Fifth National Climate Assessment: Chapter 18

Sector Interactions, Multiple Stressors, and Complex Systems

Chapter 18. Sector Interactions, Multiple Stressors, and Complex Systems

Authors and Contributors

Federal Coordinating Lead Author

Robert Vallario, US Department of Energy

Chapter Lead Author

Katharine J. Mach, University of Miami

Chapter Authors

Jeffrey R. Arnold, MITRE Corporation

Christa Brelsford, Oak Ridge National Laboratory

Katherine V. Calvin, Pacific Northwest National Laboratory (through January 2022)

Alejandro N. Flores, Boise State University

Jing Gao, University of Delaware

Kripa Jagannathan, Lawrence Berkeley National Laboratory

David Judi, Pacific Northwest National Laboratory

Carlos E. Martín, Brookings Institution

Frances C. Moore, University of California, Davis (through August 2022)

Richard Moss, Pacific Northwest National Laboratory, Joint Global Change Research Institute (through April 2023)

Earthea Nance, Texas Southern University (through December 2021)

Brenda Rashleigh, US Environmental Protection Agency

Patrick M. Reed, Cornell University

Linda Shi, Cornell University

Lynée L. Turek-Hankins, University of Miami

Review Editor

David L. McCollum, Oak Ridge National Laboratory

Cover Art

Carolina Aragon

Recommended Citation

Mach, K.J., R. Vallario, J.R. Arnold, C. Brelsford, K.V. Calvin, A.N. Flores, J. Gao, K. Jagannathan, D. Judi, C.E. Martín, F.C. Moore, R. Moss, E. Nance, B. Rashleigh, P.M. Reed, L. Shi, and L.L. Turek-Hankins, 2023: Ch. 18. Sector interactions, multiple stressors, and complex systems. In: *Fifth National Climate Assessment*. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.CH18

Table of Contents

Introduction

The Fifth National Climate Assessment assesses the many ways climate change affects people, nature, and infrastructure across the Nation and around the world. The chapters are divided up by sectors and topics, such as water (Ch. 4), food (Ch. 11), economics (Ch. 19), and social justice (Ch. 20). They are also organized by region, from the Northeast (Ch. 21) to Hawai'i and the US-Affiliated Pacific Islands (Ch. 30).

But in reality, the impacts and risks of climate change unfold across interacting sectors and regions. For example, a forest fire in one region (Ch. 7) can affect air quality (Ch. 14) and human health (Ch. 15) in other regions as well (Chs. 21–30), depending on where winds blow. Further, climate-related hazards interact with multiple stressors that might seem like they have nothing to do with climate change, such as the COVID-19 pandemic, economic recessions, or social inequities. For instance, different households with different levels of wealth can have very different capacities to evacuate in advance of a hurricane or recover if their homes are damaged (Chs. 9, 20, 22, 23).

As a result, if the perspective of only a single sector, topic, or region were considered, many climate impacts might be missed or overlooked. The consequences of climate change would be unexpected and surprising. And at the same time, the prospects for climate responses, whether through adaptation or mitigation, also fundamentally depend on these same interactions across sectors and regions. For example, using water (Ch. 4) for hydropower (Ch. 5) can impact fish in rivers (Ch. 8), as well as water supply for agriculture in rural communities (Ch. 11) and residential use in big cities (Ch. 12). Without considering such types of interactions, climate responses will be less effective, and there could be missed opportunities.

This chapter is about these deep connections inherent to climate impacts, risks, and responses. The chapter considers these interactions and interdependencies across sectors and regions as complex systems that can lead to cascading impacts and sudden failures, as well as sometimes surprising potential for reducing our emissions of heat-trapping gases and preparing for climate risks that can't be avoided.

The chapter is organized as follows. First, it introduces what we know about complex systems and explains how complex systems—involving interactions across sectors and regions—can lead to climate impacts that happen faster than expected or can limit future options (KM 18.1). Second, the chapter assesses how complex, interacting climate impacts and responses can be most stressful for overburdened communities (KM 18.2). Third, the chapter evaluates how collaborative approaches to generating knowledge about complex systems can lead to better climate responses (KM 18.3). Finally, the chapter considers the degree to which current governance approaches are adequately prepared to handle the complexity of climate change (KM 18.4).

Key Message 18.1

Human–Nature Interconnections Create Unexpected Climate Risks and Opportunities

Human–natural systems are dynamic and complex. Interconnected networks of people, infrastructure, commodities, goods, and services influence changing climate risks and are increasingly vulnerable to their impacts (*high confidence*). The vulnerabilities in these networks, and their effects on human–natural systems, strongly depend on human responses and other compounding stressors (*high confidence*). Decision-makers seeking to reduce climate change risks have to navigate diverse and sometimes competing objectives and perspectives across many actors, institutions, and geographic scales while reconciling deep uncertainties and limits to predictability (*high confidence*).

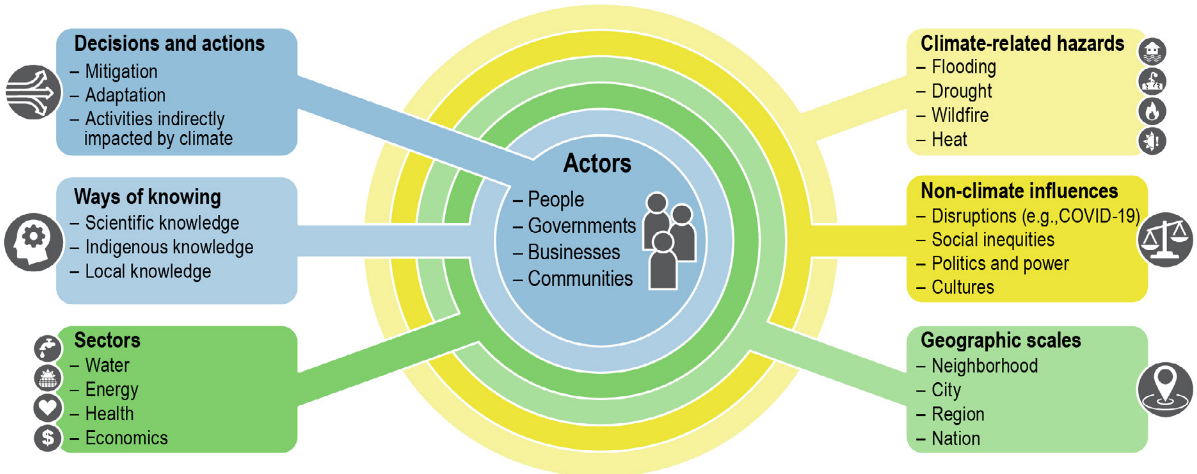
In a changing climate, interconnections among human and natural systems give rise to both successes and failures. For example, power systems can fail if exposed to extreme wind or extreme heat (KM 5.2). When they fail, transportation, water and wastewater treatment, telecommunications, health services, and many other economic activities are also disrupted (KM 19.3).[1,2] The interactions among people, systems (e.g., networks, nature), and sectors thereby transmit opportunities and risks from one to another (e.g., KM 27.4), such as from the power system to the transportation system. These interactions lead to new risks and can both increase and limit existing threats.[3,4,5,6] Figure 18.1 shows six interconnected and overlapping features of human–natural systems; each of these features contributes to the complexity of the systems and influences the effectiveness of climate mitigation and adaptation actions. Box 18.1 illustrates these types of interactions through a specific example, data centers.

Climate change makes the existing interconnections between human and natural systems more important for two reasons. First, many human and natural systems have conditions in which a small shock or change can produce very large impacts, but these conditions are rarely known in advance.[7] For example, the winter storm in Texas in February 2021 was a relatively brief 10-day shock of extreme cold weather, but it caused cascading failures across many sectors (e.g., energy, water, health), as well as fatalities and long-lived economic impacts for the region and for individuals.[8] There is evidence that warming in the polar north can increase the potential for these types of winter storm shocks in the US.[9] Second, climate change puts natural systems into fundamentally new conditions, so there is a greater chance of experiencing these large potentially negative impacts. Climate change–driven aridification of the American Southwest is an example of a fundamental change that has resulted in more persistent and severe heat as well as drought extremes. The consequences of this fundamental change are complex, increasing the potential for compounding and cascading impacts. These effects include simultaneous increases in the potential risks for human health, disruptions to critical transportation services, stress on power systems, and water scarcity conflicts across regions and sectors.[10,11] The overall risk of bad outcomes increases, and the sources of risk are more complex. There has been substantial progress in the study of complex, adaptive human–natural systems.[3,12,13,14,15,16,17,18] Innovations across many disciplines are helping to address interconnected risks.[19,20,21,22,23,24,25,26] Further, climate mitigation and adaptation actions depend on one another and interact. They both require resilience to intensifying and increasingly complex mixtures of future influences, shocks, and hazards. Figure 18.1 shows how these future influences can be climate-related hazards, such as floods, droughts, or wildfires; environmental shifts, such as changes in forest composition; or social trends or disruptions, such as from changes in economies, political contexts, cultures, or disease.[2,5,12,16,22,23,26,27,28,29] Mitigation and adaptation involve major changes to human–natural systems with global to local implications (KMs 31.1, 32.5). They can create fundamental shifts in supply chains, consumption patterns, technologies, and competition over constrained natural resources (also see Focus on Risks to Supply Chains).[13,27,30,31,32,33,34] These changes are expected to continue to have disproportionate impacts on exposed populations and ecosystems (KMs 4.2, 5.2, 8.3, 9.3, 15.2).

There are therefore trade-offs, linked benefits, and dependencies among energy transitions, adaptation actions, and sustainability goals (KMs 17.4, 25.4, 31.3, 32.2).[12,15,19,22,28,35,36,37,38,39,40] For example, an increased supply of clean energy helps power air-conditioning to keep homes cool under intensifying heat while also ensuring that this increased energy usage does not cause emissions of heat-trapping gases. This situation also has implications for social equity and justice, as poverty reduction and improved energy security are needed for all households to afford adequate air-conditioning. These interactions demonstrate the importance of accounting for diverse forms of knowledge, social and institutional power dynamics, and justice in navigating risks, challenges, and benefits of interventions and policies (Figure 18.1; KMs 16.3, 17.4, 20.1, 31.3).[31,41,42,43] Recent advances offer promise for assessing risk–benefit trade-offs, interconnections, and sequences of action or inaction across scales.[44,45,46,47] However, rapidly changing human systems, their multisectoral dynamics, and their interconnections with natural systems create deeply uncertain futures. Many futures are possible, and there is disagreement on how probable they are or how they may shape different human–natural systems' responses. Therefore, significant challenges remain for measuring risk–benefit trade-offs when evaluating potential actions.[48,49,50,51]

Recognition of these deep uncertainties and the difficulties in predicting complex interconnections among human and natural systems over long time periods has led to an approach called exploratory systems modeling.[52,53,54] This approach considers diverse scientific perspectives and uses scenarios to better understand a wide array of possible future outcomes. For example, scenarios can examine the consequences of extreme weather conditions that have never previously happened but may happen under a future climate. The approach aims to discover what future conditions, actions, and outcomes are the most consequential.[45,47,55,56,57] Capital investments associated with new energy sources and climate adaptation are both expensive and long-lived. Exploratory modeling of benefits and impacts of these investments can help avoid the unintended amplification of risks and increase future resilience. Exploratory modeling can support adaptation planning by providing a wider array of futures, such as for coastal systems under sea level rise,[58] and by more clearly identifying responses as they occur among interconnected, complex human and natural systems.

Interacting and Overlapping Features of Human–Natural Systems



Climate-related experiences and actions connect with many other activities and contexts.

Figure 18.1. Interacting and overlapping features of human–natural systems shape actors' capacities to respond to climate change. The effectiveness of decisions and actions—taken or not (teal center of the figure)—is shaped by multiple other features (outer rings). Ways of knowing (light blue ring), such as local, Indigenous, or scientific knowledge, are a foundation that determines how climate risks and responses are perceived and understood. Moving outward, interactions across sectors (e.g., water and energy) and geographic scales (e.g., from local neighborhoods to the Nation as a whole) determine risks and responses under both climate-related hazards (e.g., flooding, drought, wildfire, and heat) and non-climate influences (e.g., social inequities and cultures). Ultimately, these features together define the complexity inherent to climate risks and responses. Adapted from Brelsford and Jones 2021.[59]

Box 18.1. Data Centers Create a Critical New Interconnection Between Energy, Water, and the Economy

Data centers are buildings that house large computer systems that support online activities and much of the US economy. There has been rapid growth in the number and size of data centers as the national economy has shifted toward digital communication and activities. Although water and energy use of individual data centers can be difficult to measure precisely,[60] their water and energy footprint is large—accounting for 1.8% of total US electricity usage and 510 million cubic meters of water in 2018—and is an increasing focus of research.[61,62,63] The siting of data centers is a complex problem, influenced by local and state government incentives as well as by land, energy, and water availability to support cooling, such as in climates favoring evaporative cooling. The future demand for data centers, together with their needs for water and energy and their influence on linked water–energy–land systems, will vary considerably geographically.[62] Given that data centers depend on both water and energy and are themselves infrastructure critical for the functioning of the economy, data centers create a new interconnection between energy, water, and the economy.

In the western US, where arid climates are favorable to the evaporative cooling often sought out for data center operations, water and land are inextricably linked through prior-appropriation water law (KM 28.1).[64] As a result, securing adequate supplies of water to support data center demands can become a complex and potentially contentious exercise in acquiring agricultural land and fallowing it, a process that is dependent on state laws governing the transfer of water rights. Moreover, the increasing potential for large-scale, long-term droughts in the western US could lead to unanticipated events (KMs 4.1, 6.1, 28.3). For example, increasingly heavy base-load water consumers such as data centers may make the water system less able to adapt to drought through short-term conservation. Increasing attention to the environmental footprints of new data center projects in the western US potentially signals a new interconnection and potential point of conflict between economic sectors (KM 6.3), such as technological industries versus agriculture.

Key Message 18.2

Complex Climate Impacts and Responses Further Burden Frontline Communities

Compounding and cascading interactions among sectors, hazards, and geographies magnify the impact of climate change and societal responses for already-overburdened groups (*high confidence*). However, social vulnerability assessments tend to evaluate risks and impacts by sector, hazard, or jurisdiction, and most complex-systems models do not yet account for social and political dynamics (*high confidence*). Data about how complex systems affect frontline communities under climate change are severely lacking, especially for hard-to-reach populations, and this can lead to disproportionate risks and impacts for these groups (*high confidence*).

The complex systems described in KM 18.1 can create cascading and compounding climate impacts that particularly affect people and communities with little flexibility to absorb additional stress. This includes smaller and more rural communities, lower-income households, racialized minorities, people with health conditions and disabilities, pregnant people, caregivers, young children, and older adults (KMs 4.2, 15.2, 16.2).[18,65,66,67,68,69,70,71] The combination of complex societal factors (Figure 18.1) with people's multiple roles and identities shapes their lived experiences of multiple shocks and stressors (Figure 18.2).[72,73,74] It is not an accident that access to land, housing, infrastructure, food, and water in the US is highly unequal.[67,75] Within a context of institutionalized inequality and uneven access to safe housing and quality infrastructure, new and conflicting private- and public-sector responses to complex climatic and non-climate events often reinforce existing inequities.[18] At the same time, each person carries multiple identities and plays multiple roles, creating intersectional vulnerabilities that can intensify direct impacts of climate change and indirect impacts of climate actions by more privileged groups. For instance, in rural Alaska, climate change is rendering more difficult the lives of Iñupiat women as they care for multiple generations, maintain land-based food and cultural systems, and endure gender-based violence,[76] while young, single men working in the oil and gas industry are experiencing the energy transition very differently.

Increased exposure to flooding provides an example of how compounding and cascading interactions and intersectional vulnerabilities can amplify harm in already-burdened communities. Legacies of inequitable access to residential home loans, municipal incorporation to isolate wealth in suburbs, and infrastructure investments that privileged certain neighborhoods and municipalities over others have concentrated low-income people, African Americans, and other frontline communities in places with high flood risk.[77,78,79,80] Federal flood risk response programs privilege predominantly White and wealthier communities by giving them more funding for levees or seawalls.[81] These measures worsen downstream or down-coast flooding in places that might not be able to afford such infrastructure.[80] Federal programs also disproportionately fund predominantly White communities to voluntarily relocate from floodplains (Figure 20.3),[82,83,84] while low-income people, including renters, receive less assistance and have to move farther away to places with fewer amenities.[85] Box 18.2 shows a different example of how cascading and compounding events can worsen long-standing inequities. It discusses how a wildfire exacerbated social conflict over land, housing, and infrastructure in California. Accordingly, people's cumulative vulnerability can be understood and addressed only through multiple scales of analysis (e.g., Turek-Hankins et al. 2020[86]) and through integrated strategies for housing, planning, social services, lending, and racial justice.

Models of how climate impacts affect complex systems and how societies can respond usually do not account for people's diverse roles, identities, and lived experiences nor the social, political, and governance characteristics of decision-making.[3,87,88,89,90] For example, political polarization, in addition to structural inequities, increasingly shapes individual and government responses to disasters and long-term planning.[91,92] This can lead to a patchwork of mitigation and adaptation efforts across a region, which can weaken overall system function.[93,94,95] Data gaps exacerbate the modeling uncertainties described in Key Message 18.1, especially for smaller, less studied urban, suburban, and rural areas and Indigenous communities (KMs 11.3, 16.2).[69,96,97] Research on the linkages between places, such as how impacts on agriculture systems affect urban food security, migration, and housing demand, is also limited (KM 11.2).[98] The absence of research on the lived experiences, climate impacts and risks, and implementation outcomes for overburdened communities often leads to their underrepresentation in decision-making.[99] Accounting for people's diverse roles and identities, modeling social and political responses to climate change, and improving data availability can improve the modeling of complex systems and the inclusivity of decision-making tools.

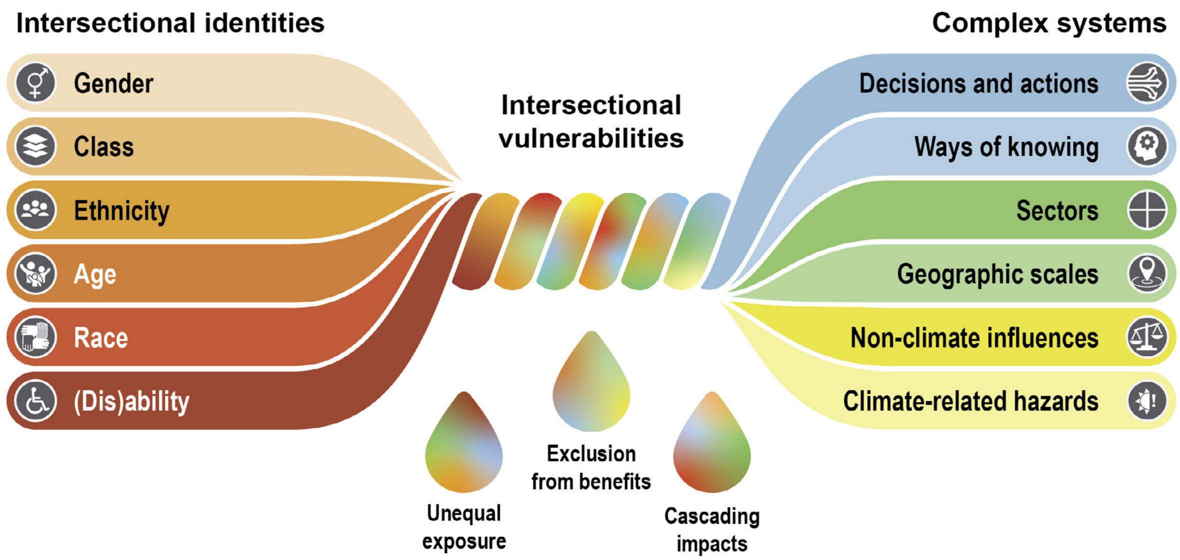
Box 18.2. Wildfire and COVID-19 Lead to Compounding and Cascading Impacts over Time

Disasters can trigger compounding and cascading effects on displacement. While research has focused on flood-driven displacement in the US,[100,101] other hazards are also intensifying migration pressures (see Figure 20.5). The Camp Fire, which devastated Paradise and surrounding Northern California communities in November 2018, illustrates how climate migration can trigger cascading impacts in places receiving displaced persons (KM 28.4). The Camp Fire killed 85 people, destroyed roughly 19,000 buildings, and displaced more than 50,000 people.[102,103] Many evacuees fled to the nearby city of Chico, which swelled from 93,000 to more than 111,000 people.[104] Chico Police Chief Michael O'Brien said, "You normally would have a decade to prepare for such growth. We had about 10 hours."[102]

In-migration increased traffic by 25%, sewage inflows by 16%, and annual sewage treatment costs by more than $725,000 (in 2022 dollars). It also turned Chico into America's hottest real estate market.[102,105] Telecommuters fleeing the Bay Area during the COVID-19 pandemic further fueled Chico's housing affordability crisis. Even before 2018, only 1.5% of housing starts were affordable to people with very low incomes, and the vacancy rate was less than 1%.[106,107] A political action committee stoked fears around skyrocketing housing prices, new homeless encampments, and crime and drugs to shift the city council from predominantly liberal to conservative. Housing policy began to emphasize evictions and criminalizing unsheltered "vagrants," creating significantly greater risks and impacts for Indigenous Peoples, who are disproportionately represented among the unsheltered.[106]

Since then, climate change, worsening air quality due to subsequent wildfire seasons (Figure 14.3), housing unaffordability, the COVID-19 pandemic, and the shift to teleworking are fueling migration in California from rural to urban areas, from smaller to larger cities, and from coastal cities to more affordable and scenic suburban and rural areas.[108,109,110,111] Across the country, most cities' climate vulnerability and risk assessments focus on future climate impacts to current populations without considering disasters taking place elsewhere that could affect their outlook.[112] Models and assessment tools that account for cascading impacts, especially those conducted at regional scales, can help steer or anticipate the effects of climate-exacerbated migration (e.g., Zoraghein and O'Neill 2020[113]). In addition, national and regional climate-migration and housing-resource models can help inform national and local government infrastructure, land use, and housing decisions.

Intersectional Vulnerabilities



Intersecting social and environmental factors privilege some people's ability to respond to climate change.

Figure 18.2. Climate impacts and societal responses exacerbate intersectional vulnerabilities. People's gender, class, ethnicity, age, race, and ability form their intersectional identity (left). Intersectional vulnerabilities emerge when intersectional identities interact with inequities in complex systems, as outlined in Figure 18.1 (right). In the face of climate risks and responses, these intersectional vulnerabilities can result in unequal exposure, exclusion from benefits, and cascading impacts that further impact already-overburdened groups. Societal responses to climate change—including uneven existing resources across municipalities, decisions about where to allocate investments, and noninclusive ways of knowing—can exacerbate existing harms and generate new ones. Adapted with permission from Box TS.4, Figure 1 of Field et al. 2014.[114]

Key Message 18.3

Collaborations Among Diverse Knowledge Holders Improve Responses to Complex Climate Challenges

Responding effectively to complex climate challenges benefits from integrated frameworks and modeling approaches that incorporate diverse types of knowledges suited to specific contexts and needs (*high confidence*). Participatory and collaborative approaches and tools bring together diverse knowledge holders and improve the generation and use of actionable knowledge for complex-systems decision-making (*medium confidence*). These collaborative approaches help navigate complex challenges, such as competing perspectives and knowledge uncertainties, thereby improving climate responses (*low confidence*).

Complex-systems responses to climate change require diverse types of knowledge, incorporating different ways of thinking about climate change and complexity, and often arise through participatory and collaborative processes (KMs 12.4, 20.2, 31.3, 31.4).[115,116] While much research focuses on analyses, modeling, or projections specific to individual sectors, regions, or actors, a richer diversity of information is needed to fully understand complexity.[116,117] Decision-making for complex systems benefits from knowledge of the interdependence of human–natural systems; the venues where decisions are made; the actors participating and impacted by decisions, politics and ideologies; and the values, attitudes, and beliefs of people and institutions (Figure 18.3).[117] Such knowledge stems from diverse disciplines as well as interdisciplinary and transdisciplinary endeavors. Interdisciplinary work integrates knowledge from different disciplines, and transdisciplinary approaches often additionally integrate knowledge from researchers and nonacademic partners such as communities or decision-makers.[118,119,120,121,122] For instance, social science and humanities research that examines the distribution of inequities of climate change has helped to highlight the overlapping and often compounding impacts on overburdened groups and can be used to ensure the inclusion of those communities in climate response decision-making (KM 18.2). Transdisciplinary knowledge that draws from both academic and nonacademic actors can help clarify systemic feedbacks and path dependencies that might go unnoticed if viewed from siloed disciplinary perspectives alone (Figures 18.3, 29.16).[123,124] Overall, complex-systems responses necessitate moving beyond traditional siloed knowledge production processes to integrated approaches that include diverse types of knowledge and actors.[125,126,127]

The diverse types of actionable knowledge needed for responding to complex climate risks include data and modeling, decision support tools, case studies, art, and lived experiences (KMs 4.3, 13.2, 17.1; Box 19.1). Different types of knowledge can be critical depending on the context and needs. For instance, qualitative forms of knowledge, such as oral histories or ethnographies, provide rich, place-specific understandings of how complex systems function and how climate-related experiences influence behavior.[128] Narratives and crowdsourced data of extreme events, including how people cope with them, have improved the integration of climate knowledge into social and cultural life.[129] Stories have advanced climate and energy solutions by allowing exploration of the intersection of nature, humanity, and technology.[130]

Integrated frameworks that bring together different knowledge types across various sectoral and regional contexts are essential for holistic analyses of complex systems. For example, recent developments in coupled human–natural systems modeling have not only examined cascading impacts across sectors and scales but have also incorporated the feedback relationships from social and political systems back into the models.[131] The Water Utility Climate Alliance has used a "chain of models" approach to link global climate models (GCMs) to hydrological models and then water utility decision-making tools.[132] Connections between GCMs and urban tree canopy models have supported analysis of heat management strategies across multiple dimensions, including air quality, irrigation demand, and greenhouse gas emissions.[133,134,135] Food–Energy–Water (FEW) systems studies have developed frameworks[126,136] to better understand regional to global dynamics within cross-sectoral FEW systems.[131,137]

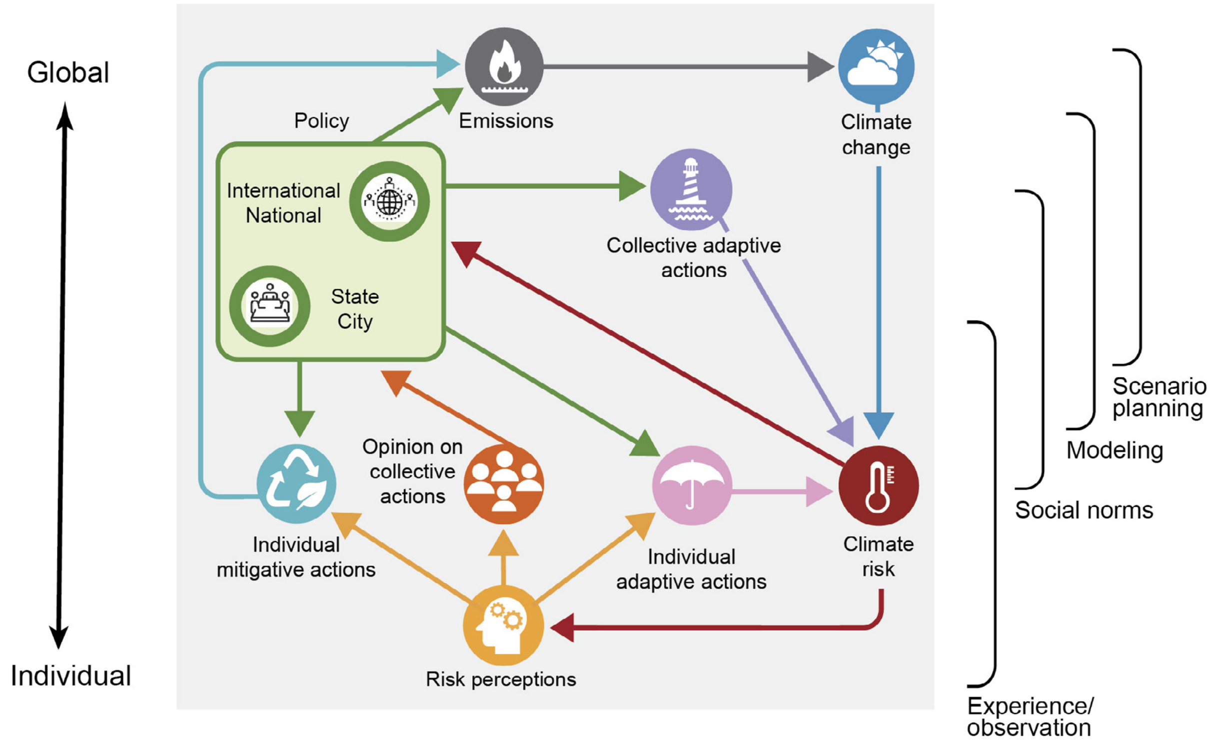
These advanced integrated frameworks draw on knowledge that stems not just from academics and researchers, but also from a wide range of experts, including practitioners, decision-makers, and local and Indigenous Peoples.[116,127,138,139,140] There are increasing examples of community and citizen scientists monitoring specific environmental indicators at temporal and spatial scales otherwise infeasible (see Table 12.2).[141,142,143,144] The long-term environmental knowledge and socioecological memory held by Indigenous Peoples has helped to detect, understand, and predict complex changes in climate systems.[138,145] Further, land management approaches based on Indigenous Knowledge have long emphasized flexibility and diversity of resources and serve as successful examples of resilient practices under complex environmental changes (e.g., Box 27.3).[138]

Connecting different knowledge holders and knowledges requires a different type of scientific practice that is more collaborative, participatory, or community-engaged.[116,146,147,148,149] Approaches such as coproduction, which bring together diverse knowledge holders with potential knowledge users, have proven to be successful in developing actionable knowledge for complex systems (Box 18.3; see Key Message 20.2 for more on engaging diverse stakeholders).[150,151,152] Such approaches allow for iteration and deliberation about multiple worldviews and have been effective in improving credibility, relevance, and trust in knowledge.[115,139,153,154] They also enable better understanding and management of knowledge uncertainties.[154,155,156] For example, participatory modeling of complex socioecological systems has included experience-based practitioner knowledge to improve identification of system boundaries, elicit realistic management alternatives, and increase the decision-relevance of outputs.[21,132,140,157] The county of Los Angeles has used participatory modeling to identify cascading impacts across infrastructural systems, their downstream effects for residents, and key intervention points.[158] Collaborative decision-making under deep uncertainty (DMDU) approaches, such as flexible adaptation pathways, scenario planning, and decision scaling, seek to develop robust climate responses for multiple potential futures rather than planning for a single best-estimate future, and they have also been positively received by decision-makers (see Figure 18.4).[159,160,161] The US National Park Service has used collaborative scenario planning, bringing together natural and cultural resource managers and subject-matter experts, to negotiate social and scientific uncertainties associated with climate change and inform the setting of conservation and resource stewardship goals.[162,163,164,165]

Effectively implementing and sustaining such collaborative processes requires specialized boundary organizations and climate services agencies (Box 18.3).[166,167,168] These boundary agencies facilitate, translate, and mediate engagements between scientists and different actor groups. NOAA's Climate Adaptation Partnerships, USGS's Climate Adaptation Science Centers, USDA's Climate Hubs, and university agricultural extension services have emerged as leading boundary agencies for the production and use of climate information through trust- and partnership-building with various knowledge-holder and user groups.[169,170]

Evaluation of effectiveness and equity is an important aspect of efforts to use climate-relevant knowledge in complex-systems decision-making. While there is increasing evidence that many collaborative approaches (such as coproduction, collaborative scenario planning, and DMDU tools) have been effective in improving the production and use of complex-systems knowledge in decision-making (Box 18.3), there has been limited examination of the long-term outcomes and equity of these processes and tools.[151,152,171] Additionally, the relative advantages and disadvantages of when and where different types of knowledges are most useful is also not well understood.[119,172] Overall, despite preliminary successes, understanding of the transferability, impact, and equity of different collaboratively generated knowledge and tools is still emerging.

Interacting Climate Responses and Knowledges Across Scales



Climate responses, ranging from the individual to global scale, interact with and draw from diverse knowledges.

Figure 18.3. Activities of government at multiple scales (green) affect climate risk (red) via multiple pathways, by decreasing or increasing greenhouse gas emissions (gray) and supporting adaptive (or maladaptive) actions (pink, purple). Moreover, government actions are influenced by the opinion and interests of residents, businesses, and other organizations (orange), and they in turn shape the actions of households and businesses (pink, blue). Interacting actors are nested within multiple spatial scales (left) and also rely on different knowledge sources for decision-making (right). Adapted from Moore et al. 2022.[88]

Box 18.3. Different Forms of Knowledge and Collaboration Across Groups Support Local Adaptation

Governments, businesses, community organizations, and residents in coastal cities have been early implementers of collaborative approaches to create actionable knowledge for complex climate responses (KM 22.1; see also Box 9.1). The Little River Adaptation Action Area in Miami-Dade County, Florida, is one such example of a new flexible planning tool.[173] This area is exposed to flooding worsened by sea level rise, and the challenges can be particularly stark. For example, when high tides and rainfall happen at the same time, septic tanks fail, leading sewage to back up into homes and spill into and contaminate waterways. As one resident described it, "I could live with a little bit of flooding if I knew the water wasn't full of sewage."[173] Systemic drivers of disparities across neighborhoods go back decades, and financial hardship means that households often struggle to reduce risks from flooding, as well as from chronic humid heat in the home.[174] Starting out in 2020, the Little River Adaptation Action Area has three main goals: 1) to use data to inform capital projects reducing climate risks (see also KM 31.5), 2) to support collaborative approaches in which community members' knowledge and experience guide climate solutions (see also KM 31.3), and 3) to break down silos and coordinate responses across governments, households, and the private sector. Implementation of this flexible adaptation tool has been led by resilience staff in the region, including importantly municipal chief resilience officers. Supported by research–practice partnerships such as the Resilient305 Collaborative, the county has enabled community-based implementation of multiple regional climate strategies.[173,175,176,177,178]

The Little River Adaptation Action Area has thereby been able to test out collaborative approaches and improve responses to complex climate challenges. First, the planning effort has been guided by overarching principles such as making residents safer through equitable engagement, fair policies, and direct investments; working with nature; and supporting flexible, integrated climate responses.[173,175,176] These guiding principles create clear signposts for designing and updating the collaborative planning process. Second, community workshops and research–practice networks have supported the use of physical and socioeconomic information and diverse knowledges in exploring locally preferred response strategies with support from state and federal partners, such as septic-to-sewer conversion, expansion of green spaces, and improvement of housing.[174,178,179] Granular, transparent data are being used to understand the distribution of climate and policy impacts such as flood and heat exposure across communities, as well as to understand building, household, and neighborhood characteristics that shape impacts on families. Third, evaluation has been embedded into planning efforts, such as by monitoring investments made and how residents perceive them.[180] These evaluation efforts require commitment and rigor, and they are necessary to understand how effective climate responses are for both climate goals and broader priorities, to identify unexpected benefits, and to support course corrections where needed. Fourth, approaches are expanding to address deeper uncertainties, such as the implications of large amounts of sea level rise and pathways that could help ensure longer-term flexibility where it may be needed.[181]

Key Message 18.4

New Governance Approaches Are Emerging, but Gaps in Practice and Evidence Persist

Climate change presents challenges for managing risks and responses across different levels of government, the private sector, and civil society. Current governance entities and their existing jurisdictional authorities are often unable to resolve conflicts posed by the wide-ranging and unprecedented interactions and complexities of climate risks and more localized compounding stressors (*high confidence*). Local and regional governments have experimented with alternative institutional arrangements, funding mechanisms, and decision coordination (*medium confidence*). Thus far, however, there is only preliminary evidence of their effectiveness (*low confidence*). These pilots and other innovations developed for climate mitigation and adaptation may well present opportunities for replication and broader successes in other locations and different local contexts (*medium confidence*).

Climate responses and management practices are expanding to address complexity in coevolving human–natural systems. The need for science-informed, inclusive decision-making around complex climate risks is immense. The form and quality of governance of individual and interacting systems are shaped by government agencies, civil-sector actors, and private-sector entities.[182] The actors and their roles vary across jurisdictions and are dependent on constitutional authorities, modes of control (e.g., proprietary, regulatory, budgetary), geographic territories, climate-related functions, technical capacities, budgets, access to financial and intellectual resources, and institutional or political power. The current state of these factors depends on institutional legacies and their momentum or inertia in response to changing climate conditions.[183]

There are inherent challenges in governing complex systems in response to climate change (KM 31.3). Relevant jurisdictions tend to be highly defined and siloed despite overlapping social or environmental system interactions.[184] Structural inequities established in past governance institutions are often inextricable from current decision-making processes (KM 20.1). Market failures are sometimes ignored (e.g., disclosure of a property's climate risks) or exacerbated by public policy (e.g., securitizing mortgages for risky properties, paying out insurance claims for repeat losses, or decreasing housing affordability as a result of mitigation efforts). Access to financial and intellectual resources has historically been weak at the local level and highly variable across geographies and urban to rural gradients.[185] Governance of complex systems requires flexibility beyond the formal governance of any one system.[186] Alternative processes for decision-making have been proposed or are in preliminary levels of implementation. These include an increased and explicit reliance on available scientific, engineering, and social-science evidence to inform policy. Iterative, participatory planning and deliberation inclusive of all residents or stakeholders are also possible. Similarly, transparency and accountability in public information and deliberations are increasingly important. Improved coordination strategies between governing entities—adjusting to evolving conditions and improving information—include decentralization and de-siloing in the public sector across agencies or jurisdictions, effectively reorganizing government. Governing entities are also looking at making longer-term commitments in public works and social programming and in longer-term visioning scenarios than their current budgetary and planning terms have traditionally prescribed (KM 12.4). Finally, governing institutions increasingly recognize the distribution of risks, path dependencies, and costs and burdens across communities.[18,187]

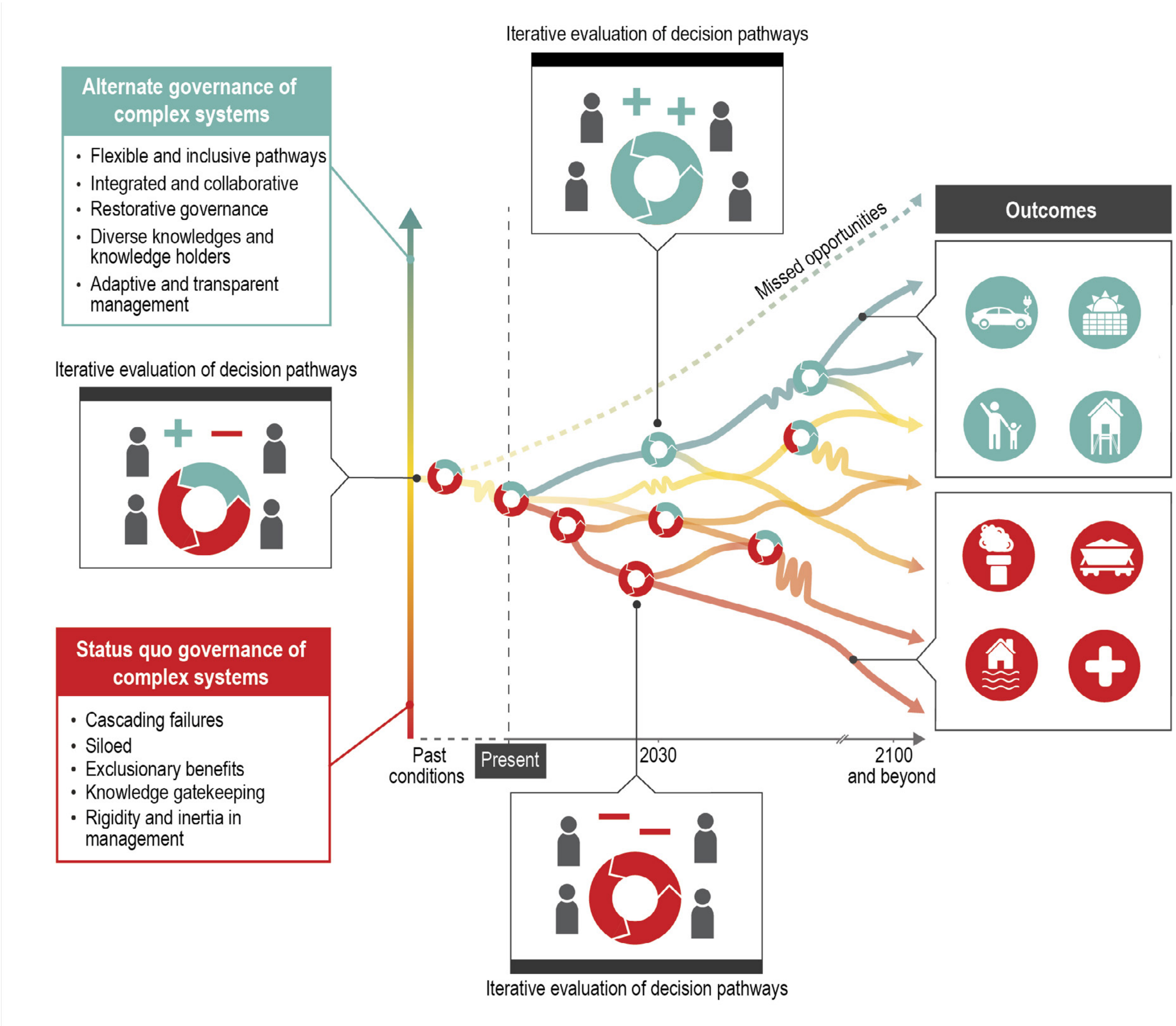
The state of evidence on effective governance approaches varies for each characteristic of complex-systems management:

- Complex systems are often characterized by *deep uncertainty*—the presence of systemic structural uncertainties or unknowns without objective probabilities. Climate risks and possible scenarios exacerbate this uncertainty (KM 18.1). Stakeholders such as private-sector interests, public-sector officials, and civil-sector representatives may disagree about the likelihood of future scenarios or consequences of decisions. Effective governance approaches include transparency in system frameworks, integration of contingencies and redundancies, and flexible planning and operations to avoid decisions that are costly or impossible to reverse (Figure 18.4).[188,189,190,191] Actors are already revisiting their crisis management plans to avoid worst-case outcomes and reduce short-term losses.
- Wide-ranging actors within complex systems may have *multiple, often competing objectives* regarding climate actions. In response, effective governance approaches include establishing consistent criteria to evaluate alternative actions, sometimes using consensus-based principles. Inclusive governance, stakeholder consultation, and explicit consideration of multiple criteria are other strategies for addressing cross-system conflicts. However, interactions among actors across overlapping governance structures and systems, combined with strategic behavior for individual decisions, can complicate these processes.[192,193,194,195,196]
- Complex systems are often characterized by *broadly distributed knowledge and power*—with diverse actors controlling knowledge about different parts of the system. Approaches in these polycentric governance systems include processes for data sharing, decision coordination and deliberation, and de-siloing of decision-making in related areas.[117,197,198,199,200,201,202,203,204,205,206,207,208,209,210,211,212] Mechanisms such as market-based approaches can sometimes allow for interaction of diverse actors via price signals, reducing the need for direct, centralized regulations, although these efforts may not account for inequitable financial access and outcomes across stakeholders, particularly overburdened communities.[213,214]
- Governance of complex systems tends to be *geographically and functionally nested*—controlled by multiple jurisdictions such as municipal, state, and federal authorities (Figure 31.4). Coordination across actors in different jurisdictions, together with improved clarity and boundary definitions, can therefore be valuable (Figure 18.3). The primary tools of nested governance structures—that is, regulation, statute, program rules, and coordinated budget transfers from multiple sources—can be negotiated through coordination rather than preemption.[202,215,216,217,218,219,220,221,222,223,224]
- Finally, *feedbacks and path dependencies* are common in complex systems. Choices at one point in time, such as the capacity and siting of physical infrastructure projects, can either expand or limit options later on (Figure 18.4). As a result, the full effects of management actions can be difficult to anticipate, particularly in the longer run. Path dependencies and policy feedbacks can lead to immediate commitments that restrict later change. Effective governance strategies include adaptive management approaches that repeatedly monitor, evaluate, and amend actions, although such governance strategies are not well developed.[225,226,227,228,229,230,231,232,233,234,235]

Overall, there is only preliminary evidence of the effects of alternative governance structures on climate mitigation and adaptation actions or their outcomes. Existing governance structures largely predate contemporary public climate responses and extend histories of US federalism, home rule, privatization, and ad hoc regional collaborations or special districts created in response to temporal needs or crises. These structures have generally not been reconfigured in the face of complex climate challenges, with some exceptions (KM 31.3). The governance structure between the Federal Government and state governments across and between most systems is constitutionally defined. The resulting flows of resources and other forms of assistance are therefore statutorily defined by program authorizations and appropriations. Existing governance entities such as state government agencies have attempted broad internal coordination among sub-state governments, although adjustments have met with varied success and contested leadership.[236]

There are more examples of alternative governance structures between and within subnational governments. Examples of the former include the cross-state Regional Greenhouse Gas Initiative for climate mitigation actions or the cross-county Southeast Florida Regional Climate Change Compact (Box 18.3) for climate adaptation; these efforts attempt to manage multiple systems across different jurisdictions.[237,238] Other regional coordinating entities have been created across states, counties within states, or cities within counties, including those affiliated with the Alliance of Regional Collaboratives for Climate Adaptation. But these efforts are typically preempted or bounded by the constitutional authorities allowed by the superseding level of government (for example, a state over counties). There is preliminary evidence about the effectiveness of individual climate professionals (e.g., chief resilience officers and related boundary-spanners).[203,239] However, the long-term outcomes from these efforts have not been conclusively measured.[240]

Governance of Complex Systems



Governing complex systems involves pathways of decision-making across time.

Figure 18.4. Adaptively managing complex systems involves a series of choices and actions through time. There are path dependencies shaped by the past and present, opportunities for maintaining flexibility under deep uncertainties, and needs for iterative learning through time. Governance of complex systems is more effective when it is flexible, inclusive, integrated, collaborative, and adaptive. At each decision point in time (circles with arrows), diverse decision-makers evaluate possible solutions available at that time and choose a path forward (people in gray considering benefits and trade-offs of different possible pathways). Given these responses, alternate pathways (red, orange, yellow, and green) may remain possible for the future or become closed off. At each decision point, an important consideration is how actions taken may expand or contract the options available in the future. Adapted with permission from Figure SPM.6 in IPCC 2023.[241]

Traceable Accounts

Process Description

The scope of this chapter was first developed by considering 1) the corresponding chapter in the Fourth National Climate Assessment (NCA4) as a starting point; 2) new emphases on topics relevant to complex systems, intersectoral interactions, and multiple stressors across NCA5; and 3) evolving areas of research and practice. The chapter lead identified important areas of expertise for the author team, including complex-systems methods, engagement methods, and topical expertise (e.g., energy–water–land, coastal, urban). Potential authors were identified from the nominations database, literature searches by the chapter lead and coordinating lead author, and the authors of the NCA4 chapter.

The First Order Draft, Second Order Draft (2OD), Third Order Draft (3OD), and Fourth Order Draft (4OD) were developed from the Zero Order Draft (ZOD) narrative outline through a multistage process. First, feedback on the framework and topics of the chapter was solicited via a public engagement workshop. Discussions focused on the NCA5 chapter framework for complexity, lived experiences, and the management of complex interactions. Second, chapter authors discussed the outline, and a lead author, along with accompanying contributors, was identified for each Key Message, figure, and box. Third, drafting proceeded through iterative processes of full-team and subgroup conversations on the scope and approach for each chapter element, literature reviews, and preparation of text and graphics, as well as identifying emerging assessment findings, areas of overlap across chapter sections, and potential directions for refinement in subsequent drafting stages. Fourth, cross-chapter discussions and the ZOD public review comments were used in the revision of the 2OD. These themes were further prioritized as the chapter was revised in the development of 3OD text and figures, also incorporating the review comments on the 2OD. The 4OD was then developed on the basis of public review and NASEM (National Academies of Sciences, Engineering, and Medicine) comments, with monitoring by the chapter review editor.

Key Message 18.1

Human–Nature Interconnections Create Unexpected Climate Risks and Opportunities

Description of Evidence Base

Key Message 18.1 material draws heavily from the recent assessment conducted in development of the Multisector Dynamics (MSD) vision report,[3] which was an in-depth assessment by a diverse research community directly building from NCA4, as well as recent literature outside the scope of that report. In addition to citing the report itself, Key Message 18.1 directly cites underlying literature from the MSD vision report and other fields such as socio-ecological-technical systems, sociohydrology, complex systems, exploratory modeling, and decision-making under deep uncertainty.[5,12,13,14,15,16,17,18,25,54,56,242] Given this foundation, the Key Message draws from an expansive evidence base, for which agreement in the literature pertains both to areas of agreement across studies and to deep uncertainties that remain.

Figure 18.1 is a combination of new and existing work. The underlying source was a conceptual diagram of complexity in urban systems and the lenses through which it can be organized and understood. Here, the figure has been adapted for complex systems as a whole, pursued through an actor-oriented lens and reflecting the authors' review of figures that explain different aspects of complexity in socioecological systems or coupled human–natural systems under a changing climate.[5,29,243,244,245,246,247,248,249] The MSD vision report executive summary Figure 1 was also a source of inspiration, yet the figure included in this

Assessment centers actors and their capacities to respond. This adjustment reflects increasing recognition of the role of people in complex systems and associated climate risks and responses.

Major Uncertainties and Research Gaps

Major uncertainties are explicitly acknowledged in the discussion of deep uncertainties inherent to complex systems. Based on the available literature, we provide assessment of emerging approaches relevant to complex systems under such uncertainties. There are deep uncertainties in predicting complex interconnections among human and natural systems over long time periods, which are particularly exacerbated by a lack of human systems research that focuses on the interactions between human and natural systems.[12,14,22] Exploratory systems modeling[52,53,54] is developing approaches to address these deep uncertainties.

Description of Confidence and Likelihood

Given the robust evidence underpinning this foundational section of the chapter, along with high agreement about that evidence (see especially the foundational assessment by Reed et al. 2022b[3]) Key Message 18.1 is assessed with *high confidence* overall. The first confidence-assigned statement in the Key Message describes the increasing vulnerability of interconnected human–natural systems to risks from climate change. Given the high degree of agreement among voluminous sources of evidence,[1,3,5,12,14,15,16,20,25,26,28,29,30,35,242,248,250], we assign *high confidence* to this statement. The second statement describes how these vulnerabilities depend on human responses and other compounding stressors. Given the high degree of agreement among many sources of evidence (see above), we assign *high confidence* to this statement. The final statement describes the diverse and sometimes competing objectives that decision-makers will need to navigate in managing climate risks. Given the high degree of agreement among ample sources of evidence (see above), we assign *high confidence* to this statement.

Key Message 18.2

Complex Climate Impacts and Responses Further Burden Frontline Communities

Description of Evidence Base

Evidence of the intersectional impacts of natural hazards, decarbonization efforts, and climate adaptation is well documented. Quantitative assessments of program outcomes and post-disaster outcomes, with a large number of data points, consistently show that more rural or smaller municipalities are less able to attract resources for adaptation (e.g., Mach et al. 2019[83]). Numerous case studies and spatial and quantitative assessments provide evidence of the displacement tendencies of climate-exacerbated disasters and climate mitigation and resilience initiatives.[73,85,109,251,252,253] In-depth qualitative research and longitudinal studies of overburdened communities have studied how cyclical disasters erode community response capacity[254,255,256] and trigger cascading infrastructure and housing effects in cities receiving groups migrating from or displaced by climate-related events and trends.[103] Research on the climate transition from fossil fuel economies shows that these efforts intersect with social, cultural, and political challenges to create intersectional vulnerabilities and complexities.[257,258]

Major Uncertainties and Research Gaps

Just as important as what we know about distributive impacts in complex systems is what we do not know or measure. Most research assessing complex systems is highly technocratic, focusing on specific events, discrete risks, and the impacts of cascading infrastructure systems, demographic change, and natural resource systems. However, complexity studies do not tend to encompass the large body of social and humanities research—increasingly focusing on climate change—related to cultural, psychological, and effective responses to shocks; racial, gender-based, and equity-oriented studies of vulnerabilities, risks, and societal responses; or the roles of political ideology and violent conflict (e.g., Palmer and Smith 2014;[89] Beckage et al. 2020;[87] Moore et al. 2022;[88] Reed et al. 2022,[242] 2022;[3] Rising et al. 2022[90]). These issues can help explain political decision-making, protests, and post-disaster conflicts and are important for understanding interactions across social and physical systems in the near and long term. There is a resulting lack of tools and communities of practice to integrate disciplinary divides in support of complex-systems research.

Limited knowledge about climate-exacerbated migration and how receiving cities are responding results in uncertainties about how climate migration differs from other forms of migration, what migration means for overall vulnerability trends, and how it will impact other interlinked physical and natural systems. Information on urban–rural linkages is limited, especially in forms that can support complex-systems modeling. Trade-offs between mitigation efforts and adaptation strategies with competing impacts on individuals' well-being are also understudied.

Description of Confidence and Likelihood

There is *high confidence* in each statement of Key Message 18.2. First, there is high agreement in the literature that climate change disproportionately impacts already-overburdened groups (statement 1), as recently assessed in the comprehensive Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Working Group II.[69] Second, multiple studies with high agreement across them have documented the lack of social and political dynamics in complex-systems models and limitations resulting from sectoral, regional and jurisdictional, and disciplinary silos of vulnerability and risk assessments (statement 2).[3,86,87,88,89,90,242] Some complex-systems analyses have made first steps in incorporating social and political dynamics (e.g., Moore et al. 2022[88]), but these are emerging efforts, and statement 2 is therefore made with *high confidence*. Third, data about how complex systems affect frontline communities is lacking for hard-to-reach populations, and this can lead to disproportionate climate impacts (statement 3).[97,99] This statement is made with *high confidence* given the large evidence basis on inequalities in data availability and quality across communities and the focus of the literature on data-rich places (e.g., Friel et al. 2011;[98] Pörtner et al. 2022;[69] Reed et al. 2022[3]).

Key Message 18.3

Collaborations Among Diverse Knowledge Holders Improve Responses to Complex Climate Challenges

Description of Evidence Base

Key Message 18.3 and corresponding text draw from a review of various types of literature on knowledge for complex systems, several author team meetings and deliberations over written documents, and takeaways from the public engagement workshop. The write-up was also coordinated with authors of other Key Messages, especially Key Messages 18.2 and 18.4. Literature reviewed for this Key Message spanned several topical areas. The authors reviewed literature describing integrated frameworks and modeling for complex systems,[3,123,126,127,131,136] as well as characteristics of actionable or usable knowledge.[115,116,120,153,154] Authors also focused on literature showcasing the role of qualitative knowledge such as narratives in managing complex systems.[128,129,130] In terms of knowledge production processes, the team reviewed the latest papers on co-production of knowledge and collaborative research approaches, as well as on interdisciplinary and transdisciplinary research.[115,124,147,259] The authors also reviewed literature and case studies on Indigenous and Traditional Knowledges and their role in complex systems, as well as the role of citizen science.[141,142,143,144]

Studies on participatory modeling,[21,140,156,157] as well as collaborative decision-support tools for complex systems such as decision-making under deep uncertainty and scenario planning, were also reviewed. Finally, research on climate services and boundary agencies was also reviewed.

Box 18.3 centers on complex coastal governance, drawing from evaluations of climate responses in Metropolitan regions including the San Francisco Bay area, Los Angeles County, Southeast Florida, and metropolitan New York; a specific case example of the Little River Adaptation Action Area is discussed here. Multiple recent studies have examined the science–policy–practice processes and partnerships, along with the evolving governance systems, inherent to complex coastal climate responses (e.g., Treuer et al. 2017;[260] Kim 2019;[261] Solecki et al. 2021;[262] Tedesco et al. 2021;[179] Troxler et al. 2021;[178] Lubell and Robbins 2022[263]). Direct references are provided to relevant regional strategies and decision support forums (e.g., Miami-Dade County 2021;[176] Miami-Dade County 2021;[175] SFWMD 2021[177]).

Major Uncertainties and Research Gaps

Despite the promise and potential of collaborative knowledge production processes and collaborative decision tools, long-term monitoring and evaluation of these processes and tools are largely lacking; hence, the long-term impact and effectiveness of such collaboratively generated knowledge in responding to complex climate risks in complex systems are not well understood.[147,151,172,264] In addition, the impact of collaboratively generated actionable knowledge on long-term management of complex climate-impacted systems, particularly as it relates to procedural or distributive justice in outcomes, is not well understood.[265]

Description of Confidence and Likelihood

There is high agreement in the literature, from both theoretical[120,124,127] and empirical studies,[117,123,131,263] that effective complex systems responses benefit from integrated frameworks that bring together diverse and context-specific knowledge. Therefore, there is *high confidence* in the first statement in this Key Message. A growing number of studies provide evidence that participatory and collaborative approaches that bring together diverse actors have improved the actionability of knowledge for managing complex systems,[150,151,152] but more evidence is needed on the extent to which this actionable knowledge has actually been used in complex-systems decision-making.[266,267,268] Hence, there is *medium confidence* in the second statement. Although the theoretical literature suggests that collaborative approaches help to navigate competing perspectives of different actors and knowledge uncertainties,[43,117,119] there are very few studies that have evaluated the extent to which these approaches have successfully led to improved climate responses in the long term.[171,267,269,270] Hence, there is *low confidence* in the third statement.

Key Message 18.4

New Governance Approaches Are Emerging, but Gaps in Practice and Evidence Persist

Description of Evidence Base

The subgroup of authors for Key Message 18.4 pulled from a multidisciplinary set of research products at the intersection of governance, regional planning, systems theory, and jurisdictional authority in relation to both climate mitigation and adaptation planning, actions, outputs, and outcomes.[202] The subgroup identified key peer-reviewed research products based on the themes categorized by subgroup members' expertise, as well as the themes that surfaced in the public engagement workshop; essentially, the identification of sources was expansive, but the themes from which the sources were identified and classified were necessarily limited. Further, the subgroup sought to identify documentation of alternative governance successes and failures in relation to climate mitigation and adaptation in order to expand the pool of sources to other disciplines that may not explicitly use governance terms.[191] For each of the themes identified, there is a vast literature from which to pull findings. Identifying these was a straightforward process, and there was minimal disagreement on either the themes or the sources.

In slight contrast, there was significant discussion regarding the level of confidence around the synthesis of sources' findings, given their range of empirical inquiry and methodological rigor. The vast majority of evidentiary sources rely on either singular governance case studies (or, less often, a few cases) or theoretical exploration in either qualitative or quantitative ways.[195,199] Fewer studies include sample sizes of governance cases that are powerful enough—or that employ comparison groups of any design—to produce conclusive and generalizable findings.[203,221] Consequently, assessments of uncertainties and confidence are based largely on the variable rigor of these sources.

Major Uncertainties and Research Gaps

Governance, by definition, varies by geographic, social, and political landscapes, among many contextual factors. The first factor—geography—poses a particular challenge for the development of conclusive evidence of governance actions and effects.[188] Essentially, each place has a unique governance framework.[117] Although rigorous qualitative and quantitative studies have been conducted regarding governance interventions and their outcomes in specific places, the sample sizes of individual monographs and consistent application of terms across them have consequently produced only preliminary evidence to date. As with urban studies and political geography, there are few multisite studies of complex-systems governance at any level of quasi-experimental rigor, or even basic outcome evaluations, that allow for replicable responses to the fundamental question posed in the public engagement workshop: What is "good" climate governance?

Description of Confidence and Likelihood

This fundamental methodological challenge, then, prohibits an assessment of *high confidence* for all complex-systems governance themes—with the sole exception of their current inability to produce consistently positive outcomes. Further study with larger sample sizes and consistent terms of governance frameworks—including their inputs, activities, outputs, and outcomes—is necessary to assess higher levels of confidence. Statements in the Key Message regarding evaluation/learning, effectiveness, and replicability are therefore made with *low* and *medium confidence*. The quantity of evidence around climate governance implementation and outcomes is too small to conclude that their findings are externally valid and replicable.[203] Policy and governance literature for other subject domains beyond climate mitigation and adaptation for which there has been more extensive study, however, suggests that pilot governance efforts' success may not be insignificant, implying a higher confidence that the implementation of current climate pilots may also yield positive outcomes.[200,224]

References

1. Helbing, D., 2013: Globally networked risks and how to respond. *Nature*, **497** (7447), 51–59. https://doi.org/10.1038/nature12047

2. Schweikert, A.E. and M.R. Deinert, 2021: Vulnerability and resilience of power systems infrastructure to natural hazards and climate change. *WIREs Climate Change*, **12** (5), e724. https://doi.org/10.1002/wcc.724

3. Reed, P.M., A. Hadjimichael, R.H. Moss, E. Monier, S. Alba, C. Brelsford, C. Burleyson, S. Cohen, A. Dyreson, D. Gold, R. Gupta, K. Keller, M. Konar, J. Macknick, J. Morris, V. Srikrishnan, N. Voisin, and J. Yoon, 2022: MultiSector Dynamics: Scientific Challenges and a Research Vision for 2030. U.S. Department of Energy, Office of Science. https://doi.org/10.5281/zenodo.6144309

4. Rinaldi, S.M., J.P. Peerenboom, and T.K. Kelly, 2001: Identifying, understanding, and analyzing critical infrastructure interdependencies. *IEEE Control Systems Magazine*, **21** (6), 11–25. https://doi.org/10.1109/37.969131

5. Simpson, N.P., K.J. Mach, A. Constable, J. Hess, R. Hogarth, M. Howden, J. Lawrence, R.J. Lempert, V. Muccione, B. Mackey, M.G. New, B. O'Neill, F.E. Otto, H.-O. Pörtner, A. Reisinger, D. Roberts, D.N. Schmidt, S. Seneviratne, and C.H. Trisos, 2021: A framework for complex climate change risk assessment. *One Earth*, **4** (4), 489–501. https://doi.org/10.1016/j.oneear.2021.03.005

6. Vespignani, A., 2010: The fragility of interdependency. *Nature*, **464** (7291), 984–985. https://doi.org/10.1038/464984a

7. Lenton, T.M., H. Held, E. Kriegler, J.W. Hall, W. Lucht, S. Rahmstorf, and H.J. Schellnhuber, 2008: Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences of the United States of America*, **105** (6), 1786–1793. https://doi.org/10.1073/pnas.0705414105

8. Glazer, Y.R., D.M. Tremaine, J.L. Banner, M. Cook, R.E. Mace, J. Nielsen-Gammon, E. Grubert, K. Kramer, A.M.K. Stoner, B.M. Wyatt, A. Mayer, T. Beach, R. Correll, and M.E. Webber, 2021: Winter storm Uri: A test of Texas' water infrastructure and water resource resilience to extreme winter weather events. *Journal of Extreme Events*, **08** (04), 2150022. https://doi.org/10.1142/s2345737621500226

9. Cohen, J., L. Agel, M. Barlow, C.I. Garfinkel, and I. White, 2021: Linking Arctic variability and change with extreme winter weather in the United States. *Science*, **373** (6559), 1116–1121. https://doi.org/10.1126/science.abi9167

10. Overpeck, J.T. and B. Udall, 2020: Climate change and the aridification of North America. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (22), 11856–11858. https://doi.org/10.1073/pnas.2006323117

11. Wieder, W.R., D. Kennedy, F. Lehner, K.N. Musselman, K.B. Rodgers, N. Rosenbloom, I.R. Simpson, and R. Yamaguchi, 2022: Pervasive alterations to snow-dominated ecosystem functions under climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **119** (30), e2202393119. https://doi.org/10.1073/pnas.2202393119

12. Bai, X., R.J. Dawson, D. Ürge-Vorsatz, G.C. Delgado, A.S. Barau, S. Dhakal, D. Dodman, L. Leonardsen, V. Masson-Delmotte, D.C. Roberts, and S. Schultz, 2018: Six research priorities for cities and climate change. *Nature*, **555**, 23–25. https://doi.org/10.1038/d41586-018-02409-z

13. Berrang-Ford, L., A.R. Siders, A. Lesnikowski, A.P. Fischer, M.W. Callaghan, et al., 2021: A systematic global stocktake of evidence on human adaptation to climate change. *Nature Climate Change*, **11** (11), 989–1000. https://doi.org/10.1038/s41558-021-01170-y

14. Brelsford, C., M. Dumas, E. Schlager, B.J. Dermody, M. Aiuvalasit, M.R. Allen-Dumas, J. Beecher, U. Bhatia, P. D'Odorico, M. Garcia, P. Gober, D. Groenfeldt, S. Lansing, K. Madani, L.E. Méndez-Barrientos, E. Mondino, M.F. Müller, F.C. O'Donnell, P.M. Owuor, J. Rising, M.R. Sanderson, F.A.A. Souza, and S.C. Zipper, 2020: Developing a sustainability science approach for water systems. *Ecology and Society*, **25** (2), 23. https://doi.org/10.5751/es-11515-250223

15. Di Baldassarre, G., N. Wanders, A. AghaKouchak, L. Kuil, S. Rangecroft, T.I.E. Veldkamp, M. Garcia, P.R. van Oel, K. Breinl, and A.F. Van Loon, 2018: Water shortages worsened by reservoir effects. *Nature Sustainability*, **1** (11), 617–622. https://doi.org/10.1038/s41893-018-0159-0

16. Mora, C., D. Spirandelli, E.C. Franklin, J. Lynham, M.B. Kantar, W. Miles, C.Z. Smith, K. Freel, J. Moy, L.V. Louis, E.W. Barba, K. Bettinger, A.G. Frazier, J.F. Colburn Ix, N. Hanasaki, E. Hawkins, Y. Hirabayashi, W. Knorr, C.M. Little, K. Emanuel, J. Sheffield, J.A. Patz, and C.L. Hunter, 2018: Broad threat to humanity from cumulative climate hazards intensified by greenhouse gas emissions. *Nature Climate Change*, **8** (12), 1062–1071. https://doi.org/10.1038/s41558-018-0315-6

17. Müller, M.F. and M.C. Levy, 2019: Complementary vantage points: Integrating hydrology and economics for Sociohydrologic knowledge generation. *Water Resources Research*, **55** (4), 2549–2571. https://doi.org/10.1029/2019wr024786

18. Shi, L. and S. Moser, 2021: Transformative climate adaptation in the United States: Trends and prospects. *Science*, **372** (6549), 8054. https://doi.org/10.1126/science.abc8054

19. Andersen, A.D., M. Steen, T. Mäkitie, J. Hanson, T.M. Thune, and B. Soppe, 2020: The role of inter-sectoral dynamics in sustainability transitions: A comment on the transitions research agenda. *Environmental Innovation and Societal Transitions*, **34**, 348–351. https://doi.org/10.1016/j.eist.2019.11.009

20. Aven, T. and E. Zio, 2021: Globalization and global risk: How risk analysis needs to be enhanced to be effective in confronting current threats. *Reliability Engineering & System Safety*, **205**, 107270. https://doi.org/10.1016/j.ress.2020.107270

21. Elsawah, S., T. Filatova, A.J. Jakeman, A. Kettner, M. Zellner, I. Athanasiadis, S. Hamilton, R. Axtell, D. Brown, J. Gilligan, M. Janssen, D. Robinson, J. Rozenberg, I. Ullah, and S. Lade, 2020: Eight grand challenges in socio-environmental systems modeling. *Socio-Environmental Systems Modelling*, **2**, 16226–16226. https://doi.org/10.18174/sesmo.2020a16226

22. Hino, M. and E. Nance, 2021: Five ways to ensure flood-risk research helps the most vulnerable. *Nature*, **595**, 27–29. https://doi.org/10.1038/d41586-021-01750-0

23. Levi, P.J., S.D. Kurland, M. Carbajales-Dale, J.P. Weyant, A.R. Brandt, and S.M. Benson, 2019: Macro-energy systems: Toward a new discipline. *Joule*, **3** (10), 2282–2286. https://doi.org/10.1016/j.joule.2019.07.017

24. Levin, S.A., J.M. Anderies, N. Adger, S. Barrett, E.M. Bennett, J.C. Cardenas, S.R. Carpenter, A.-S. Crépin, P. Ehrlich, J. Fischer, C. Folke, N. Kautsky, C. Kling, K. Nyborg, S. Polasky, M. Scheffer, K. Segerson, J. Shogren, J. van den Bergh, B. Walker, E.U. Weber, and J. Wilen, 2021: Governance in the face of extreme events: Lessons from evolutionary processes for structuring interventions, and the need to go beyond. *Ecosystems*, **25**, 697–711. https://doi.org/10.1007/s10021-021-00680-2

25. Markolf, S.A., M.V. Chester, D.A. Eisenberg, D.M. Iwaniec, C.I. Davidson, R. Zimmerman, T.R. Miller, B.L. Ruddell, and H. Chang, 2018: Interdependent infrastructure as linked social, ecological, and technological systems (SETSs) to address lock-in and enhance resilience. *Earth's Future*, **6** (12), 1638–1659. https://doi.org/10.1029/2018ef000926

26. Szostak, R., 2017: Stability, instability, and interdisciplinarity. *Issues in Interdisciplinary Studies*, **35**, 65–87. https://eric.ed.gov/?id=ej1193677

27. de Vos, L., H. Biemans, J.C. Doelman, E. Stehfest, and D.P. van Vuuren, 2021: Trade-offs between water needs for food, utilities, and the environment—A nexus quantification at different scales. *Environmental Research Letters*, **16** (11), 115003. https://doi.org/10.1088/1748-9326/ac2b5e

28. Drakes, O. and E. Tate, 2022: Social vulnerability in a multi-hazard context: A systematic review. *Environmental Research Letters*, **17**, 033001. https://doi.org/10.1088/1748-9326/ac5140

29. 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. https://doi.org/10.1038/s41558-018-0156-3

30. Dearing, J.A., R. Wang, K. Zhang, J.G. Dyke, H. Haberl, M.S. Hossain, P.G. Langdon, T.M. Lenton, K. Raworth, S. Brown, J. Carstensen, M.J. Cole, S.E. Cornell, T.P. Dawson, C.P. Doncaster, F. Eigenbrod, M. Flörke, E. Jeffers, A.W. Mackay, B. Nykvist, and G.M. Poppy, 2014: Safe and just operating spaces for regional social-ecological systems. *Global Environmental Change*, **28**, 227–238. https://doi.org/10.1016/j.gloenvcha.2014.06.012

31. Eriksen, S., E.L.F. Schipper, M. Scoville-Simonds, K. Vincent, H.N. Adam, N. Brooks, B. Harding, D. Khatri, L. Lenaerts, D. Liverman, M. Mills-Novoa, M. Mosberg, S. Movik, B. Muok, A. Nightingale, H. Ojha, L. Sygna, M. Taylor, C. Vogel, and J.J. West, 2021: Adaptation interventions and their effect on vulnerability in developing countries: Help, hindrance or irrelevance? *World Development*, **141**, 105383. https://doi.org/10.1016/j.worlddev.2020.105383

32. Hallegatte, S. and N.L. Engle, 2019: The search for the perfect indicator: Reflections on monitoring and evaluation of resilience for improved climate risk management. *Climate Risk Management*, **23**, 1–6. https://doi.org/10.1016/j.crm.2018.12.001

33. Hallegatte, S., J. Rentschler, and J. Rozenberg, 2019: *Lifelines: The Resilient Infrastructure Opportunity*. World Bank Group, Washington, DC. http://hdl.handle.net/10986/31805

34. Lempert, R.J., 2021: Measuring global climate risk. *Nature Climate Change*, **11** (10), 805–806. https://doi.org/10.1038/s41558-021-01165-9

35. de Ruiter, M.C. and A.F. van Loon, 2022: The challenges of dynamic vulnerability and how to assess it. *iScience*, **25** (8). https://doi.org/10.1016/j.isci.2022.104720

36. Dolan, F., J. Lamontagne, R. Link, M. Hejazi, P. Reed, and J. Edmonds, 2021: Evaluating the economic impact of water scarcity in a changing world. *Nature Communications*, **12** (1), 1915. https://doi.org/10.1038/s41467-021-22194-0

37. Moallemi, E.A. and F.J. de Haan, 2019: *Modelling Transitions: Virtues, Vices, Visions of the Future*, 1st ed. Routledge, London, UK, 276 pp. https://doi.org/10.4324/9780429056574

38. Siders, A.R., M. Hino, and K.J. Mach, 2019: The case for strategic and managed climate retreat. *Science*, **365** (6455), 761. https://doi.org/10.1126/science.aax8346

39. Trutnevyte, E., L.F. Hirt, N. Bauer, A. Cherp, A. Hawkes, O.Y. Edelenbosch, S. Pedde, and D.P. Vuuren, 2019: Societal transformations in models for energy and climate policy: The ambitious next step. *One Earth*, **1** (4), 423–433. https://doi.org/10.1016/j.oneear.2019.12.002

40. Wible, B., 2021: Out of harm's way. *Science*, **372** (6548), 1274–1275. https://doi.org/10.1126/science.abi9209

41. Avelino, F., 2021: Theories of power and social change. Power contestations and their implications for research on social change and innovation. *Journal of Political Power*, **14** (3), 425–448. https://doi.org/10.1080/2158379x.2021.1875307

42. Jafino, B.A., J.H. Kwakkel, and B. Taebi, 2021: Enabling assessment of distributive justice through models for climate change planning: A review of recent advances and a research agenda. *WIREs Climate Change*, **12** (4), e721. https://doi.org/10.1002/wcc.721

43. Wyborn, C., A. Datta, J. Montana, M. Ryan, P. Leith, B. Chaffin, C. Miller, and L. van Kerkhoff, 2019: Co-producing sustainability: Reordering the governance of science, policy, and practice. *Annual Review of Environment and Resources*, **44** (1), 319–346. https://doi.org/10.1146/annurev-environ-101718-033103

44. Filatova, T., J.G. Polhill, and S. van Ewijk, 2016: Regime shifts in coupled socio-environmental systems: Review of modelling challenges and approaches. *Environmental Modelling & Software*, **75**, 333–347. https://doi.org/10.1016/j.envsoft.2015.04.003

45. Gold, D.F., P.M. Reed, D.E. Gorelick, and G.W. Characklis, 2022: Power and pathways: Exploring robustness, cooperative stability, and power relationships in regional infrastructure investment and water supply management portfolio pathways. *Earth's Future*, **10** (2), e2021EF002472. https://doi.org/10.1029/2021ef002472

46. Iwanaga, T., H.-H. Wang, S.H. Hamilton, V. Grimm, T.E. Koralewski, A. Salado, S. Elsawah, S. Razavi, J. Yang, P. Glynn, J. Badham, A. Voinov, M. Chen, W.E. Grant, T.R. Peterson, K. Frank, G. Shenk, C.M. Barton, A.J. Jakeman, and J.C. Little, 2021: Socio-technical scales in socio-environmental modeling: Managing a system-of-systems modeling approach. *Environmental Modelling & Software*, **135**, 104885. https://doi.org/10.1016/j.envsoft.2020.104885

47. Lamontagne, J.R., P.M. Reed, R. Link, K.V. Calvin, L.E. Clarke, and J.A. Edmonds, 2018: Large ensemble analytic framework for consequence-driven discovery of climate change scenarios. *Earth's Future*, **6** (3), 488–504. https://doi.org/10.1002/2017ef000701

48. Kasprzyk, J.R., S. Nataraj, P.M. Reed, and R.J. Lempert, 2013: Many objective robust decision making for complex environmental systems undergoing change. *Environmental Modelling & Software*, **42**, 55–71. https://doi.org/10.1016/j.envsoft.2012.12.007

49. Lempert, R.J., 2002: A new decision sciences for complex systems. *Proceedings of the National Academy of Sciences of the United States of America*, **99** (suppl_3), 7309–7313. https://doi.org/10.1073/pnas.082081699

50. Walker, W.E., M. Haasnoot, and J.H. Kwakkel, 2013: Adapt or perish: A review of planning approaches for adaptation under deep uncertainty. *Sustainability*, **5** (3), 955–979. https://doi.org/10.3390/su5030955

51. Walker, W.E., P. Harremoës, J. Rotmans, J.P. van der Sluijs, M.B. van Asselt, P. Janssen, and M.P. Krayer von Krauss, 2003: Defining uncertainty: A conceptual basis for uncertainty management in model-based decision support. *Integrated Assessment*, **4** (1), 5–17. https://doi.org/10.1076/iaij.4.1.5.16466

52. Bankes, S., 1993: Exploratory modeling for policy analysis. *Operations Research*, **41** (3), 435–449. https://doi.org/10.1287/opre.41.3.435

53. Marchau, V.A.W.J., W.E. Walker, P.J.T.M. Bloemen, and S.W. Popper, 2019: *Decision Making Under Deep Uncertainty*. Springer, Cham, Switzerland, 405 pp. https://doi.org/10.1007/978-3-030-05252-2

54. Moallemi, E.A., J. Kwakkel, F.J. de Haan, and B.A. Bryan, 2020: Exploratory modeling for analyzing coupled human-natural systems under uncertainty. *Global Environmental Change*, **65**, 102186. https://doi.org/10.1016/j.gloenvcha.2020.102186

55. Bryant, B.P. and R.J. Lempert, 2010: Thinking inside the box: A participatory, computer-assisted approach to scenario discovery. *Technological Forecasting and Social Change*, **77** (1), 34–49. https://doi.org/10.1016/j.techfore.2009.08.002

56. Hadjimichael, A., J. Quinn, E. Wilson, P. Reed, L. Basdekas, D. Yates, and M. Garrison, 2020: Defining robustness, vulnerabilities, and consequential scenarios for diverse stakeholder interests in institutionally complex river basins. *Earth's Future*, **8** (7), e2020EF001503. https://doi.org/10.1029/2020ef001503

57. Popper, S.W., 2019: Robust decision making and scenario discovery in the absence of formal models. *Futures & Foresight Science*, **1** (3-4), e22. https://doi.org/10.1002/ffo2.22

58. Kopp, R.E., E.A. Gilmore, C.M. Little, J. Lorenzo-Trueba, V.C. Ramenzoni, and W.V. Sweet, 2019: Usable science for managing the risks of sea-level rise. *Earth's Future*, **7** (12), 1235–1269. https://doi.org/10.1029/2018ef001145

59. Brelsford, C., A. Jones, M. Allen-Dumas, M. Bukovsky, I. Dronova, T. Hong, D. Iwaniec, S. Markolf, M. Newcomer, P. Nico, D. Rastogi, S. Reid, K. Sparks, J. Tucillo, and Z. Zheng, 2021: Workshop Report: Multi-Sectoral Urban Interactions: Fundamental Science Needs to Inform Pathways to More Resilient Communities in a Changing Climate. MultiSector Dynamics Community of Practice. https://multisectordynamics.org/working-groups/urban/workshop-report-multi-sectoral-urban-interactions/

60. Mytton, D., 2021: Data centre water consumption. *npj Clean Water*, **4** (1), 11. https://doi.org/10.1038/s41545-021-00101-w

61. Masanet, E., A. Shehabi, N. Lei, S. Smith, and J. Koomey, 2020: Recalibrating global data center energy-use estimates. *Science*, **367** (6481), 984–986. https://doi.org/10.1126/science.aba3758

62. Siddik, M.A.B., A. Shehabi, and L. Marston, 2021: The environmental footprint of data centers in the United States. *Environmental Research Letters*, **16** (6), 064017. https://doi.org/10.1088/1748-9326/abfba1

63. Whitehead, B., D. Andrews, A. Shah, and G. Maidment, 2014: Assessing the environmental impact of data centres part 1: Background, energy use and metrics. *Building and Environment*, **82**, 151–159. https://doi.org/10.1016/j.buildenv.2014.08.021

64. Kenney, D.S., 2005: Prior appropriation and water rights reform in the western United States. In: *Water Rights Reform: Lessons for Institutional Design*. Bruns, B.R., C. Ringler, and R.S. Meinzen-Dick, Eds. International Food Policy Research Institute, Washington, DC. https://doi.org/10.2499/0896297497.ch7

65. Anguelovski, I., L. Shi, E. Chu, D. Gallagher, K. Goh, Z. Lamb, K. Reeve, and H. Teicher, 2016: Equity impacts of urban land use planning for climate adaptation: Critical perspectives from the global north and south. *Journal of Planning Education and Research*, **36** (3), 333–348. https://doi.org/10.1177/0739456x16645166

66. Chen, T.H.Y. and B. Lee, 2022: Income-based inequality in post-disaster migration is lower in high resilience areas: Evidence from U.S. internal migration. *Environmental Research Letters*, **17** (3), 034043. https://doi.org/10.1088/1748-9326/ac5692

67. Gonzalez, C., 2021: Racial capitalism, climate justice, and climate displacement. *Oñati Socio-Legal Series*, **11** (1), 108–147. https://doi.org/10.35295/osls.iisl/0000-0000-0000-1137

68. Knighton, J., K. Hondula, C. Sharkus, C. Guzman, and R. Elliott, 2021: Flood risk behaviors of United States riverine metropolitan areas are driven by local hydrology and shaped by race. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (13), e2016839118. https://doi.org/10.1073/pnas.2016839118

69. Pörtner, H.-O., D.C. Roberts, H. Adams, I. Adelekan, C. Adler, et al., 2022: Technical summary. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, E.S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, and A. Okem, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 37–118. https://doi.org/10.1017/9781009325844.002

70. Prins, S.J. and B. Story, 2020: Connecting the dots between mass incarceration, health inequity, and climate change. *American Journal of Public Health*, **110** (S1), S35–S36. https://doi.org/10.2105/ajph.2019.305470

71. Wing, O.E.J., W. Lehman, P.D. Bates, C.C. Sampson, N. Quinn, A.M. Smith, J.C. Neal, J.R. Porter, and C. Kousky, 2022: Inequitable patterns of US flood risk in the Anthropocene. *Nature Climate Change*, **12** (2), 156–162. https://doi.org/10.1038/s41558-021-01265-6

72. Amorim-Maia, A.T., I. Anguelovski, E. Chu, and J. Connolly, 2022: Intersectional climate justice: A conceptual pathway for bridging adaptation planning, transformative action, and social equity. *Urban Climate*, **41**, 101053. https://doi.org/10.1016/j.uclim.2021.101053

73. Anguelovski, I., A.L. Brand, J.J.T. Connolly, E. Corbera, P. Kotsila, J. Steil, M. Garcia-Lamarca, M. Triguero-Mas, H. Cole, F. Baró, J. Langemeyer, C.P. del Pulgar, G. Shokry, F. Sekulova, and L. Argüelles Ramos, 2020: Expanding the boundaries of justice in urban greening scholarship: Toward an emancipatory, antisubordination, intersectional, and relational approach. *Annals of the American Association of Geographers*, **110** (6), 1743–1769. https://doi.org/10.1080/24694452.2020.1740579

74. Kuran, C.H.A., C. Morsut, B.I. Kruke, M. Krüger, L. Segnestam, K. Orru, T.O. Nævestad, M. Airola, J. Keränen, F. Gabel, S. Hansson, and S. Torpan, 2020: Vulnerability and vulnerable groups from an intersectionality perspective. *International Journal of Disaster Risk Reduction*, **50**, 101826. https://doi.org/10.1016/j.ijdrr.2020.101826

75. Pulido, L., 2017: Geographies of race and ethnicity II: Environmental racism, racial capitalism and state-sanctioned violence. *Progress in Human Geography*, **41** (4), 524–533. https://doi.org/10.1177/0309132516646495

76. Stone, K., N. Blinn, and R. Spencer, 2022: Mental health impacts of climate change on women: A scoping review. *Current Environmental Health Reports*, **9** (2), 228–243. https://doi.org/10.1007/s40572-022-00346-8

77. Bigger, P. and N. Millington, 2020: Getting soaked? Climate crisis, adaptation finance, and racialized austerity. *Environment and Planning E: Nature and Space*, **3** (3), 601–623. https://doi.org/10.1177/2514848619876539

78. Huang, X. and C. Wang, 2020: Estimates of exposure to the 100-year floods in the conterminous United States using national building footprints. *International Journal of Disaster Risk Reduction*, **50**, 101731. https://doi.org/10.1016/j.ijdrr.2020.101731

79. Tate, E., M.A. Rahman, C.T. Emrich, and C.C. Sampson, 2021: Flood exposure and social vulnerability in the United States. *Natural Hazards*, **106** (1), 435–457. https://doi.org/10.1007/s11069-020-04470-2

80. USGCRP, 2018: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 1515 pp. https://doi.org/10.7930/nca4.2018

81. Siders, A.R. and J.M. Keenan, 2020: Variables shaping coastal adaptation decisions to armor, nourish, and retreat in North Carolina. *Ocean & Coastal Management*, **183**, 105023. https://doi.org/10.1016/j.ocecoaman.2019.105023

82. Barile, J.P., S.B. Binder, and C.K. Baker, 2020: Recovering after a natural disaster: Differences in quality of life across three communities after Hurricane Sandy. *Applied Research in Quality of Life*, **15** (4), 1151–1159. https://doi.org/10.1007/s11482-019-09722-3

83. Mach, K.J., C.M. Kraan, M. Hino, A.R. Siders, E.M. Johnston, and C.B. Field, 2019: Managed retreat through voluntary buyouts of flood-prone properties. *Science Advances*, **5** (10), 8995. https://doi.org/10.1126/sciadv.aax8995

84. McGhee, D.J., S.B. Binder, and E.A. Albright, 2020: First, do no harm: Evaluating the vulnerability reduction of post-disaster home buyout programs. *Natural Hazards Review*, **21** (1), 05019002. https://doi.org/10.1061/(asce)nh.1527-6996.0000337

85. Elliott, J.R., K. Loughran, and P.L. Brown, 2021: Divergent residential pathways from flood-prone areas: How neighborhood inequalities are shaping urban climate adaptation. *Social Problems*, spab059. https://doi.org/10.1093/socpro/spab059

86. Turek-Hankins, L.L., M. Hino, and K.J. Mach, 2020: Risk screening methods for extreme heat: Implications for equity-oriented adaptation. *PLoS ONE*, **15** (11), e0240841. https://doi.org/10.1371/journal.pone.0240841

87. Beckage, B., K. Lacasse, J.M. Winter, L.J. Gross, N. Fefferman, F.M. Hoffman, S.S. Metcalf, T. Franck, E. Carr, A. Zia, and A. Kinzig, 2020: The Earth has humans, so why don't our climate models? *Climatic Change*, **163** (1), 181–188. https://doi.org/10.1007/s10584-020-02897-x

88. Moore, F.C., K. Lacasse, K.J. Mach, Y.A. Shin, L.J. Gross, and B. Beckage, 2022: Determinants of emissions pathways in the coupled climate–social system. *Nature*, **603** (7899), 103–111. https://doi.org/10.1038/s41586-022-04423-8

89. Palmer, P.I. and M.J. Smith, 2014: Earth systems: Model human adaptation to climate change. *Nature*, **512** (7515), 365–366. https://doi.org/10.1038/512365a

90. Rising, J., M. Tedesco, F. Piontek, and D.A. Stainforth, 2022: The missing risks of climate change. *Nature*, **610** (7933), 643–651. https://doi.org/10.1038/s41586-022-05243-6

91. Cain, B.E., E.R. Gerber, and I. Hui, 2020: Getting bipartisan support for sea level rise adaptation policies. *Ocean & Coastal Management*, **197**, 105298. https://doi.org/10.1016/j.ocecoaman.2020.105298

92. Willison, C.E., P.M. Singer, M.S. Creary, S. Vaziri, J. Stott, and S.L. Greer, 2021: How do you solve a problem like Maria? The politics of disaster response in Puerto Rico, Florida and Texas. *World Medical & Health Policy*, **14** (3), 490–506. https://doi.org/10.1002/wmh3.476

93. Garrick, D., L. De Stefano, W. Yu, I. Jorgensen, E. O'Donnell, L. Turley, I. Aguilar-Barajas, X. Dai, R. de Souza Leão, B. Punjabi, B. Schreiner, J. Svensson, and C. Wight, 2019: Rural water for thirsty cities: A systematic review of water reallocation from rural to urban regions. *Environmental Research Letters*, **14** (4), 043003. https://doi.org/10.1088/1748-9326/ab0db7

94. Kelly-Reif, K. and S. Wing, 2016: Urban-rural exploitation: An underappreciated dimension of environmental injustice. *Journal of Rural Studies*, **47**, 350–358. https://doi.org/10.1016/j.jrurstud.2016.03.010

95. Shi, L., S. Ahmad, P. Shukla, and S. Yupho, 2021: Shared injustice, splintered solidarity: Water governance across urban-rural divides. *Global Environmental Change*, **70**, 102354. https://doi.org/10.1016/j.gloenvcha.2021.102354

96. Bukvic, A. and J. Harrald, 2019: Rural versus urban perspective on coastal flooding: The insights from the U.S. Mid-Atlantic communities. *Climate Risk Management*, **23**, 7–18. https://doi.org/10.1016/j.crm.2018.10.004

97. Hansen, G. and W. Cramer, 2015: Global distribution of observed climate change impacts. *Nature Climate Change*, **5** (3), 182–185. https://doi.org/10.1038/nclimate2529

98. Friel, S., D. Vlahov, and R.M. Buckley, 2011: No data, no problem, no action: Addressing urban health inequity in the 21st century. *Journal of Urban Health*, **88** (5), 858. https://doi.org/10.1007/s11524-011-9616-z

99. Bullard, R.D. and B. Wright, 2012: *The Wrong Complexion for Protection: How the Government Response to Disaster Endangers African American Communities*. New York University Press. https://doi.org/10.18574/nyu/9780814799932.001.0001

100. Andrews, C.J., 2020: Toward a research agenda on climate-related migration. *Journal of Industrial Ecology*, **24** (2), 331–341. https://doi.org/10.1111/jiec.13005

101. Sastry, N. and J. Gregory, 2014: The location of displaced New Orleans residents in the year after Hurricane Katrina. *Demography*, **51** (3), 753–775. https://doi.org/10.1007/s13524-014-0284-y

102. Beam, A., 2019: Chico didn't burn but Camp fire brought a new way of life. *The Press Democrat*, November 7, 2019. https://www.pressdemocrat.com/article/news/chico-didnt-burn-but-camp-fire-brought-a-new-way-of-life/

103. Spearing, L.A. and K.M. Faust, 2020: Cascading system impacts of the 2018 Camp Fire in California: The interdependent provision of infrastructure services to displaced populations. *International Journal of Disaster Risk Reduction*, **50**, 101822. https://doi.org/10.1016/j.ijdrr.2020.101822

104. Lefebvre, B., 2021: How 'climate migrants' are roiling American politics. *POLITICO*. https://www.politico.com/news/magazine/2021/11/27/how-climate-migrants-are-roiling-american-politics-523295

105. Rainey, J., 2019: Fire turns Chico, California, into a boomtown, but at what cost? *NBC News*, January 20, 2019. https://www.nbcnews.com/news/us-news/fire-turns-chico-california-boomtown-what-cost-n960081

106. Klein, N., 2021: A climate dystopia in Northern California. *The Intercept*, May 7 2021. https://theintercept.com/2021/05/07/california-fires-chico-housing-real-estate/

107. Wedgeworth, C., 2019: Hottest U.S. real estate market for December 2018 is Chico, CA. *Realtor*, January 9, 2019. https://www.realtor.com/news/trends/december-2018-hottest-real-estate-markets-wildfire-boosts-chico/

108. Curtis, K.J., J. DeWaard, E. Fussell, and R.A. Rosenfeld, 2020: Differential recovery migration across the rural–urban gradient: Minimal and short-term population gains for rural disaster-affected Gulf Coast counties. *Rural Sociology*, **85** (4), 856–898. https://doi.org/10.1111/ruso.12305

109. de Koning, K. and T. Filatova, 2020: Repetitive floods intensify outmigration and climate gentrification in coastal cities. *Environmental Research Letters*, **15** (3), 034008. https://doi.org/10.1088/1748-9326/ab6668

110. Friedman, N., 2021: The pandemic ignited a housing boom—But it's different from the last one. *The Wall Street Journal*, March 15, 2021. https://www.wsj.com/articles/the-pandemic-ignited-a-housing-boombut-its-different-from-the-last-one-11615824558

111. Patino, M., A. Kessler, S. Holder, J. Gu, and M. Rojanasakul, 2021: More Americans are leaving cities, but don't call it an urban exodus. *Bloomberg*, April 26, 2021. https://www.bloomberg.com/graphics/2021-citylab-how-americans-moved/

112. Moser, S.C. and J.A.F. Hart, 2015: The long arm of climate change: Societal teleconnections and the future of climate change impacts studies. *Climatic Change*, **129** (1), 13–26. https://doi.org/10.1007/s10584-015-1328-z

113. Zoraghein, H. and B.C. O'Neill, 2020: A spatial population downscaling model for integrated human-environment analysis in the United States. *Demographic Research*, **43**, 1563–1606. https://doi.org/10.4054/demres.2020.43.54

114. Field, C.B., V.R. Barros, K.J. Mach, M.D. Mastrandrea, M. van Aalst, W.N. Adger, D.J. Arent, J. Barnett, R. Betts, T.E. Bilir, J. Birkmann, J. Carmin, D.D. Chadee, A.J. Challinor, M. Chatterjee, W. Cramer, D.J. Davidson, Y.O. Estrada, J.P. Gattuso, Y. Hijioka, O. Hoegh-Guldberg, H.Q. Huang, G.E. Insarov, R.N. Jones, R.S. Kovats, P.R. Lankao, J.N. Larsen, I.J. Losada, J.A. Marengo, R.F. McLean, L.O. Mearns, R. Mechler, J.F. Morton, I. Niang, T. Oki, J.M. Olwoch, M. Opondo, E.S. Poloczanska, H.O. Pörtner, M.H. Redsteer, A. Reisinger, A. Revi, D.N. Schmidt, M.R. Shaw, W. Solecki, D.A. Stone, J.M.R. Stone, K.M. Strzepek, A.G. Suarez, P. Tschakert, R. Valentini, S. Vicuña, A. Villamizar, K.E. Vincent, R. Warren, L.L. White, T.J. Wilbanks, P.P. Wong, and G.W. Yohe, 2014: Technical summary. 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*. Field, C.B., 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. Cambridge University Press, Cambridge, UK and New York, NY, USA, 35–94. https://www.ipcc.ch/report/ar5/wg2/

115. Hulme, M., 2018: "Gaps" in climate change knowledge: Do they exist? Can they be filled? *Environmental Humanities*, **10** (1), 330–337. https://doi.org/10.1215/22011919-4385599

116. Stern, M.J., D.D. Briske, and A.M. Meadow, 2021: Opening learning spaces to create actionable knowledge for conservation. *Conservation Science and Practice*, **3** (5), e378. https://doi.org/10.1111/csp2.378

117. Lubell, M. and T.H. Morrison, 2021: Institutional navigation for polycentric sustainability governance. *Nature Sustainability*, **4** (8), 664–671. https://doi.org/10.1038/s41893-021-00707-5

118. Härtel, C.E.J. and G.I. Pearman, 2010: Understanding and responding to the climate change issue: Towards a whole-of-science research agenda. *Journal of Management & Organization*, **16** (1), 16–47. https://doi.org/10.5172/jmo.16.1.16

119. Lemos, M.C., H. Eakin, L. Dilling, and J. Worl, 2019: Social sciences, weather, and climate change. *Meteorological Monographs*, **59**, 26.1–26.25. https://doi.org/10.1175/amsmonographs-d-18-0011.1

120. Meinke, H., R. Nelson, P. Kokic, R. Stone, R. Selvaraju, and W. Baethgen, 2006: Actionable climate knowledge: From analysis to synthesis. *Climate Research*, **33**, 101–110. https://doi.org/10.3354/cr033101

121. Moss, R.H., J.A. Edmonds, K.A. Hibbard, M.R. Manning, S.K. Rose, D.P. van Vuuren, T.R. Carter, S. Emori, M. Kainuma, T. Kram, G.A. Meehl, J.F.B. Mitchell, N. Nakicenovic, K. Riahi, S.J. Smith, R.J. Stouffer, A.M. Thomson, J.P. Weyant, and T.J. Wilbanks, 2010: The next generation of scenarios for climate change research and assessment. *Nature*, **463**, 747–756. https://doi.org/10.1038/nature08823

122. Tribbia, J. and S.C. Moser, 2008: More than information: What coastal managers need to plan for climate change. *Environmental Science & Policy*, **11** (4), 315–328. https://doi.org/10.1016/j.envsci.2008.01.003

123. Liu, J., T. Dietz, S.R. Carpenter, M. Alberti, C. Folke, E. Moran, A.N. Pell, P. Deadman, T. Kratz, J. Lubchenco, E. Ostrom, Z. Ouyang, W. Provencher, C.L. Redman, S.H. Schneider, and W.W. Taylor, 2007: Complexity of coupled human and natural systems. *Science*, **317** (5844), 1513–1516. https://doi.org/10.1126/science.1144004

124. Polk, M., 2015: Transdisciplinary co-production: Designing and testing a transdisciplinary research framework for societal problem solving. *Futures*, **65**, 110–122. https://doi.org/10.1016/j.futures.2014.11.001

125. Jagannathan, K., A.D. Jones, and I. Ray, 2021: The making of a metric: Co-producing decision-relevant climate science. *Bulletin of the American Meteorological Society*, **102** (8), E1579–E1590. https://doi.org/10.1175/bams-d-19-0296.1

126. Miralles-Wilhelm, F., 2016: Development and application of integrative modeling tools in support of food-energy-water nexus planning—A research agenda. *Journal of Environmental Studies and Sciences*, **6** (1), 3–10. https://doi.org/10.1007/s13412-016-0361-1

127. Moss, R.H., S. Avery, K. Baja, M. Burkett, A.M. Chischilly, J. Dell, P.A. Fleming, K. Geil, K. Jacobs, A. Jones, K. Knowlton, J. Koh, M.C. Lemos, J. Melillo, R. Pandya, T.C. Richmond, L. Scarlett, J. Snyder, M. Stults, A. Waple, J. Whitehead, D. Zarrilli, J. Fox, A. Ganguly, L. Joppa, S. Julius, P. Kirshen, R. Kreutter, A. McGovern, R. Meyer, J. Neumann, W. Solecki, J. Smith, P. Tissot, G. Yohe, and R. Zimmerman, 2019: A framework for sustained climate assessment in the United States. *Bulletin of the American Meteorological Society*, **100** (5), 897–907. https://doi.org/10.1175/bams-d-19-0130.1

128. Biehl, P.F., S. Crate, M. Gardezi, L. Hamilton, S.L. Harlan, C. Hritz, B. Hubbell, T.A. Kohler, N. Peterson, and J. Silva, 2018: Innovative Tools, Methods, and Analysis: Social Science Perspectives on Climate Change, Part 3. U.S. Global Change Research Program, Social Science Coordinating Committee, Washington, DC. https://www.globalchange.gov/sites/globalchange/files/Methods_SSCC.pdf

129. Krauß, W. and S. Bremer, 2020: The role of place-based narratives of change in climate risk governance. *Climate Risk Management*, **28**, 100221. https://doi.org/10.1016/j.crm.2020.100221

130. Moezzi, M., K.B. Janda, and S. Rotmann, 2017: Using stories, narratives, and storytelling in energy and climate change research. *Energy Research & Social Science*, **31**, 1–10. https://doi.org/10.1016/j.erss.2017.06.034

131. Calvin, K., P. Patel, L. Clarke, G. Asrar, B. Bond-Lamberty, R.Y. Cui, A. Di Vittorio, K. Dorheim, J. Edmonds, C. Hartin, M. Hejazi, R. Horowitz, G. Iyer, P. Kyle, S. Kim, R. Link, H. McJeon, S.J. Smith, A. Snyder, S. Waldhoff, and M. Wise, 2019: GCAM v5.1: Representing the linkages between energy, water, land, climate, and economic systems. *Geoscientific Model Development*, **12** (2), 677–698. https://doi.org/10.5194/gmd-12-677-2019

132. Vogel, J., E. McNie, and D. Behar, 2016: Co-producing actionable science for water utilities. *Climate Services*, **2–3**, 30–40. https://doi.org/10.1016/j.cliser.2016.06.003

133. Epstein, S.A., S.-M. Lee, A.S. Katzenstein, M. Carreras-Sospedra, X. Zhang, S.C. Farina, P. Vahmani, P.M. Fine, and G. Ban-Weiss, 2017: Air-quality implications of widespread adoption of cool roofs on ozone and particulate matter in southern California. *Proceedings of the National Academy of Sciences of the United States of America*, **114** (34), 8991–8996. https://doi.org/10.1073/pnas.1703560114

134. Vahmani, P. and A.D. Jones, 2017: Water conservation benefits of urban heat mitigation. *Nature Communications*, **8** (1), 1072. https://doi.org/10.1038/s41467-017-01346-1

135. Vahmani, P., F. Sun, A. Hall, and G. Ban-Weiss, 2016: Investigating the climate impacts of urbanization and the potential for cool roofs to counter future climate change in Southern California. *Environmental Research Letters*, **11** (12), 124027. https://doi.org/10.1088/1748-9326/11/12/124027

136. Szinai, J.K., R. Deshmukh, D.M. Kammen, and A.D. Jones, 2020: Evaluating cross-sectoral impacts of climate change and adaptations on the energy-water nexus: A framework and California case study. *Environmental Research Letters*, **15** (12), 124065. https://doi.org/10.1088/1748-9326/abc378

137. Scanlon, B.R., B.L. Ruddell, P.M. Reed, R.I. Hook, C. Zheng, V.C. Tidwell, and S. Siebert, 2017: The food-energy-water nexus: Transforming science for society. *Water Resources Research*, **53** (5), 3550–3556. https://doi.org/10.1002/2017wr020889

138. Ford, J.D., N. King, E.K. Galappaththi, T. Pearce, G. McDowell, and S.L. Harper, 2020: The resilience of Indigenous peoples to environmental change. *One Earth*, **2** (6), 532–543. https://doi.org/10.1016/j.oneear.2020.05.014

139. Petzold, J., N. Andrews, J.D. Ford, C. Hedemann, and J.C. Postigo, 2020: Indigenous knowledge on climate change adaptation: A global evidence map of academic literature. *Environmental Research Letters*, **15** (11), 113007. https://doi.org/10.1088/1748-9326/abb330

140. Voinov, A. and E.B. Gaddis, 2017: Ch. 3. Values in participatory modeling: Theory and practice. In: *Environmental Modeling with Stakeholders: Theory, Methods, and Applications*. Gray, S., M. Paolisso, R. Jordan, and S. Gray, Eds. Springer, Cham, Switzerland, 47–63. https://doi.org/10.1007/978-3-319-25053-3_3

141. Bremer, S., M.M. Haque, S.B. Aziz, and S. Kvamme, 2019: 'My new routine': Assessing the impact of citizen science on climate adaptation in Bangladesh. *Environmental Science & Policy*, **94**, 245–257. https://doi.org/10.1016/j.envsci.2018.12.029

142. Cooper, C.B., J. Shirk, and B. Zuckerberg, 2014: The invisible prevalence of citizen science in global research: Migratory birds and climate change. *PLoS ONE*, **9** (9), e106508. https://doi.org/10.1371/journal.pone.0106508

143. Danielsen, F., K. Pirhofer-Walzl, T.P. Adrian, D.R. Kapijimpanga, N.D. Burgess, P.M. Jensen, R. Bonney, M. Funder, A. Landa, N. Levermann, and J. Madsen, 2014: Linking public participation in scientific research to the indicators and needs of international environmental agreements. *Conservation Letters*, **7** (1), 12–24. https://doi.org/10.1111/conl.12024

144. Rubio-Iglesias, J.M., T. Edovald, R. Grew, T. Kark, A.E. Kideys, T. Peltola, and H. Volten, 2020: Citizen science and environmental protection agencies: Engaging citizens to address key environmental challenges. *Frontiers in Climate*, **2**, 600998. https://doi.org/10.3389/fclim.2020.600998

145. Weatherhead, E., S. Gearheard, and R.G. Barry, 2010: Changes in weather persistence: Insight from Inuit knowledge. *Global Environmental Change*, **20** (3), 523–528. https://doi.org/10.1016/j.gloenvcha.2010.02.002

146. Bremer, S. and S. Meisch, 2017: Co-production in climate change research: Reviewing different perspectives. *WIREs Climate Change*, **8** (6), e482. https://doi.org/10.1002/wcc.482

147. Lemos, M.C., J.C. Arnott, N.M. Ardoin, K. Baja, A.T. Bednarek, A. Dewulf, C. Fieseler, K.A. Goodrich, K. Jagannathan, N. Klenk, K.J. Mach, A.M. Meadow, R. Meyer, R. Moss, L. Nichols, K.D. Sjostrom, M. Stults, E. Turnhout, C. Vaughan, G. Wong-Parodi, and C. Wyborn, 2018: To co-produce or not to co-produce. *Nature Sustainability*, **1** (12), 722–724. https://doi.org/10.1038/s41893-018-0191-0

148. Mach, K.J., M.C. Lemos, A.M. Meadow, C. Wyborn, N. Klenk, J.C. Arnott, N.M. Ardoin, C. Fieseler, R.H. Moss, L. Nichols, M. Stults, C. Vaughan, and G. Wong-Parodi, 2020: Actionable knowledge and the art of engagement. *Current Opinion in Environmental Sustainability*, **42**, 30–37. https://doi.org/10.1016/j.cosust.2020.01.002

149. Miller, C.A. and C. Wyborn, 2020: Co-production in global sustainability: Histories and theories. *Environmental Science & Policy*, **113**, 88–95. https://doi.org/10.1016/j.envsci.2018.01.016

150. Chambers, J.M., C. Wyborn, M.E. Ryan, R.S. Reid, M. Riechers, A. Serban, N.J. Bennett, C. Cvitanovic, M.E. Fernández-Giménez, K.A. Galvin, B.E. Goldstein, N.L. Klenk, M. Tengö, R. Brennan, J.J. Cockburn, R. Hill, C. Munera, J.L. Nel, H. Österblom, A.T. Bednarek, E.M. Bennett, A. Brandeis, L. Charli-Joseph, P. Chatterton, K. Curran, P. Dumrongrojwatthana, A.P. Durán, S.J. Fada, J.-D. Gerber, J.M.H. Green, A.M. Guerrero, T. Haller, A.-I. Horcea-Milcu, B. Leimona, J. Montana, R. Rondeau, M. Spierenburg, P. Steyaert, J.G. Zaehringer, R. Gruby, J. Hutton, and T. Pickering, 2021: Six modes of co-production for sustainability. *Nature Sustainability*, **4** (11), 983–996. https://doi.org/10.1038/s41893-021-00755-x

151. Jagannathan, K., J.C. Arnott, C. Wyborn, N. Klenk, K.J. Mach, R.H. Moss, and K.D. Sjostrom, 2020: Great expectations? Reconciling the aspiration, outcome, and possibility of co-production. *Current Opinion in Environmental Sustainability*, **42**, 22–29. https://doi.org/10.1016/j.cosust.2019.11.010

152. Owen, G., 2020: What makes climate change adaptation effective? A systematic review of the literature. *Global Environmental Change*, **62**, 102071. https://doi.org/10.1016/j.gloenvcha.2020.102071

153. Cash, D.W., W.C. Clark, F. Alcock, N.M. Dickson, N. Eckley, D.H. Guston, J. Jäger, and R.B. Mitchell, 2003: Knowledge systems for sustainable development. *Proceedings of the National Academy of Sciences of the United States of America*, **100** (14), 8086–8091. https://doi.org/10.1073/pnas.1231332100

154. Lemos, M.C., C.J. Kirchhoff, and V. Ramprasad, 2012: Narrowing the climate information usability gap. *Nature Climate Change*, **2** (11), 789–794. https://doi.org/10.1038/nclimate1614

155. Briley, L., D. Brown, and S.E. Kalafatis, 2015: Overcoming barriers during the co-production of climate information for decision-making. *Climate Risk Management*, **9**, 41–49. https://doi.org/10.1016/j.crm.2015.04.004

156. Voinov, A. and F. Bousquet, 2010: Modelling with stakeholders. *Environmental Modelling & Software*, **25** (11), 1268–1281. https://doi.org/10.1016/j.envsoft.2010.03.007

157. Voinov, A., N. Kolagani, M.K. McCall, P.D. Glynn, M.E. Kragt, F.O. Ostermann, S.A. Pierce, and P. Ramu, 2016: Modelling with stakeholders – Next generation. *Environmental Modelling & Software*, **77**, 196–220. https://doi.org/10.1016/j.envsoft.2015.11.016

158. County of Los Angeles, 2021: LA County Climate Vulnerability Assessment. County of Los Angeles, LA County Chief Sustainability Office, Los Angeles, CA. https://ceo.lacounty.gov/wp-content/uploads/2021/10/LA-County-Climate-Vulnerability-Assessment-1.pdf

159. California Coastal Commission, 2020: California Coastal Commission Final Strategic Plan 2021–2025. State of California, California Natural Resources Agency, San Francisco, CA. https://documents.coastal.ca.gov/assets/strategicplan/ccc_strategic_plan_adopted_11.06.20_rev.pdf

160. Stanton, M.C.B. and K. Roelich, 2021: Decision making under deep uncertainties: A review of the applicability of methods in practice. *Technological Forecasting and Social Change*, **171**, 120939. https://doi.org/10.1016/j.techfore.2021.120939

161. Werners, S.E., R.M. Wise, J.R.A. Butler, E. Totin, and K. Vincent, 2021: Adaptation pathways: A review of approaches and a learning framework. *Environmental Science & Policy*, **116**, 266–275. https://doi.org/10.1016/j.envsci.2020.11.003

162. Cobb, A.N. and J.L. Thompson, 2012: Climate change scenario planning: A model for the integration of science and management in environmental decision-making. *Environmental Modelling & Software*, **38**, 296–305. https://doi.org/10.1016/j.envsoft.2012.06.012

163. Lawrence, D.J. and A.N. Runyon, 2019: Implications of Climate Change for the Water Supply of the Chisos Mountains Developed Area. Natural Resource Report NPS/NRSS/CCRP/NRR—2019/2045. U.S. Department of the Interior, National Park Service, Fort Collins, CO. https://irma.nps.gov/datastore/downloadfile/631301

164. Miller, B.W., G.W. Schuurman, A.J. Symstad, A.N. Runyon, and B.C. Robb, 2022: Conservation under uncertainty: Innovations in participatory climate change scenario planning from U.S. national parks. *Conservation Science and Practice*, **4** (3), 12633. https://doi.org/10.1111/csp2.12633

165. Runyon, A.N., A.R. Carlson, J. Gross, D.J. Lawrence, and G.W. Schuurman, 2020: Repeatable approaches to work with scientific uncertainty and advance climate change adaptation in US national parks. *Parks Stewardship Forum*, **36** (1), 98–104. https://doi.org/10.5070/p536146402

166. Bremer, S., A. Wardekker, S. Dessai, S. Sobolowski, R. Slaattelid, and J. van der Sluijs, 2019: Toward a multi-faceted conception of co-production of climate services. *Climate Services*, **13**, 42–50. https://doi.org/10.1016/j.cliser.2019.01.003

167. Vaughan, C., L. Buja, A. Kruczkiewicz, and L. Goddard, 2016: Identifying research priorities to advance climate services. *Climate Services*, **4**, 65–74. https://doi.org/10.1016/j.cliser.2016.11.004

168. Vaughan, C. and S. Dessai, 2014: Climate services for society: Origins, institutional arrangements, and design elements for an evaluation framework. *Wiley Interdisciplinary Reviews: Climate Change*, **5** (5), 587–603. https://doi.org/10.1002/wcc.290

169. Goodrich, K.A., K.D. Sjostrom, C. Vaughan, L. Nichols, A. Bednarek, and M.C. Lemos, 2020: Who are boundary spanners and how can we support them in making knowledge more actionable in sustainability fields? *Current Opinion in Environmental Sustainability*, **42**, 45–51. https://doi.org/10.1016/j.cosust.2020.01.001

170. Lemos, M.C., C.J. Kirchhoff, S.E. Kalafatis, D. Scavia, and R.B. Rood, 2014: Moving climate information off the shelf: Boundary chains and the role of Risas as adaptive organizations. *Weather, Climate, and Society*, **6** (2), 273–285. https://doi.org/10.1175/wcas-d-13-00044.1

171. Meadow, A.M. and G. Owen, 2021: Planning and Evaluating the Societal Impacts of Climate Change Research Projects: A Guidebook for Natural and Physical Scientists Looking to Make a Difference. University of Arizona, Tucson, AZ. https://doi.org/10.2458/10150.658313

172. Wong-Parodi, G., K.J. Mach, K. Jagannathan, and K.D. Sjostrom, 2020: Insights for developing effective decision support tools for environmental sustainability. *Current Opinion in Environmental Sustainability*, **42**, 52–59. https://doi.org/10.1016/j.cosust.2020.01.005

173. Miami-Dade County, 2022: Little River Adaptation Action Area [Website]. https://adaptation-action-area-in-little-river-mdc.hub.arcgis.com/

174. Harrison, T.R., A. Clark, A. Clement, J. Lombard, G. Maranto, A. Parrish, S. Purkis, M. Reamer, O. Collins, C. Lewis, M. Cruz, and A. Solache, 2022: Advancing a hyperlocal approach to community engagement in climate adaptation: Results from a South Florida pilot study in two communities. *PLoS Climate*, **1** (6), e0000041. https://doi.org/10.1371/journal.pclm.0000041

175. Miami-Dade County, 2021: Climate Action Strategy [Webpage]. https://www.miamidade.gov/global/economy/resilience/climate-strategy/home.page

176. Miami-Dade County, 2021: Miami-Dade County Sea Level Rise Strategy. Miami-Dade County. https://miami-dade-county-sea-level-rise-strategy-draft-mdc.hub.arcgis.com/

177. SFWMD, 2021: SFWMD seeking public input on draft sea level rise and flood resiliency plan. South Florida Water Management District, West Palm Beach, FL, November 29, 2021. https://www.sfwmd.gov/news-events/news/sfwmd-seeking-public-input-draft-sea-level-rise-and-flood-resiliency-plan

178. Troxler, T.G., A.C. Clement, Y. Arditi-Rocha, G. Beesing, M. Bhat, J. Bolson, C. Cabán-Alemán, K. Castillo, O. Collins, M. Cruz, A. Dodd, S.D. Evans, A.L. Fleming, C. Genatios, J. Gilbert, A. Hernandez, C. Holder, M. Ilcheva, E. Kelly, and E. Wheaton, 2021: A system for resilience learning: Developing a community-driven, multi-sector research approach for greater preparedness and resilience to long-term climate stressors and extreme events in the Miami metropolitan region. *Journal of Extreme Events*, **08** (03), 2150019. https://doi.org/10.1142/s2345737621500196

179. Tedesco, M., C.G. Hultquist, and A. Sherbinin, 2021: A new dataset integrating public socioeconomic, physical risk, and housing data for climate justice metrics: A test-case study in Miami. *Environmental Justice*, **15** (3), 149–159. https://doi.org/10.1089/env.2021.0059

180. Miami-Dade County, 2022: Planning for Sea Level Rise in the Little River Adaptation Action Area. Resilient 305: Adaptation Action Area in Little River. Miami-Dade County, Office of Resilience. https://adaptation-action-area-in-little-river-mdc.hub.arcgis.com/

181. Southeast Florida Regional Climate Change Compact Sea Level Rise Work Group, 2020: Unified Sea Level Rise Projections: 2019 Update. Southeast Florida Regional Climate Change Compact, 36 pp. https://southeastfloridaclimatecompact.org/unified-sea-level-rise-projections/

182. Huitema, D., W.N. Adger, F. Berkhout, E. Massey, D. Mazmanian, S. Munaretto, R. Plummer, and C.C.J.A.M. Termeer, 2016: The governance of adaptation: Choices, reasons, and effects. Introduction to the Special Feature. *Ecology and Society*, **21** (3), 37. https://doi.org/10.5751/es-08797-210337

183. Reed, T., L.R. Mason, and C.C. Ekenga, 2020: Adapting to climate change in the Upper Mississippi River Basin: Exploring stakeholder perspectives on river system management and flood risk reduction. *Environmental Health Insights*, **14**, 1178630220984153. https://doi.org/10.1177/1178630220984153

184. Ulibarri, N. and N. Escobedo Garcia, 2020: Comparing complexity in watershed governance: The case of California. *Water*, **12** (3). https://doi.org/10.3390/w12030766

185. Moser, S.C., J.A. Ekstrom, J. Kim, and S. Heitsch, 2019: Adaptation finance archetypes: Local governments' persistent challenges of funding adaptation to climate change and ways to overcome them. *Ecology and Society*, **24** (2), 28. https://doi.org/10.5751/es-10980-240228

186. Fried, H., M. Hamilton, and R. Berardo, 2022: Closing integrative gaps in complex environmental governance systems. *Ecology and Society*, **27** (1). https://doi.org/10.5751/es-12996-270115

187. Munaretto, S., G. Siciliano, and M.E. Turvani, 2014: Integrating adaptive governance and participatory multicriteria methods: A framework for climate adaptation governance. *Ecology and Society*, **19** (2), 74. https://doi.org/10.5751/es-06381-190274

188. Bai, X., R.R.J. McAllister, R.M. Beaty, and B. Taylor, 2010: Urban policy and governance in a global environment: Complex systems, scale mismatches and public participation. *Current Opinion in Environmental Sustainability*, **2** (3), 129–135. https://doi.org/10.1016/j.cosust.2010.05.008

189. Folke, C., T. Hahn, P. Olsson, and J. Norberg, 2005: Adaptive governance of social-ecological systems. *Annual Review of Environment and Resources*, **30** (1), 441–473. https://doi.org/10.1146/annurev.energy.30.050504.144511

190. Hurlbert, M.A. and J. Gupta, 2019: An institutional analysis method for identifying policy instruments facilitating the adaptive governance of drought. *Environmental Science & Policy*, **93**, 221–231. https://doi.org/10.1016/j.envsci.2018.09.017

191. Wheeler, S.M., 2008: State and municipal climate change plans: The first generation. *Journal of the American Planning Association*, **74** (4), 481–496. https://doi.org/10.1080/01944360802377973

192. Brown, A., A. Dayal, and C. Rumbaitis Del Rio, 2012: From practice to theory: Emerging lessons from Asia for building urban climate change resilience. *Environment and Urbanization*, **24** (2), 531–556. https://doi.org/10.1177/0956247812456490

193. Brown, A. and S. Kernaghan, 2011: Beyond climate-proofing: Taking an integrated approach to building climate resilience in Asian Cities. *Urbanisation and Global Environmental Change Viewpoints*, **6**, 4–7. https://www.acccrn.net/resources/beyond-climate-proofing-taking-integrated-approach-building-climate-resilience-asian

194. De Wandeler, K., 2014: Social resilience and urban growth: Exploring urban 'strategies' and 'tactics' in Bangkok and Colombo. In: *Proceedings of the International Conference on 'Cities, People and Places'*. Colombo, Sri Lanka, 31 October–2 November 2014, 23 pp. https://uom.lk/sites/default/files/cfc/files/ICCPP-2014%20%20Programme%20%26%20Abstract_0.pdf

195. Ekstrom, J. and S. Moser, 2013: Ch. 6. Institutions as key element to successful climate adaptation processes: Results from the San Francisco Bay Area. In: *Successful Adaptation to Climate Change*, 1st ed. Routledge, London, UK, 97–113. https://doi.org/10.4324/9780203593882

196. Oberlack, C., 2017: Diagnosing institutional barriers and opportunities for adaptation to climate change. *Mitigation and Adaptation Strategies for Global Change*, **22** (5), 805–838. https://doi.org/10.1007/s11027-015-9699-z

197. Antrobus, D., 2011: Smart green cities: From modernization to resilience? *Urban Research & Practice*, **4** (2), 207–214. https://doi.org/10.1080/17535069.2011.579777

198. Arellano-Gonzalez, J., A. AghaKouchak, M.C. Levy, Y. Qin, J. Burney, S.J. Davis, and F.C. Moore, 2021: The adaptive benefits of agricultural water markets in California. *Environmental Research Letters*, **16** (4), 044036. https://doi.org/10.1088/1748-9326/abde5b

199. Aylett, A., 2015: Institutionalizing the urban governance of climate change adaptation: Results of an international survey. *Urban Climate*, **14**, 4–16. https://doi.org/10.1016/j.uclim.2015.06.005

200. Bahadur, A.V. and T. Tanner, 2014: Policy climates and climate policies: Analysing the politics of building urban climate change resilience. *Urban Climate*, **7**, 20–32. https://doi.org/10.1016/j.uclim.2013.08.004

201. Considine, M., J.M. Lewis, and D. Alexander, 2009: *Networks, Innovation and Public Policy: Politicians, Bureaucrats and the Pathways to Change inside Government*, 1st ed. Palgrave Macmillan, London, UK, 231 pp. https://doi.org/10.1057/9780230595040

202. Hamilton, M. and M. Lubell, 2018: Collaborative governance of climate change adaptation across spatial and institutional scales. *Policy Studies Journal*, **46** (2), 222–247. https://doi.org/10.1111/psj.12224

203. Martín, C. and S. McTarnaghan, 2018: Institutionalizing Urban Resilience: A Midterm Monitoring and Evaluation Report of 100 Resilient Cities. Urban Institute, Washington, DC. https://www.urban.org/research/publication/institutionalizing-urban-resilience

204. Moon, M.J. and D.F. Norris, 2005: Does managerial orientation matter? The adoption of reinventing government and e-government at the municipal level. *Information Systems Journal*, **15** (1), 43–60. https://doi.org/10.1111/j.1365-2575.2005.00185.x

205. Nelson, K.L. and J.H. Svara, 2010: Adaptation of models versus variations in form: Classifying structures of city government. *Urban Affairs Review*, **45** (4), 544–562. https://doi.org/10.1177/1078087409356349

206. Nelson, K.L. and J.H. Svara, 2012: Form of government still matters: Fostering innovation in U.S. municipal governments. *The American Review of Public Administration*, **42** (3), 257–281. https://doi.org/10.1177/0275074011399898

207. Nelson, K.L. and J.H. Svara, 2015: The roles of local government managers in theory and practice: A centennial perspective. *Public Administration Review*, **75** (1), 49–61. https://doi.org/10.1111/puar.12296

208. Nelson, K.L., C.H. Wood, and G.T. Gabris, 2011: Innovation management in local government: An empirical analysis of suburban municipalities. *International Journal of Organization Theory & Behavior*, **14** (3), 301–328. https://doi.org/10.1108/ijotb-14-03-2011-b001

209. Tanner, T., T. Mitchell, E. Polack, and B. Guenther, 2009: Urban governance for adaptation: Assessing climate change resilience in ten Asian cities. *IDS Working Papers*, **2009** (315), 01–47. https://doi.org/10.1111/j.2040-0209.2009.00315_2.x

210. Tyler, S. and M. Moench, 2012: A framework for urban climate resilience. *Climate and Development*, **4** (4), 311–326. https://doi.org/10.1080/17565529.2012.745389

211. Wallace, D. and R. Wallace, 2008: Urban systems during disasters: Factors for resilience. *Ecology and Society*, **13** (1), 18. https://doi.org/10.5751/es-02386-130118

212. Woodruff, S.C., S. Meerow, M. Stults, and C. Wilkins, 2022: Adaptation to resilience planning: Alternative pathways to prepare for climate change. *Journal of Planning Education and Research*, **42** (1), 64–75. https://doi.org/10.1177/0739456x18801057

213. Gourevitch, J.D., C. Kousky, Y. Liao, C. Nolte, A.B. Pollack, J.R. Porter, and J.A. Weill, 2023: Unpriced climate risk and the potential consequences of overvaluation in US housing markets. *Nature Climate Change*, **13** (3), 250–257. https://doi.org/10.1038/s41558-023-01594-8

214. Kousky, C. and K. French, 2023: Inclusive Insurance for Climate-Related Disasters: A Roadmap for the United States. Ceres, Boston, MA. https://www.ceres.org/resources/reports/report-inclusive-insurance-climate-related-disasters

215. Berke, P.R., W. Lyles, and G. Smith, 2014: Impacts of federal and state hazard mitigation policies on local land use policy. *Journal of Planning Education and Research*, **34** (1), 60–76. https://doi.org/10.1177/0739456x13517004

216. Bryan, T.K. and J.F. Wolf, 2010: Soft regionalism in action: Examining voluntary regional councils' structures, processes and programs. *Public Organization Review*, **10** (2), 99–115. https://doi.org/10.1007/s11115-009-0090-y

217. Chu, E.K., S. Hughes, and S.G. Mason, 2018: Ch. 18. Conclusion: Multilevel governance and climate change innovations in cities. In: *Climate Change in Cities: Innovations in Multi-Level Governance*. Hughes, S., E. Chu, and S. Mason, Eds. Springer, Cham, Switzerland, 361–378. https://doi.org/10.1007/978-3-319-65003-6_18

218. Cole, D.H., 2015: Advantages of a polycentric approach to climate change policy. *Nature Climate Change*, **5** (2), 114–118. https://doi.org/10.1038/nclimate2490

219. GAO, 2009: Climate Change Adaptation: Strategic Federal Planning Could Help Government Officials Make More Informed Decisions. GAO-10-113. U.S. Government Accountability Office. https://www.gao.gov/assets/gao-10-113.pdf

220. Hsu, A. and R. Rauber, 2021: Diverse climate actors show limited coordination in a large-scale text analysis of strategy documents. *Communications Earth & Environment*, **2** (1), 30. https://doi.org/10.1038/s43247-021-00098-7

221. Landauer, M., S. Juhola, and J. Klein, 2019: The role of scale in integrating climate change adaptation and mitigation in cities. *Journal of Environmental Planning and Management*, **62** (5), 741–765. https://doi.org/10.1080/09640568.2018.1430022

222. Ostrom, E., 2010: Polycentric systems for coping with collective action and global environmental change. *Global Environmental Change*, **20** (4), 550–557. https://doi.org/10.1016/j.gloenvcha.2010.07.004

223. Ostrom, E., 2012: Nested externalities and polycentric institutions: Must we wait for global solutions to climate change before taking actions at other scales? *Economic Theory*, **49** (2), 353–369. https://doi.org/10.1007/s00199-010-0558-6

224. Pendall, R., S. Rosenbloom, D.K. Levy, E. Oo, G. Knaap, J. Sartori, and A. Chakraborty, 2013: Can Federal Efforts Advance Federal and Local De-Siloing? UI No. 08752-000-00. Urban Institute, Washington, DC. https://www.urban.org/research/publication/can-federal-efforts-advance-federal-and-local-de-siloing-full-report

225. Davies, J.S., 2009: The limits of joined-up government: Towards a political analysis. *Public Administration*, **87** (1), 80–96. https://doi.org/10.1111/j.1467-9299.2008.01740.x

226. Fernandez, S. and H.G. Rainey, 2006: Managing successful organizational change in the public sector. *Public Administration Review*, **66** (2), 168–176. https://doi.org/10.1111/j.1540-6210.2006.00570.x

227. Franzel, J.M., 2008: Urban government innovation: Identifying current innovations and factors that contribute to their adoption. *Review of Policy Research*, **25** (3), 253–277. https://doi.org/10.1111/j.1541-1338.2008.00326.x

228. Fu, X., 2020: Measuring local sea-level rise adaptation and adaptive capacity: A national survey in the United States. *Cities*, **102**, 102717. https://doi.org/10.1016/j.cities.2020.102717

229. Kimble, D., J. Boex, and G. Kapitanova, 2012: Making Decentralization Work in Developing Countries: Transforming Local Government Entities into High-Performing Local Government Organizations. IDG Policy Brief. Urban Institute Center on International Development and Governance, 6 pp. https://www.urban.org/sites/default/files/publication/26271/412710-Making-Decentralization-Work-in-Developing-Countries-Transforming-Local-Government-Entities-into-High-Performing-Organizations.PDF

230. Krebs, T.B. and J.P. Pelissero, 2010: What influences city council adoption and support for reinventing government? Environmental or institutional factors? *Public Administration Review*, **70** (2), 258–267. https://doi.org/10.1111/j.1540-6210.2010.02132.x

231. Kwon, M., F.S. Berry, and R.C. Feiock, 2009: Understanding the adoption and timing of economic development strategies in US cities using innovation and institutional analysis. *Journal of Public Administration Research and Theory*, **19** (4), 967–988. https://doi.org/10.1093/jopart/mun026

232. Olazabal, M. and M. Ruiz De Gopegui, 2021: Adaptation planning in large cities is unlikely to be effective. *Landscape and Urban Planning*, **206**, 103974. https://doi.org/10.1016/j.landurbplan.2020.103974

233. Olazabal, M., M. Ruiz de Gopegui, E.L. Tompkins, K. Venner, and R. Smith, 2019: A cross-scale worldwide analysis of coastal adaptation planning. *Environmental Research Letters*, **14** (12), 124056. https://doi.org/10.1088/1748-9326/ab5532

234. Rosenbloom, D., J. Meadowcroft, and B. Cashore, 2019: Stability and climate policy? Harnessing insights on path dependence, policy feedback, and transition pathways. *Energy Research & Social Science*, **50**, 168–178. https://doi.org/10.1016/j.erss.2018.12.009

235. Stokes, L.C., 2020: *Short Circuiting Policy: Interest Groups and the Battle Over Clean Energy and Climate Policy in the American States*. Oxford University Press, New York. https://doi.org/10.1093/oso/9780190074258.001.0001

236. Ruppert, T. and E.L. Deady, 2017: Ch. 7. Climate change impacts on law and policy in Florida. In: *Florida's Climate: Changes, Variations, & Impacts*. Florida Climate Institute, 209–234. https://doi.org/10.17125/fci2017.ch07

237. Bushnell, J.B., S.P. Holland, J.E. Hughes, and C.R. Knittel, 2017: Strategic policy choice in state-level regulation: The EPA's clean power plan. *American Economic Journal: Economic Policy*, **9** (2), 57–90. https://doi.org/10.1257/pol.20150237

238. Vella, K., W.H. Butler, N. Sipe, T. Chapin, and J. Murley, 2016: Voluntary collaboration for adaptive governance: The southeast Florida regional climate change compact. *Journal of Planning Education and Research*, **36** (3), 363–376. https://doi.org/10.1177/0739456x16659700

239. Fastiggi, M., S. Meerow, and T.R. Miller, 2021: Governing urban resilience: Organisational structures and coordination strategies in 20 North American city governments. *Urban Studies*, **58** (6), 1262–1285. https://doi.org/10.1177/0042098020907277

240. McTarnaghan, S., J. Morales-Burnett, and R. Marx, 2022: Urban Resilience: From Global Vision to Local Practice. Urban Institute. https://www.urban.org/research/publication/urban-resilience-global-vision-local-practice

241. IPCC, 2023: Summary for policymakers. In: *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Lee, H. and J. Romero, Eds. Intergovernmental Panel on Climate Change, Geneva, Switzerland, 1-34. https://doi.org/10.59327/IPCC/AR6-9789291691647.001

242. Reed, P.M., A. Hadjimichael, R.H. Moss, C. Brelsford, C.D. Burleyson, S. Cohen, A. Dyreson, D.F. Gold, R.S. Gupta, K. Keller, M. Konar, E. Monier, J. Morris, V. Srikrishnan, N. Voisin, and J. Yoon, 2022: Multisector dynamics: Advancing the science of complex adaptive human-Earth systems. *Earth's Future*, **10** (3), e2021EF002621. https://doi.org/10.1029/2021ef002621

243. Carter, T.R., M. Benzie, E. Campiglio, H. Carlsen, S. Fronzek, M. Hildén, C.P.O. Reyer, and C. West, 2021: A conceptual framework for cross-border impacts of climate change. *Global Environmental Change*, **69**, 102307. https://doi.org/10.1016/j.gloenvcha.2021.102307

244. Challinor, A.J., W.N. Adger, T.G. Benton, D. Conway, M. Joshi, and D. Frame, 2018: Transmission of climate risks across sectors and borders. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376** (2121), 20170301. https://doi.org/10.1098/rsta.2017.0301

245. Gill, J.C. and B.D. Malamud, 2014: Reviewing and visualizing the interactions of natural hazards. *Reviews of Geophysics*, **52** (4), 680–722. https://doi.org/10.1002/2013rg000445

246. Leonard, M., S. Westra, A. Phatak, M. Lambert, B. van den Hurk, K. McInnes, J. Risbey, S. Schuster, D. Jakob, and M. Stafford-Smith, 2014: A compound event framework for understanding extreme impacts. *WIREs Climate Change*, **5** (1), 113–128. https://doi.org/10.1002/wcc.252

247. Pescaroli, G. and D. Alexander, 2018: Understanding compound, interconnected, interacting, and cascading risks: A holistic framework. *Risk Analysis*, **38** (11), 2245–2257. https://doi.org/10.1111/risa.13128

248. 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. https://doi.org/10.1038/s41558-020-0790-4

249. Zscheischler, J., O. Martius, S. Westra, E. Bevacqua, C. Raymond, R.M. Horton, B. van den Hurk, A. AghaKouchak, A. Jézéquel, M.D. Mahecha, D. Maraun, A.M. Ramos, N.N. Ridder, W. Thiery, and E. Vignotto, 2020: A typology of compound weather and climate events. *Nature Reviews Earth & Environment*, **1** (7), 333–347. https://doi.org/10.1038/s43017-020-0060-z

250. Callaghan, M., C.-F. Schleussner, S. Nath, Q. Lejeune, T.R. Knutson, M. Reichstein, G. Hansen, E. Theokritoff, M. Andrijevic, R.J. Brecha, M. Hegarty, C. Jones, K. Lee, A. Lucas, N. van Maanen, I. Menke, P. Pfleiderer, B. Yesil, and J.C. Minx, 2021: Machine-learning-based evidence and attribution mapping of 100,000 climate impact studies. *Nature Climate Change*, **11** (11), 966–972. https://doi.org/10.1038/s41558-021-01168-6

251. Aune, K.T., D. Gesch, and G.S. Smith, 2020: A spatial analysis of climate gentrification in Orleans Parish, Louisiana post-Hurricane Katrina. *Environmental Research*, **185**, 109384. https://doi.org/10.1016/j.envres.2020.109384

252. Gould, K.A. and T.L. Lewis, 2018: From green gentrification to resilience gentrification: An example from Brooklyn. *City & Community*, **17** (1), 12–15. https://doi.org/10.1111/cico.12283

253. Immergluck, D. and T. Balan, 2018: Sustainable for whom? Green urban development, environmental gentrification, and the Atlanta Beltline. *Urban Geography*, **39** (4), 546–562. https://doi.org/10.1080/02723638.2017.1360041

254. Laska, S., Ed. 2020: *Louisiana's Response to Extreme Weather: A Coastal State's Adaptation Challenges and Successes*. Springer, Cham, Switzerland, 361 pp. https://doi.org/10.1007/978-3-030-27205-0

255. Marino, E., 2015: *Fierce Climate, Sacred Ground: An Ethnography of Climate Change in Shishmaref, Alaska*. University of Alaska Press, Fairbanks, AK, 122 pp. https://upcolorado.com/university-of-alaska-press/item/5674-fierce-climate-sacred-ground

256. Marino, E., 2018: Adaptation privilege and voluntary buyouts: Perspectives on ethnocentrism in sea level rise relocation and retreat policies in the US. *Global Environmental Change*, **49**, 10–13. https://doi.org/10.1016/j.gloenvcha.2018.01.002

257. Cha, J.M., 2020: A just transition for whom? Politics, contestation, and social identity in the disruption of coal in the Powder River Basin. *Energy Research and Social Science*, **69**, 101657. https://doi.org/10.1016/j.erss.2020.101657

258. Rice, J.L., D.A. Cohen, J. Long, and J.R. Jurjevich, 2020: Contradictions of the climate-friendly city: New perspectives on eco-gentrification and housing justice. *International Journal of Urban and Regional Research*, **44** (1), 145–165. https://doi.org/10.1111/1468-2427.12740

259. Moon, K. and D. Blackman, 2014: A guide to understanding social science research for natural scientists. *Conservation Biology*, **28** (5), 1167–1177. https://doi.org/10.1111/cobi.12326

260. Treuer, G., E. Koebele, A. Deslatte, K. Ernst, M. Garcia, and K. Manago, 2017: A narrative method for analyzing transitions in urban water management: The case of the Miami-Dade water and sewer department. *Water Resources Research*, **53** (1), 891–908. https://doi.org/10.1002/2016wr019658

261. Kim, S.K., 2019: The Economic Effects of Climate Change Adaptation Measures: Evidence from Miami-Dade County and New York City. Joint Center for Housing Studies of Harvard University, Cambridge, MA. https://www.jchs.harvard.edu/research-areas/working-papers/economic-effects-climate-change-adaptation-measures-evidence-miami

262. Solecki, W., G.C. Delgado Ramos, D. Roberts, C. Rosenzweig, and B. Walsh, 2021: Accelerating climate research and action in cities through advanced science-policy-practice partnerships. *Npj Urban Sustainability*, **1** (1), 3. https://doi.org/10.1038/s42949-021-00015-z

263. Lubell, M. and M. Robbins, 2022: Adapting to sea-level rise: Centralization or decentralization in polycentric governance systems? *Policy Studies Journal*, **50** (1), 143–175. https://doi.org/10.1111/psj.12430

264. Djenontin, I.N.S. and A.M. Meadow, 2018: The art of co-production of knowledge in environmental sciences and management: Lessons from international practice. *Environmental Management*, **61** (6), 885–903. https://doi.org/10.1007/s00267-018-1028-3

265. Araos, M., K. Jagannathan, R. Shukla, I. Ajibade, E. Coughlan de Perez, K. Davis, J.D. Ford, E.K. Galappaththi, C. Grady, A.J. Hudson, E.T. Joe, C.J. Kirchhoff, A. Lesnikowski, G.N. Alverio, M. Nielsen, B. Orlove, B. Pentz, D. Reckien, A.R. Siders, N. Ulibarri, M. van Aalst, T.Z. Abu, T. Agrawal, L. Berrang-Ford, R.B. Kerr, S. Coggins, M. Garschagen, A. Harden, K.J. Mach, A.M. Nunbogu, P. Spandan, S. Templeman, and L.L. Turek-Hankins, 2021: Equity in human adaptation-related responses: A systematic global review. *One Earth*, **4** (10), 1454–1467. https://doi.org/10.1016/j.oneear.2021.09.001

266. Arnott, J.C. and M.C. Lemos, 2021: Understanding knowledge use for sustainability. *Environmental Science & Policy*, **120**, 222–230. https://doi.org/10.1016/j.envsci.2021.02.016

267. Karcher, D.B., C. Cvitanovic, R.M. Colvin, I.E. van Putten, and M.S. Reed, 2021: Is this what success looks like? Mismatches between the aims, claims, and evidence used to demonstrate impact from knowledge exchange processes at the interface of environmental science and policy. *Environmental Science & Policy*, **125**, 202–218. https://doi.org/10.1016/j.envsci.2021.08.012

268. Owen, G., 2021: Evaluating socially engaged climate research: Scientists' visions of a climate resilient U.S. southwest. *Research Evaluation*, **30** (1), 26–38. https://doi.org/10.1093/reseval/rvaa028

269. Jagannathan, K., G. Emmanuel, J. Arnott, K.J. Mach, A. Bamzai-Dodson, K. Goodrich, R. Meyer, M. Neff, K.D. Sjostrom, K.M.F. Timm, E. Turnhout, G. Wong-Parodi, A.T. Bednarek, A. Meadow, A. Dewulf, C.J. Kirchhoff, R.H. Moss, L. Nichols, E. Oldach, M.C. Lemos, and N. Klenk, 2023: A research agenda for the science of actionable knowledge: Drawing from a review of the most misguided to the most enlightened claims in the science-policy interface literature. *Environmental Science & Policy*, **144**, 174–186. https://doi.org/10.1016/j.envsci.2023.03.004

270. Turnhout, E., T. Metze, C. Wyborn, N. Klenk, and E. Louder, 2020: The politics of co-production: Participation, power, and transformation. *Current Opinion in Environmental Sustainability*, **42**, 15–21. https://doi.org/10.1016/j.cosust.2019.11.009