischler, J., S. Westra, B. J. J. M. van den Hurk, S. I. Seneviratne, P. J. Ward, A. Pitman, A. AghaKouchak, D. N. Bresch, M. Leonard, T. Wahl, and X. Zhang. 2018. Future climate risk from compound events. *Nature Climate Change* 8(6):469-477.

APPENDIX A

COMMITTEE MEMBER BIOGRAPHICAL SKETCHES

Steve Moddemeyer (Chair) is principal for planning, sustainability, and resilience at 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. Mr. Moddemeyer works on climate change adaptation; sustainability strategies for large urban redevelopments; and advanced sustainability strategies for landowners, cities, counties, and utilities. He is a past member of the National Academies of Sciences, Engineering, and Medicine's Resilient America Roundtable (two terms). Additionally, he serves as advisor to the University of Washington Masters in Infrastructure Management and Planning; is a member of the International Union for the Conservation of Nature: Resilience Theme Group; and is a founding member of The Little Think Tank, a group of academic and policy experts who 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 socioecological principles to system, urban, and policy design, as well as industrial symbiosis development.

Christopher Todd Emrich is Boardman endowed associate professor of environmental science and public administration within the University of Central Florida's (UCF's) School of Public Administration and director of research in UCF's newly formed National Center for Integrated Coastal Research (UCF Coastal). His focus 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, Dr. Emrich 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. He is actively working at pinpointing challenges to equity in disaster recovery and mitigation; he has most recently assisted in conducting empirically based and result-oriented impacts assessments to inform recovery programs in several states and U.S. territories. Dr. Emrich 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. is dean of the College of Engineering at the University of Nevada, Reno (UNR). Before joining UNR in September 2022, he was George and Elizabeth Pickett endowed professor in industrial, manufacturing, and systems engineering at the University of Texas at Arlington. Dr. Jones 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 with the Jefferson Science Fellowship, through the National Academies of Sciences, Engineering, and Medicine, focusing on resilient supply chains. His industry background spans working as an engineer to an executive at Fortune 500 companies leading projects including ERP (enterprise resource planning) implementations, business process reengineering, and corporate mergers and acquisitions. Dr. Jones has produced four academic textbooks and more than 200 other publications; has advised 17 PhDs (7 from underrepresented groups); and has acquired funding from national agencies, including the National Aeronautics and Space Administration, the Department of Transportation, and the National Science Foundation. 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 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 is director of research at Physicians, Scientists, and Engineers for Healthy Energy (PSE), which she joined in 2013 to launch the organization's clean energy practice area. Her current work focuses on accelerating the transition to clean energy resources and developing transition pathways that realize non-energy co-benefits. Dr. Krieger 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. Dr. Krieger 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 is community resilience group leader and program manager in the Engineering Laboratory at the National Institute of Standards and Technology (NIST). She is also liaison for the Center for Risk-Based Community Resilience Planning (an NIST-funded center of excellence), led by Colorado State University. Dr. McAllister's research focuses 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. Dr. McAllister co-led detailed structural

analyses of the World Trade Center (WTC) towers and WTC 7 for the NIST World Trade Center Investigation, conducted reliability studies of levee systems for the U.S. Army Corps of Engineers following Hurricane Katrina, and evaluated Hurricane Sandy flood effects on infrastructure systems as part of the Federal Emergency Management Agency Mitigation Assessment Team. She 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 7 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 is 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 pioneered research on economic resilience at individual business/household, market/industry, and regional/national levels. He is currently principal investigator on a National Science Foundation grant on advanced computational methods for improving reliability and resilience of interdependent systems, as well as a contract with the Critical Infrastructure Resilience Institute to measure the cost-effectiveness of individual resilience tactics. Dr. Rose has authored 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 has received several honors and awards, including 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. Dr. Rose is also an elected fellow of the Regional Science Association International and has served on the National Academy of Sciences panels on Earthquake Resilience and Seismic Warning.

Stacy Swann is CEO and founding partner of Climate Finance Advisors, a benefit LLC based in Washington, DC, with expertise in banking, development finance, and climate change. She has

held senior positions with the International Finance Corporation, as well as the U.S. Department of Treasury, Enron Corporation, and other organizations. For more than 25 years, Ms. Swann 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 identifying, assessing, and managing climate risk. Additionally, Ms. Swann is currently 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. Ms. Swann 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 2: Compounding and Cascading Events

Tuesday, May 31, 2022
11:00 AM - 6:00 PM ET

11:00 am – 11:15 am	**Welcome** **Negin Sobhani**, Director, Science and Technology for Resilience, National Academy of Sciences **Steve Moddemeyer,** *Committee Chair,* Principal for Planning, Sustainability, and Resilience, CollinsWoerman Architects
11:15 am – 11:45 am	**Keynote** **Miguel O. Román**, Chief Climate Scientist, Leidos
11:45 am – 12:45 pm	**Panel 1: Toward a Better Understanding of Cascading and Compounding Disasters: Characterizing Drivers, Systems, and Relationships** **Ben Zaitchik,** Professor, Department of Earth & Planetary Sciences, Johns Hopkins University **Felicia Jefferson,** Associate Professor, Department of Biology, Fort Valley State University **Negar Elhami-Khorasani**, Associate Professor, Department of Civil, Structural and Environmental Engineering, University at Buffalo **Moderators**: **Chris Emrich**, *Committee Member*, Boardman Endowed Associate Professor of Environmental Science and Public Administration, University of Central Florida **Erick Jones**, *Committee Member*, George and Elizabeth Pickett Endowed Professor in Industrial, Manufacturing, and Systems Engineering, University of Texas Arlington; Jefferson Science Fellow, Office of the Chief Economist, U.S. Department of State
12:45 pm – 1:15 pm	**Break**

1:15 pm – 2:15 pm	**Panel 2: Governance Across Events: Decision Making and Policies** **Steven P. French,** Professor of City & Regional Planning, Georgia Tech **Kristen Averyt,** Senior Climate Advisor, Office of Nevada Governor Steve Sisolakto **Michael A. Sprayberry**, Senior Advisor for Emergency Management, Hagerty Consulting **Moderator**: **Terri McAllister**, *Committee Member*, Community Resilience Group Leader and Program Manager, National Institute of Standards and Technology
2:15 pm – 2:30 pm	**Break**
2:30 pm – 3:00 pm	**Keynote** **Susan Cutter**, Carolina Distinguished Professor, Director of the Hazards Vulnerability & Resilience Institute, University of South Carolina
3:00 pm – 4:00 pm	**Panel 3: Mitigating Impacts: Developing Solutions and Avoiding Unintended Consequences** **Hussam Mahmoud,** George T. Abell Professor of Infrastructure, Colorado State University **A.R. Siders**, Assistant Professor, Disaster Research Center, University of Delaware **Joshua DeFlorio,** Chief, Resilience & Sustainability/Port Authority of New York & New Jersey **Moderators**: **Elena Krieger**, *Committee Member*, Director of Research, Physicians, Scientists, and Engineers for Healthy Energy **Adam Rose**, *Committee Member*, Research Professor, Department of Public Policy; Senior Research Fellow, Center for Risk and Economic Analysis of Threats and Emergencies (CREATE), University of Southern California
4:00 pm – 4:30 pm	**Break**

4:30 pm – 5:45 pm	**Panel 4: Strategies to Effectively Apply Solutions** **Shanna N. McClain**, Disasters Program Manager, NASA Applied Sciences **Christopher Zobel**, R.B. Pamplin Professor of Business Information Technology, Pamplin College of Business, Virginia Tech **Lisa Churchill,** Principal, Climate Advisory **Gabi Brazzil,** Senior Equity Practitioner, Cofounder WSP Equity Center of Excellence **Moderators**: **Stacy Swann**, *Committee Member*, CEO, Climate Finance Advisors, BLLC
5:45 pm – 6:00 pm	**Recap and Closing** **Steve Moddemeyer**, *Committee Chair,* Principal for Planning, Sustainability, and Resilience, CollinsWoerman Architects

APPENDIX C

PANELIST BIOGRAPHICAL SKETCHES

Keynote

Miguel O. Román serves as senior director and chief scientist of climate and environment at Leidos. As part of the Leidos Civil Group, he is responsible for planning, leading, directing, and growing a portfolio of integrated mission capabilities, including earth-observing data and information systems, renewable energy, disaster resilience, and sustainable urban infrastructure. Dr. Román has served in multiple leadership, organizational management, and technical capacities across the federal government, academic, and nonprofit sectors. A leading expert in the field of satellite remote sensing, he has championed translational research, sustainability science, and data-intensive approaches to assessing and addressing climate-related risks. His work is recognized for shedding light on the disproportionate hardships experienced by socially vulnerable and underserved communities following major disasters. A native of San Juan, Puerto Rico, Dr. Román was recognized by President Barack Obama in 2016 with the Presidential Early Career Award for Scientists and Engineers (PECASE). He is also a 2014 Service to America Medal finalist, one of the highest honors for federal employees.

Panel 1: Toward a Better Understanding of Cascading and Compounding Disasters: Characterizing Drivers, Systems, and Relationships

Benjamin Zaitchik is professor in the Department of Earth and Planetary Sciences at Johns Hopkins University. He is an Earth scientist whose work includes study of fundamental atmospheric and hydrological processes, as well as application of this knowledge to problems of water resources, agriculture, and human health. In this context, he leads multiple projects focused on the propagation of climate stresses through complex coupled natural–human systems. Prior to joining Johns Hopkins, Dr. Zaitchik was a research associate at the National Aeronautics and Space Administration, and an American Association for the Advancement of Science Fellow at the U.S. Department of State. He is currently president of the GeoHealth Section of the American Geophysical Union; chair of the World Meteorological Organization Research Board Task Team on COVID-19 and climate, meteorological, and environmental factors; and a commissioner on the City of Baltimore Sustainability Commission.

Felicia Jefferson is a tenured associate professor within the University System of Georgia at Fort Valley State University. Her recent publications are in the areas of neurotoxicology, computer science, environmental biology, supply chain logistics in health, artificial intelligence in biology, CRISPR-Cas9 technology, remodeling of the CREST (coupled routing and excess

storage) model in health delivery mechanisms, and the role sleep plays in learning and memory. Dr. Jefferson has served as principal investigator (PI)on seven grants, five of which were federally funded garnering full overhead, and as co-PI on other several other grants. Funds from these grants advance scientific research, train students in technologies, and fund student participation in national conferences and other training opportunities. She was recently commissioned as lead author for a publication from the National Academies of Sciences, Engineering, and Medicine.

Negar Elhami-Khorasani is associate professor in the Department of Civil, Structural and Environmental Engineering at the University at Buffalo. Her primary areas of research are performance-based design and resilience assessment of structures and communities under extreme hazards, including structure fires, wildfires, earthquakes, and cascading multihazard events, such as post-earthquake fires. The outcomes of her research enhance safety by developing codes and guidelines, and minimize losses by optimizing mitigation, preparedness, and response strategies. Dr. Elhami-Khorasani is co-chair of the American Society of Civil Engineering/Structural Engineering Institute (ASCE/SEI) Fire Protection Committee and led the Fire Following Earthquake Task Group in charge of publishing a book on procedures for analysis of buildings for post-earthquake fires. She serves as associate editor for *Fire Technology* by Springer Nature. She is also a member of the resilience committees for fib (International Federation for Structural Concrete), International Association for Fire Safety Science, and the Structural Engineers Association of New York. Dr. Elhami-Khorasani received the 2020 American Institute of Steel Construction Early Career Faculty Award and the Fire Protection Research Foundation Medal. Her research has been funded by the National Science Foundation, Department of Transportation, U.S. Geological Survey, National Fire Protection Association, and ASCE SEI.

Panel 2: Governance Across Events: Decision Making and Policies

Kristen Averyt is senior climate advisor in the Office of Nevada Governor Steve Sisolak, where she leads climate planning and policy development for the state. She is also research professor at the University of Nevada, Las Vegas, and previously served as president of the Desert Research Institute. Her expertise covers a range of issues including climate change, water resources in the western United States, and the energy–water nexus. Dr. Averyt has a long record connecting science with public policy. She worked in the U.S. Senate as a National Oceanic and Atmospheric Association Knauss fellow and at the National Academies of Sciences, Engineering, and Medicine as a Christine Mirzayan science and technology policy fellow. As a member of the Intergovernmental Panel on Climate Change Working Group I Support Unit, Dr. Averyt was one of many scientists who shared in the 2007 Nobel Peace Prize. Of her honors, she is most proud of the Girls Scouts of the Sierra Nevada Award for Environmental Leadership. She

was recently elected to the American Meteorological Society (AMS) Council, is a senior policy fellow of the AMS, and engages in many other service and board activities.

Michael A. Sprayberry is senior advisor for emergency management at Hagerty Consulting. A proven leader and emergency manager with a career of public service spanning 42 years, Mr. Sprayberry served the Division of Emergency Management in the State of North Carolina for more than 15 years in various leadership roles, including as division director and deputy homeland security advisor, as well as leading the state's Office of Recovery and Resiliency. During his tenure as director, Mr. Sprayberry led the State Emergency Response Team's response and recovery efforts for 19 state-declared disasters and 13 federally declared disasters, including Hurricane Florence, now known as North Carolina's "Storm of Record." As director, he also served as vice chair of the state's Emergency Response Commission and as a member of the state's Radiation Protection Commission. In the last 4 years, Mr. Sprayberry has led North Carolina's recovery efforts from major hurricanes, winter storms, earthquakes, and the COVID-19 pandemic. Additionally, Mr. Sprayberry served as president of the National Emergency Management Association from 2017 to 2018. He has received numerous awards, including two departmental Secretary's Gold Circle Awards and the North Carolina Emergency Management Association Colonel William A. Thompson Award for Outstanding Achievement in Emergency Management. Before joining state government, Mr. Sprayberry honorably served in the United States Marine Corps and North Carolina Army National Guard for more than 25 years; he is a proud member of the North Carolina National Guard Officer Candidate School Hall of Fame.

Steven P. French is professor of city and regional planning at Georgia Institute of Technology, where he focuses on sustainable urban development, natural hazard risk assessment, and urban information systems. Dr. French has been principal investigator or co–principal investigator on more than 70 research projects, and is the author or coauthor of 4 books and more than 25 refereed journal articles. He has served on the editorial boards of the *Journal of the American Planning Association*, *Journal of Planning Education and Research*, *Journal of the Urban and Regional Information Systems Association*, and *Earthquake Spectra*. Dr. French has served as visiting professor of resources planning in the Civil Engineering Department at Stanford University and is a fellow of the American Institute of Certified Planners.

Keynote

Susan Cutter is Carolina distinguished professor of geography at the University of South Carolina, where she directs the Hazards & Vulnerability Research Institute. Her primary research interests are in the area of disaster vulnerability and resilience science, including how vulnerability and resilience are measured, monitored, and assessed. She has authored or edited 14 books—mostly recently, *Hurricane Katrina and the Forgotten Coast of Mississippi*, published

by Cambridge University Press—and more than 150 peer-reviewed articles and book chapters. Dr. Cutter has mentored more than 50 masters and doctoral students and has led field teams to study long-term recovery from hurricanes Katrina, Sandy, and Matthew, as well as the October 2015 South Carolina floods. She has provided expert testimony to Congress on hazards and vulnerability, was a member of the U.S. Army Corps of Engineers Interagency Performance Evaluation Task Force team that evaluated the social impacts of the New Orleans and Southeast Louisiana Hurricane Protection System in response to Hurricane Katrina, and was a juror for the Rebuild by Design competition for Hurricane Sandy reconstruction. Her policy-relevant work has received funding from the National Science Foundation (NSF), the U.S. Army Corps of Engineers, and many other state and national agencies. Dr. Cutter serves on many national advisory boards and committees, including those of NSF and the National Institute of Standards and Technology. She chaired the National Academies of Sciences, Engineering, and Medicine committee that authored the 2012 seminal report, *Disaster Resilience: A National Imperative*. Dr. Cutter serves as coexecutive editor of *Environment* and associate editor of *Weather, Climate, and Society*, and is a member of several boards, including the advisory board of the *Journal of Extreme Events* and the editorial board for *Natural Hazards*. She is also serving as editor-in-chief for the *Oxford Research Encyclopedia of Natural Hazard Science*. Dr. Cutter is an elected fellow of the American Association for the Advancement of Science, and is past president of the Association of American Geographers and of the Consortium of Social Science Associations. She held the MunichRe Foundation chair on social vulnerability through the United Nations University Institute for Environment and Human Security, and received the Decade of Behavior Research Award. In 2010, Dr. Cutter received the Lifetime Achievement Award from the Association of American Geographers. And, in 2015, she was awarded an honorary doctorate from the Norwegian University of Science and Technology in Trondheim, Norway, and was elected as a foreign member of the Royal Norwegian Society of Sciences and Letters.

Panel 3: Mitigating Impacts: Developing Solutions and Avoiding Unintended Consequences

A.R. Siders is assistant professor at the University of Delaware in the Disaster Research Center, the Biden School of Public Policy and Administration, and the department of Geography and Spatial Sciences in the College of Earth, Ocean, and Environment. Previously, she served as an environmental fellow at the Harvard University Center for the Environment, a legal fellow at the Sabin Center for Climate Change Law at Columbia University, and a presidential management fellow with the U.S. Navy. Her research focuses on climate change adaptation decision making and evaluation: how and why communities decide when, where, and how to adapt to the effects of climate change and how these decisions and decision-making processes affect outcomes such as risk reduction and equity. Her current projects focus on adaptive capacity, managed retreat, and adaptation equity. Ms. Siders believes adaptation is opportunity and that ambition, if not audacity, is necessary in dreaming of and planning for a better future.

Hussam Mahmoud is George T. Abell professor in infrastructure in the Department of Civil and Environmental Engineering at Colorado State University (CSU) and is director of the Structural Laboratory. Previously, he served as manager of the National Council of Examiners for Engineering and Surveying's Earthquake Laboratory at the University of Illinois Urbana-Champaign (UIUC). Prior to arriving at UIUC, he was a research scientist at Lehigh University, working on assessment and repair of deteriorated infrastructure. Dr. Mahmoud's research program has three major thrusts: assessing community resilience and recovery of infrastructure and socioeconomic institutions following extreme events with a focus on climate-driven hazards; quantifying building damage to extreme single and multiple hazards; and evaluating deteriorated infrastructure, such as bridges and underwater systems. He has authored more than 250 publications and has given more than 100 presentations including 70 invited talks at national and international conferences. Dr. Mahmoud has chaired and served on numerous technical committees, including the American Society of Civil Engineers committees on fire protection and on multihazard mitigation. His research has received media coverage through citations and interviews in numerous venues, including *Nature Climate Change*, *Smithsonian Magazine*, *The Independent*, *Business Insider*, and CNN.

Joshua DeFlorio is chief of resilience and sustainability at the Port Authority of New York and New Jersey (PANYNJ). He leads a team that focuses on ensuring that the aviation, port, urban rail, tunnel, bridge, terminal, and real estate facilities called for in the agency's capital plan are designed and delivered to be both environmentally sustainable and climate resilient. Prior to joining PANYNJ, Mr. DeFlorio was national practice lead for risk and resilience at Cambridge Systematics and served as a senior project manager in the New York City Economic Development Corporation's Ports & Transportation group. He is a chapter author on the Fifth National Climate Assessment and serves as a member of the New Jersey Interagency Council on Climate Resilience, created by Governor Murphy.

Panel 4: Strategies to Effectively Apply Solutions

Christopher Zobel is R. B. Pamplin professor of business information technology in the Pamplin College of Business at the Virginia Polytechnic Institute and State University. His primary research interests include disaster operations management and humanitarian supply chain resilience. Dr. Zobel has published more than 100 articles in archival journals and academic conference proceedings, and his work can be found in outlets such as the *Journal of Operations Management*, *Production and Operations Management*, *Risk Analysis*, *Decision Sciences*, and the *European Journal of Operational Research*. He is currently co–principal investigator on several National Science Foundation (NSF) grants that involve characterizing and quantifying multidimensional disaster resilience. Dr. Zobel is also one of the founding faculty

members of the NSF research traineeship graduate program on disaster resilience and risk management, located in the Center for Coastal Studies at Virginia Tech.

Gabrielle Brazzil is senior equity practitioner, project manager, and cofounder of the Equity Center of Excellence with WSP, a global engineering consulting firm. She specializes in equity services for public projects, supporting public agencies in developing operational and cultural practices to adopt and sustain equity, and project delivery services to guide equity goals and outcomes. Ms. Brazzil's experience spans transportation, housing, and water projects through work with Bay Area Rapid Transit, Caltrans, Southern California Area Council of Governments, and city departments of public works and power and water nationally. She trains and collaborates with technical experts and decision makers to integrate equity into funding prioritization, data analysis, scenario development, and public engagement. In 2021, Ms. Brazzil was honored with the Emerging Leader of the Year Award from the Conference of Minority Transportation Officials (COMTO). She is vice president of the Northern California chapter of COMTO, advancing opportunities for people of color in the industry and awarding scholarships to underrepresented students to usher in new, representative talent. She also serves as equity chair on the Transport Oakland board, a policy advocacy organization in her home base of Oakland, California.

Lisa Churchill is a climate change expert and founder of Climate Advisory, a certified women's business enterprise that focuses on climate risk and resilience strategies. She has 25 years of experience in the engineering and architectural fields, and deep expertise in leading climate resilience initiatives for public- and private-sector clients. Ms. Churchill has worked with numerous municipalities, ranging from larger urban areas, such as Washington, DC, and Boston, Massachusetts; large asset owners and operators (Massachusetts Bay Transportation Authority, Logan International Airport, Mass General Brigham); and private clients (real estate investment trusts and tech companies); as well as smaller communities and nonprofits. She has presented on climate at a congressional briefing and at the Pentagon, has taught classes at the Massachusetts Institute of Technology and University of New Hampshire, is a regular contributor to industry-leading research, and has been an invited speaker at national and international forums on climate resilience. Her training as a paleontologist with a focus on mass extinctions has given her a unique perspective on the characteristics of resilient systems. Ms. Churchill is also coeditor of *Climate Change and the Built Environment*, published in 2022 by the American Council of Engineering Companies, which outlines key trends and emerging innovations in the field.

Shanna McClain is disasters program manager for the Applied Sciences Division at the National Aeronautics and Space Administration (NASA). She also manages NASA's Global Partnerships portfolio and the Socioeconomic Assessments Initiative. Prior to working at NASA, Dr. McClain worked as a visiting scientist with the Environmental Law Institute on issues relating to environmental migration, displacement, conflict, and peacebuilding. She also worked

for the joint United Nations Environment Programme/Office for the Coordination of Humanitarian Affairs Environmental Emergencies Section on issues relating to complex, cascading, and protracted disasters and crises. Her graduate research was focused on the integration of climate change adaptation, disaster preparedness and response, and resilience into multilevel governance frameworks of international river basins.

APPENDIX D
DISCUSSION QUESTIONS FOR WORKSHOP PANELISTS

Keynotes

- What steps can government leaders take to move America beyond sequentially named disaster responses with slow, inequitable outcomes to a forward-leaning state and federal approach to compound disasters that prioritizes and funds recovery designed to increase the capacity of local governments and communities to be resilient?
- Poor land use decision making putting residents in harm's way, systemic racism, and economic bifurcation can burden communities with trauma on trauma. Trust suffers as people who try to do everything right remain vulnerable to danger and life-altering shocks. Can trust be earned through a comprehensive approach to compound disasters?

Panel 1: Toward a Better Understanding of Cascading and Compounding Disasters: Characterizing Drivers, Systems, and Relationships

- What are some mechanisms, methods or approaches to identify how disastrous events further exacerbate difficult conditions (e.g., COVID-19 pandemic that minimized the number of rescue workers available after floods)?
- How can identifying these cascading disasters make federal agency, private industry, and community support more effective (e.g., Investing in providing vaccines to emergency workers first, then deploying them to support flood activities)?
- How can a systems approach support more effective support to communities after disasters (i.e., Focusing on how a system can support a community not only after a disaster but making it more prepared for common disastrous events with the capacity to handle additional challenging conditions)?

Panel 2: Governance Across Events: Decision Making and Policies

- Cascading events require significantly more coordination across a wide range of public and private organizations and federal, state, and local agencies. Are there significant differences in risk perceptions or time horizons for risk management?
- Are there additional communication and coordination mechanisms between state, federal and local government agencies that would improve the timeliness and effectiveness of response and recovery?
- Are there significant gaps between the roles of federal, state, and local governments relative to their capacity and capabilities?
- What changes would have the largest impact on improving coordination among the complex mix of public and private actors? This could include changes to roles and responsibilities, insurance mechanisms and coverage, streamlined funding processes, and improved bases for decision making before and after disruptive events.
- What incentives could be used to encourage better coordination?

Panel 3: Mitigating Impacts: Developing Solutions and Avoiding Unintended Consequences

Strategies and investments to improve services and functions, including access and equity, to achieve resilient infrastructure for compounding and cascading extreme events.

- How can we best intercede on both short and long timescales to prevent hazards from cascading further?
- What strategies can best help reduce losses from a broad range of hazards likely to be compounding or cascading, so as to avoid duplication of effort?
- What are the major issues associated with sequencing recovery from cascading hazards?

Challenges and opportunities within these strategies and investments that may benefit from further investigation and research to facilitate better outcomes.

- How do we assess and address cumulative socioeconomic burdens and lack of human adaptive capacity in the face of compounding and cascading disasters?
- How can we improve our ability to evaluate equity and social justice of mitigation and resilience strategies for compound and cascading hazards?
- How can we encourage cooperation among communities to avoid disasters in one community from spilling over into another?
- What data are missing, what methods need to be developed, and what other applied research topics need investigation to better prepare for and respond to compounding and cascading disasters?

Panel 4: Strategies to Effectively Apply Solutions

- Climate change has the ability to both accelerate and amplify the breakdown of a number of systems—community systems, infrastructure systems, financial systems, and of course physical/environmental systems. However, solutions to address "resilience" are often thought about in the context of those specific topics—e.g., "community resilience," "financial resilience," "resilience in the face of a changing climate."
- Given your experience, how would you best think about strategies to apply solutions that are more cross-cutting (vs. specific to one type of "system") to increase the potential impact of those solutions?
- What would be, in your view, the most inclusive, representative, collection of stakeholders to address the widest possible range of systemic issues brought about by climate change? Said a different way: how can you bring together the most comprehensive set of stakeholders to build in resilience at the community level? Have you seen examples of this, and if so what worked and what didn't?
- What has been the most common oversight in your mind in addressing community resilience?