Sector Interactions, Multiple Stressors, and Complex Systems

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Sector Interactions, Multiple Stressors, and Complex Systems

Landslide blocking a road in California

Key Message 1

Interactions Among Sectors

The sectors and systems exposed to climate (for example, energy, water, and agriculture) interact with and depend on one another and other systems less directly exposed to climate (such as the financial sector). In addition, these interacting systems are not only exposed to climate-related stressors such as floods, droughts, and heat waves, they are also subject to a range of non-climate factors, from population movements to economic fluctuations to urban expansion. These interactions can lead to complex behaviors and outcomes that are difficult to predict. It is not possible to fully understand the implications of climate change on the United States without considering the interactions among sectors and their consequences.

Key Message 2

Multisector Risk Assessment

Climate change risk assessment benefits from a multisector perspective, encompassing interactions among sectors and both climate and non-climate stressors. Because such interactions and their consequences can be challenging to identify in advance, effectively assessing multisector risks requires tools and approaches that integrate diverse evidence and that consider a wide range of possible outcomes.

Key Message 3

Management of Interacting Systems

The joint management of interacting systems can enhance the resilience of communities, industries, and ecosystems to climate-related stressors. For example, during drought events, river operations can be managed to balance water demand for drinking water, navigation, and electricity production. Such integrated approaches can help avoid missed opportunities or unanticipated tradeoffs associated with the implementation of management responses to climate-related stressors.

Key Message 4

Advancing Knowledge

Predicting the responses of complex, interdependent systems will depend on developing meaningful models of multiple, diverse systems, including human systems, and methods for characterizing uncertainty.

Executive Summary

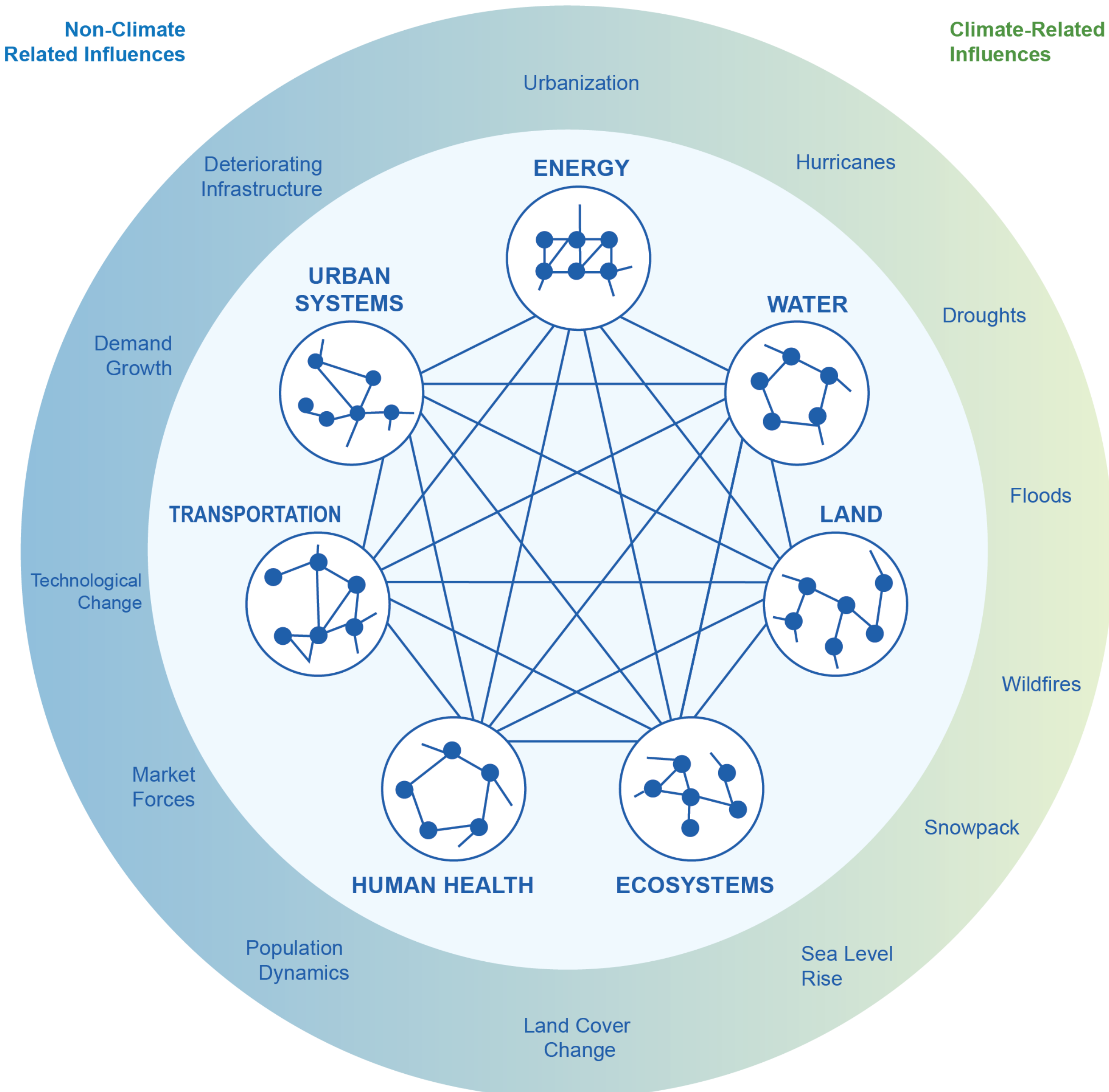
The world we live in is a web of natural, built, and social systems—from global and regional climate; to the electric grid; to water management systems such as dams, rivers, and canals; to managed and unmanaged forests; and to financial and economic systems. Climate affects many of these systems individually, but they also affect one another, and often in ways that are hard to predict. In addition, while climate-related risks such as heat waves, floods, and droughts have an important influence on these interconnected systems, these systems are also subject to a range of other factors, such as population growth, economic forces, technological change, and deteriorating infrastructure.

A key factor in assessing risk in this context is that it is hard to quantify and predict all the ways in which climate-related stressors might lead to severe or widespread consequences for natural, built, and social systems. A multisector perspective can help identify such critical risks ahead of time, but uncertainties will always remain regarding exactly how consequences will materialize in the future. Therefore, effectively assessing multisector risks requires different tools and approaches than would be applied to understand a single sector by itself.

In interacting systems, management responses within one system influence how other systems respond. Failure to anticipate interdependencies can lead to missed opportunities for managing the risks of climate change; it can also lead to management responses that increase risks to other parts of the system. Despite the challenge of managing system interactions, there are opportunities to learn from experience to guide future risk management decisions.

There is a large gap in the multisector and multiscale tools and frameworks that are available to describe how different human systems interact with one another and with the earth system, and how those interactions affect the total system response to the many stressors they are subject to, including climate-related stressors. Characterizing the nature of such interactions and building the capacity to model them are important research challenges.

Complex Sectoral Interactions



Sectors are interacting and interdependent through physical, social, institutional, environmental, and economic linkages. These sectors and the interactions among them are affected by a range of climate-related and non-climate influences. *From Figure 17.1 (Sources: Pacific Northwest National Laboratory, Arizona State University, and Cornell University).*

Introduction

The world we live in is a web of natural, built, and social systems—from global and regional climate; to the electric grid; to water management systems such as dams, rivers, and canals; to managed and unmanaged forests; and to financial and economic systems. Climate affects many of these systems individually, but they also affect one another, and often in ways that are hard to predict. In addition, while climate-related risks such as heat waves, floods, and droughts have an important influence on these interdependent systems, these systems are also subject to a range of other factors, such as population growth, economic forces, technological change, and deteriorating infrastructure (Figure 17.1).

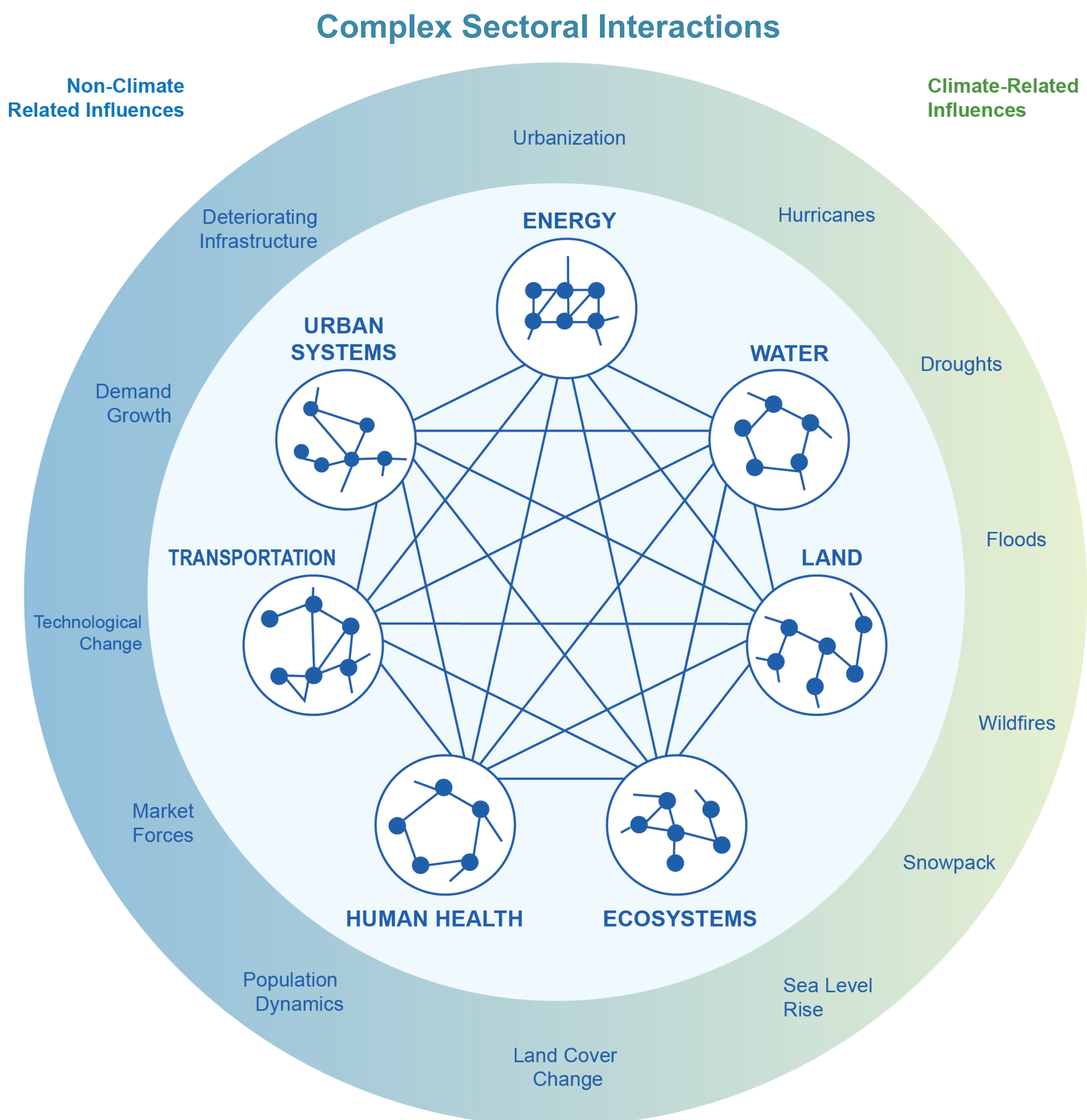


Figure 17.1: Sectors are interacting and interdependent through physical, social, institutional, environmental, and economic linkages. These sectors and the interactions among them are affected by a range of climate-related and non-climate influences. Sources: Pacific Northwest National Laboratory, Arizona State University, and Cornell University.

Assessing the risks associated with climate change requires us to acknowledge that understanding the risks to individual sectors is important but may not always be sufficient to characterize the risks to interdependent systems. Improved understanding of the complex dynamics that arise from interactions among systems is therefore essential to understand risk and manage our response to a changing climate. Characterizing the nature of such interactions and building the capacity to model them are important research challenges.

Regional and Sectoral Summary

Examples of interactions among sectors and systems can be found across the regions in this assessment. The cascading failures resulting from hurricanes are considerations across several coastal regions, including the Southern Great Plains (for example, Hurricane Harvey in 2017; see Box 17.1), the Southeast (for example, Hurricane Irma in 2017), and the Caribbean (for example, Hurricane Maria in 2017). Energy, water, and land systems subject to both climate-related stressors (such as droughts and heat waves) and non-climate influences (such as changes to population, urbanization, and economic development) are important considerations in the Southwest, the Southern Great Plains (for example, the 2012–2015 drought in Texas), and the Northwest (for example, the snow drought in Oregon in 2015). The feedbacks between forest fires and water quality and availability have created challenges in regions including the Southeast (for example, the Appalachian region in 2016) and the Southwest (for example, the Sierra Nevada range over the last five years). Changes in arctic permafrost have caused significant erosion, leading to new risks in transportation and human health in Alaska. The natural gas and other energy industries rely on the effective management of not only railroads and transportation networks but also the diminishing water supply in the Northern Great Plains region. A need for cross-sector planning for climate change impacts in the Great Lakes region has led to new adaptation networks in the Midwest. In Hawai‘i, increasing ocean temperatures and ocean acidification threaten coral reefs and marine biodiversity, with attendant economic impacts to tourism, fishery yields, and populations who depend on these for their livelihoods. Increasingly frequent and intense storms, heavy precipitation events, warmer water temperatures, and a rise in sea level in the Chesapeake Bay in the Northeast are projected to impact local populations, who depend on productive fisheries and ecosystems for their livelihoods, resources, and culture.

Box 17.1: Hurricane Harvey: Cascading Failures and Lessons from Emerging Management Approaches

Hurricane Harvey, which struck Houston, Texas, in August 2017 (Figure 17.2), provides a clear example of how impacts from extreme weather events can cascade through tightly connected natural, built, and social systems exposed to severe climate-related stressors (see Key Message 1) (see also Ch. 23: S. Great Plains, Box 23.1 for more information on Hurricane Harvey). Harvey knocked out power to 300,000 customers in Texas,[1] with cascading effects on critical infrastructure facilities such as hospitals, water and wastewater treatment plants, and refineries. Eleven percent of U.S. refining capacity and a quarter of oil production from the U.S. Gulf of Mexico were shut down. Actual and anticipated gasoline shortages caused price spikes regionally and nationally.[2]

In addition to causing direct death and injury, the storm affected public health by disrupting supporting systems. In addition, floodwaters carried toxins and pathogens. Flooding inundated a total of 43 EPA Superfund toxic sites (damaging the protective cap at one site and leading to a short-term release of dioxins), and flooded wastewater treatment plants spilled untreated sewage.[3] Although most hospitals were able to remain open

Box 17.1: Hurricane Harvey: Cascading Failures and Lessons from Emerging Management Approaches, *continued*

(sometimes on backup power), their ability to serve their patients was strained. Widespread power outages forced evacuations that exceeded the emergency shelter capacity, and otherwise healthy people who had no access to shelters or needed power for medical devices turned to hospitals. Roadways clogged with debris, and floodwater hampered the ability to get supplies and evacuate vulnerable patients. Disrupted communications networks interfered with hospitals' ability to coordinate with each other and emergency services.[4]

These interconnected infrastructure systems operate within the context of non-climate influences, including social institutions and policy environments (see Key Message 3) (see also Ch. 11: Urban, Key Message 3). For example, in the area affected by Hurricane Harvey, regional land management practices over the last several decades have reduced the area covered by wetlands, forests, and prairies, which historically absorbed storm water runoff.[5] These natural environments have been increasingly replaced with impermeable surfaces, decreasing Houston's resilience to flooding.[5]

Hurricanes have struck densely populated, interconnected U.S. urban systems several times, including Hurricane Katrina in New Orleans in 2005 and Superstorm Sandy in New York City in 2012. While each city and storm is unique, planners and decision-makers can learn from past events and outstanding examples of resilience. During Harvey, the Texas Medical Center in Houston, the world's largest medical center, remained fully functional despite disruptions to transportation, water, and electricity, in large part due to lessons learned and resilience investments made following the devastation of Tropical Storm Allison in 2001 and Hurricane Ike in 2008.[6] In the aftermath of Superstorm Sandy, the mayor of New York City explicitly brought climate-related risks into response planning and called for a more holistic risk management strategy (see Key Message 3), initiated through the Special Initiative for Rebuilding and Resiliency and the Climate Change Adaptation Task Force.[7] This task force brought together stakeholders from major infrastructure and health sectors such as water, transportation, energy, and communications to recognize and address interdependencies.

Figure 17.2: Hurricane Harvey led to widespread flooding and knocked out power to 300,000 customers in Texas in 2017, with cascading effects on critical infrastructure facilities such as hospitals, water and wastewater treatment plants, and refineries. The photo shows Port Arthur, Texas, on August 31, 2017—six days after Hurricane Harvey made landfall along the Gulf Coast. Photo credit: Staff Sgt. Daniel J. Martinez, U.S. Air National Guard.

Key Message 1

Interactions Among Sectors

The sectors and systems exposed to climate (for example, energy, water, and agriculture) interact with and depend on one another and other systems less directly exposed to climate (such as the financial sector). In addition, these interacting systems are not only exposed to climate-related stressors such as floods, droughts, and heat waves, they are also subject to a range of non-climate factors, from population movements to economic fluctuations to urban expansion. These interactions can lead to complex behaviors and outcomes that are difficult to predict. It is not possible to fully understand the implications of climate change on the United States without considering the interactions among sectors and their consequences.

The sectors and systems subject to climate-related risks do not exist in isolation; they interact with one another and with other sectors and systems. For example, agricultural systems require water for irrigation, which is supplied from lakes, rivers, dams, and reservoirs. Forest management influences the runoff that makes its way into these water systems. Electricity systems use water for hydroelectric power as well as for cooling thermoelectric power plants. Many urban transportation systems rely on electricity to power subways and buses. Meanwhile, medical services, and public health more broadly, are enabled by transportation, water, electricity, and communications (Ch. 11: Urban, KM 3). To most effectively assess the risks associated with climate-related stressors such as floods, droughts, or heat waves, the interactions among these systems must be considered in addition to the effects of these stressors on individual systems.[8]

In addition, climate-related stressors are not the only influences to which natural, built, and social systems are exposed. For example, population movements and demographic changes, economic growth, and changes in industrial activity can all influence systems exposed to climate-related stressors as well as systems that interact with them (see, for example, Box 17.3). Such factors can have powerful impacts on these systems or alter their vulnerability to climate-related stressors. For example, rapid population growth in the coastal United States over the past half-century has significantly increased society's exposure to extreme weather events like hurricanes.[9] These demographic trends may have a greater impact on future hurricane damages than sea level rise or changes in storm intensity.[10]

A long history of research on complex systems (e.g., Simon 2000[11]), spanning disciplines from meteorology[12] to ecology[13] to paleontology[14] to computer science, [15] has shown that systems that depend on one another are subject to new and often complex behaviors that do not emerge when these systems are considered in isolation. These behaviors, in turn, raise the prospect of unanticipated, and potentially catastrophic, risks.[16] For example, failures can cascade from one system to another; that is, failures in one system can lead to increased risks or failures in other systems. Such cascades have been observed with Hurricane Harvey (see Box 17.1), the Northeast blackout (see Box 17.5),[17] and erosion and permafrost thaw in Alaska (Ch. 26: Alaska, KM 3), where failures in physical infrastructure systems had downstream consequences for human health and safety. Tightly connected supply chains can quickly transmit impacts from events such as floods, droughts, heat waves, and tropical cyclones in one region or part of the world to systems in another (see Ch. 16: International, KM 1). For example, the spike in food prices in 2010–2011 was driven in part by drought-related declines in production of basic grains in Australia and Eastern Europe, which provided a short-term income increase to U.S. farmers of those commodities (see Ch. 16: International, KM 1).[18]

Similarly, changes in one part of a system may alter the thresholds and tipping points in other parts of the system (see Kopp et al. 2017[19]). For example, the overuse and depletion of groundwater removes a backstop in times of drought (see Box 17.3). Forest wildfires can affect water and air quality and render soil impermeable, altering both health and flood risks (see Box 17.4). Interactions among systems can also buffer systems from shocks and introduce a measure of system stability or recovery potential that might not have otherwise existed (see Box 17.5). For example, social networks, which are increasingly reflected in social media enabled by communications infrastructure, can have an important influence on the resilience of communities to natural hazards. Compound events, such as simultaneous temperature extremes and drought, can produce greater economic costs than events considered separately.[19] The complexity of the interactions that exist among these various systems limits the ability to predict the consequences of climate-related stressors with confidence. This poses important challenges for risk assessment as well as the management of those risks.

Box 17.2: Uncovering System Complexities: Wolves and the Yellowstone Ecosystem

A lone gray wolf in Yellowstone National Park. © Michelle Callahan/Flickr (CC BY 2.0).

One challenge in understanding interconnected systems is that interactions are often not revealed until some stress or intervention occurs (see Key Message 1). In addition, societal values and actions can play an important role in such systems. A non-climate example illustrates this challenge very clearly—the consequences of the 1995 reintroduction of wolves into the Yellowstone National Park ecosystem.[20] Concurrent with the eradication of wolves in the early 20th century, streamside willow populations declined as elk herds grew and browsed them more heavily. Willows along the small stream network were reduced to short stature or eliminated entirely. Beavers abandoned streams that lacked willows needed for food and dam construction. In spite of the controversy over wolf reintroductions because of predation on livestock, the National Park Service reintroduced wolves in 1995–1996.[21] Since wolves have been reintroduced, there have been some effects on willow stands, but these appear to largely be due to reductions in overall elk number, rather than strictly to behavioral responses to the presence of the wolves.[22] But in areas where beavers were also lost, the overall system has not returned to its state before the eradication of wolves. The changes due to the loss of beavers have apparently reduced the capacity of the system to return to its original state, even when the wolves returned.[23,24] This example illustrates the unpredictable nature of complex, interconnected systems and how they may react to multiple stressors and interventions driven by societal decisions. It also illustrates that there is no guarantee that such systems, once perturbed, will return to their original state when management actions are taken.[25] Because climate change is a stress that is outside the recent experience of species in many ecosystems, it, too, may uncover complexities due to ecosystem-level interactions that might not be immediately apparent.

Box 17.3: Energy, Water, and Land Linkages

Climate-related stressors such as extreme temperatures, large precipitation events, floods, and droughts highlight the interactions among energy, water, and land systems. These climate-related stressors also interact with non-climate influences such as population, markets, technology, and infrastructure to affect energy, water, and land systems individually as well as the dynamics between these sectors. Understanding how risks evolve under a changing climate, and classifying which risks are the most consequential, poses a significant challenge but is critically important to develop response strategies that enhance resilience across systems. Risks to energy, water, and land systems must be considered in the context of both climate-related and non-climate-related influences as well as the broader social and institutional context (Figure 17.3). As risks evolve, the vulnerabilities and exposure rates for energy, water, and land systems also evolve (see Key Message 1).[26]

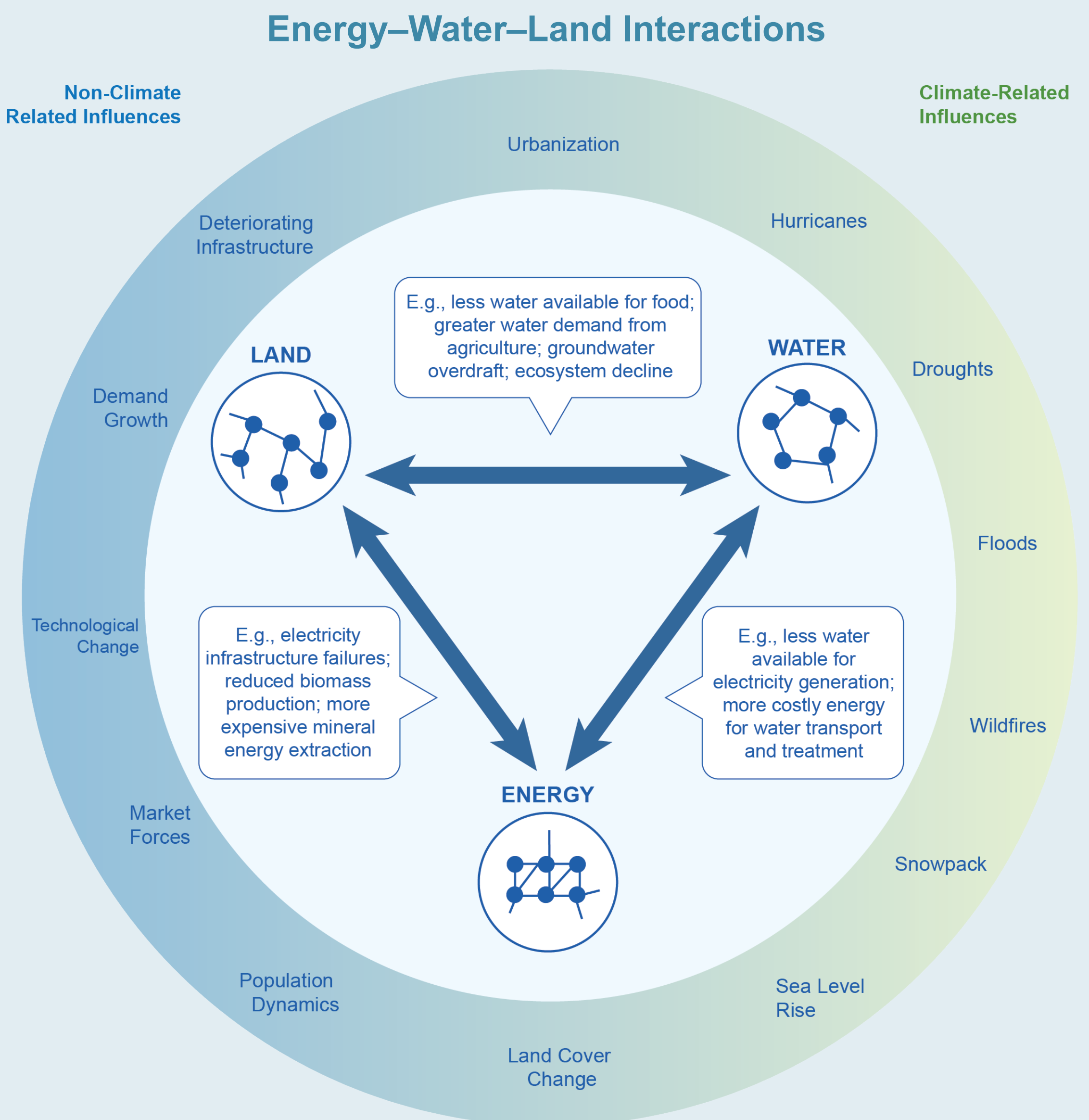


Figure 17.3: Energy, water, and land systems are interconnected and impacted by both climate-related and non-climate stressors. These influences affect these systems individually as well as the dynamics among these sectors. A multisector perspective is necessary to understand risks and develop response strategies that enhance resilience across multiple systems. Sources: Pacific Northwest National Laboratory, Arizona State University, and Cornell University.

Box 17.3: Energy, Water, and Land Linkages, *continued*

The interactions between climate, energy, water, and land in California present a compelling example that illustrates the need to understand complex systems to develop response strategies. Hydropower generation supplies an average of 15% of the state's total electricity consumption,[27] while at the same time the state's thermoelectric power plants rely on water for cooling. Meanwhile, the State Water Project is California's largest single electricity consumer, demanding an average of 2%–3% of total generation for pumping and conveyance.[28] This emphasizes the importance of water for energy and of energy for water.[29] The state's agricultural sector demands approximately 40% of average available freshwater[30] and uses substantial amounts of summer seasonal peak load electricity to pump groundwater, particularly during droughts. Along with uncertainty about future drought and precipitation extremes,[19,31,32] California faces an increasing population, deteriorating infrastructure, and potential energy and water resource limits for an agricultural sector that is evolving to depend on declining groundwater aquifers (Ch. 25: Southwest, KM 1).

The complexity of interconnected energy, water, and land systems highlights the potential impacts of societal choices and the need for institutional integration to explicitly account for sectoral interdependencies and multiple stressors (see Key Message 3).[33,34] Choices in any one sector to confront the many climate-related stressors facing that sector (such as floods, droughts, deteriorating infrastructure, land surface subsidence [sinking], landslides, and wildfires) have the potential to yield cascading cost, reliability, and resilience impacts across the full, connected system (see Key Message 3).[35,36,37,38,39] Taking California's recent droughts as an example, when surface water supplies were strongly curtailed from 2002 to 2016, the result was increased well pumping to meet agricultural demands, which led to a loss of approximately 5.0 cubic miles (20.7 km^3) of groundwater)[40]—or about the size of Lake Powell. Increasing well depths and lost hydropower production influence farmers' decisions about both capital investments in pumping wells and transitions to higher-profit tree and vine crops that cannot be fallowed.[27] Using groundwater as a key economic backstop for agriculture during droughts raises significant concerns about the reversibility of aquifer depletions, the weakening of levees, and accelerating rates of land surface subsidence,[35,39,41,42,43] all of which may alter the future resilience of California's energy, water, and land systems to climate extremes (Ch. 25: Southwest, KM 1).

Key Message 2

Multisector Risk Assessment

Climate change risk assessment benefits from a multisector perspective, encompassing interactions among sectors and both climate and non-climate stressors. Because such interactions and their consequences can be challenging to identify in advance, effectively assessing multisector risks requires tools and approaches that integrate diverse evidence and that consider a wide range of possible outcomes.

The number and complexity of possible interactions among systems affected by climate expand the scope of climate change risk assessment. Recent assessments have acknowledged the importance of this expanded perspective. For example, Chapter 10 of the Third National Climate Assessment (NCA3) [44] highlighted interactions among energy, water, and land systems that people and economies depend on. Other recent climate change impact assessments (e.g., Oppenheimer et al. 2014, Houser et al. 2015, Rosenzweig et al. 2017[45,46,47]) have highlighted risks emerging from interactions among different sectors, geographic regions, and stressors.

A key factor in assessing risk in this context is that it is hard to quantify all the ways in which climate-related stressors might lead to severe or widespread consequences for natural, built, and social systems. A multisector perspective can help identify critical risks ahead of time, but uncertainties will always remain regarding exactly how consequences will materialize in the future. In some cases, interactions are well known. For example, yearly fluctuations in river flows affect hydropower generation, in turn shaping energy costs and profits and reliance on other energy sources (see Box 17.3). Yet even in these cases, it is often difficult to quantify all relevant processes and interactions. Sometimes, interactions are only obvious in retrospect, such as those associated with many past hurricanes (see Box 17.1) or the Northeast blackout (see Box 17.5), with impacts cascading through different parts of the built environment and affecting human health, well-being, and livelihoods. In still other cases, all the relevant interactions are simply not fully understood, for example in the context of the linkages between wildfires, pine bark beetles, and forest management (see Box 17.4).

Therefore, effectively assessing multisector risks requires different tools and approaches than would be applied to understand a single sector by itself. For example, as land management, infrastructure, and climate all change through time, statistical analysis of extreme weather events based on the past becomes less accurate in predicting future outcomes (Ch. 28: Adaptation, KM 2).[48] Approaches can be applied to integrate diverse evidence, combining quantitative and qualitative results and drawing from the natural and social sciences and other forms of analysis.[49,50,51] As one example, models and numerical estimates can be complemented by methods quantifying expert judgment in order to consider uncertainties not well represented by the models. For instance, models and expert judgment have been used together to inform understanding of future sea level rise.[52] Scenarios can also be used to explore preparedness across possible futures, including extreme outcomes that have been rare in historical experience but may be particularly consequential in the future.[50,53,54,55] Such scenarios in assessment can inform understanding of different decisions and choices for managing climate risks, responding to uncertainties about the future by starting with goals and priorities people have.

Box 17.4: Wildfires, Pine Bark Beetles, and Forest Management

Multiple stressors (see Key Message 1) act on U.S. forest ecosystems, impacting wildfire frequency and intensity in complex ways (see Key Message 2) (see also Ch. 6: Forests, KM 1). In the western United States, particularly in Colorado and California, wildfires have become more frequent and larger in area (see Ch. 6: Forests, Figure 6.4; see also Ch. 24: Northwest, KM 1 for an additional example), and this trend is expected to continue as the climate warms (see Ch. 25: Southwest, KM 2).[56] Drought, preceded by warm, wet seasons, can increase fuel flammability and availability. In addition to these climate-related stresses, choices about land use and land-cover change, increased pest populations, human migration, and earth system processes all impact forest ecosystems.[56,57] The interaction of these stressors can alter the vulnerability of these systems, both exacerbating and diminishing the likelihood and impact of wildfire. For example, as humans have moved and expanded the wildland–urban interface, increased fire suppression practices have led to changes in vegetation structure.[58] Without natural fires, vegetation has become denser, resulting in significantly larger and more damaging wildfires.[56] Meanwhile, the interaction of pests with wildfire includes feedback that is oftentimes nonlinear. Warmer winters have allowed pests such as the bark beetle to reach higher elevations and cause significant tree mortality.[59] Insect-killed trees influence fuels and fire behavior, while in some cases wildfire can mitigate the risk of

Box 17.4: Wildfires, Pine Bark Beetles, and Forest Management, *continued*

bark beetle.[58] The impacts of beetle-killed trees on fire likelihood vary over time, with an initial high probability of crown fires followed by the possibility of surface fires.[60]

Wildfires have significant health and economic impacts. Fine particles and ozone precursors released during fires can lead to increased cardiovascular and respiratory damage (Ch. 13: Air Quality, KM 2).[61] Increased wildfires are projected to increase costs associated with health effects, loss of homes and other property, wildfire response, and fuel management.[62] However, risk analysis and planning around wildfire entail the challenge of accounting for all of the stressors acting on the system. Meanwhile, the stressors interact with one another and vary across temporal and sectoral scales (see Key Messages 2 and 4). Efforts are being made to improve prospective vulnerability assessments.[57] The majority of research focuses only on first-order direct fire impacts and fails to recognize indirect and cascading consequences, such as erosion and the health impacts of smoke.[63] To conduct prospective analyses, most modeling efforts include climate and land-use and land-cover change as primary drivers but have a difficult time predicting human-induced stressors such as migration and settlement.[57]

Wildfire at the Wildland–Urban Interface

Figure 17.4: Wildfires pose significant health and economic impacts through interfaces between wildlands and human settlements. Shown here is a wildfire in the Whiskeytown National Recreation Area in California in August 2004. Photo credit: Carol Jandrall, National Park Service.

Key Message 3

Management of Interacting Systems

The joint management of interacting systems can enhance the resilience of communities, industries, and ecosystems to climate-related stressors. For example, during drought events, river operations can be managed to balance water demand for drinking water, navigation, and electricity production. Such integrated approaches can help avoid missed opportunities or unanticipated tradeoffs associated with the implementation of management responses to climate-related stressors.

In interacting systems, management responses within one system influence how other systems respond. Within water basins, for example, upstream management decisions can constrain downstream water-dependent management decisions that affect agriculture, transportation, domestic and commercial use, and environmental protection. Failure to anticipate such interdependencies can lead to missed opportunities for managing the risks of climate change; they can also lead to management responses that increase risks to other parts of the system. For example, the use of groundwater in California as an agricultural backstop in the recent drought may alter California's resilience to future droughts (see Box 17.3).

In practice, managers of agricultural, natural resource, or infrastructure systems do manage at least some degree of system interdependencies. For example, electrical utilities account for the management of water resources to provide power plant cooling capacity, manage fuel supply chains through transportation networks,[64] and manage demand from customers. This requires utilities to acquire appropriate operational permits, licenses, and contracts relevant to other systems and to incorporate the characteristics of those systems in strategic planning and risk management. At the same time, water utilities are users of electricity, particularly those that rely on desalination, which is very energy intensive. Hence, efforts to enhance the resilience of water supply systems to drought can have important consequences for the energy sector and electricity costs.[65] Such indirect risks can be challenging to manage, particularly when system managers have no operational control or jurisdiction over the interacting system. When drought reduced barge traffic on the Mississippi in 2013, farmers had limited options other than seeking more expensive transportation options or incurring delays in getting their products to market.[66,67] More holistic management approaches therefore hold the potential for anticipating these risks and developing effective strategies and practices for risk reduction.

Despite the challenge of managing system interactions, there are opportunities to learn from experience to guide future risk management decisions (Ch. 28: Adaptation, KM 3). The financial sector has invested significantly in understanding and managing systemic risks—including those associated with climate change and climate policy.[68] Mechanisms include risk assessment, financial disclosures, contingency planning, and the development of regulations and industry standards that recognize system interdependencies. Another example is that of the Department of Defense (DoD), which integrates consideration for the implications of climate change and variability for food, water, energy, human migration, supply chains, conflict, and disasters into decision-making and operations around the world.[69] In so doing, the DoD focuses on enhancing preparedness, building partnerships with other public and private organizations, and including climate change in existing planning processes.[69,70]

These strategies are relevant to any organization attempting to enhance its resilience to climate change.

A multisector perspective recognizes that systems have multiple points of vulnerability, that risk can propagate between systems, and that anticipating threats and disruptions requires situational awareness within and between systems.[71,72] Translating the growing awareness of such complexities into the design of policies and practices that effectively address climate change risks, however, requires rethinking how systems are managed in order to identify opportunities for risk reduction or greater efficiency. For example, risk can be reduced by building excess capacity, flexibility, and redundancy into systems.[73] Reserve margins for electricity grids, multi-objective reservoir management, grain storage, multimodal transportation networks, and redundant communications are all mechanisms that provide flexibility for coping with a broad range of risks. Resilience can also be enhanced by planning for system recovery in the event of diverse types of disruptions. For example, restoring power in the wake of a natural disaster is critical for restoring other services such as transportation, water, health, and communications (see Box 17.5). Nevertheless, the costs of designing, constructing, operating, and monitoring resilient, interacting systems that are robust to multiple sources of stress can be significant. Hence, consideration of the costs and benefits of resilience over the entire life cycle of the system may be necessary to make the business case.

Box 17.5: Cascading Failures: Electricity, Public Health, and the 2003 Northeast Blackout

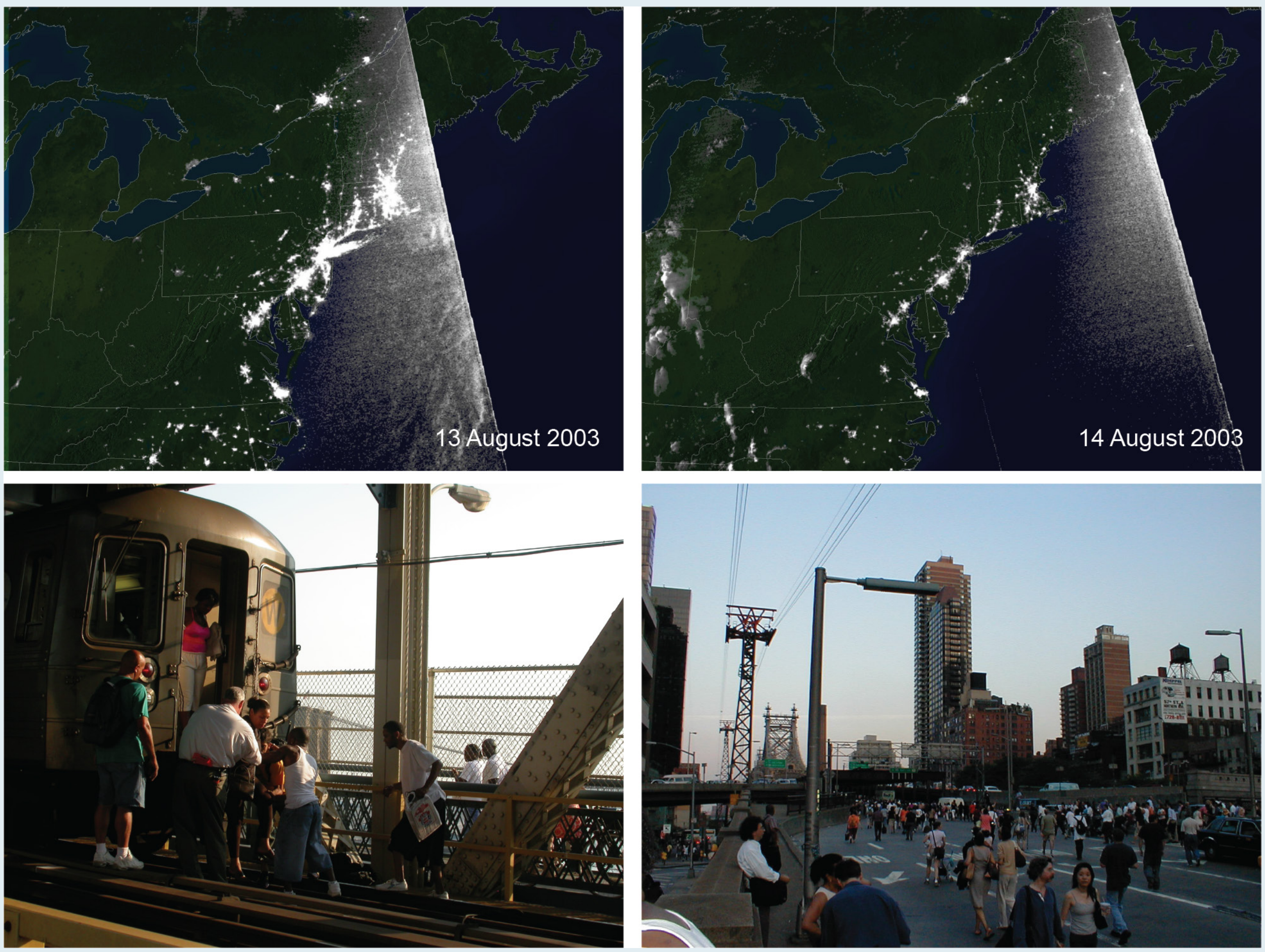
The interactions among severe weather, electric power infrastructure, and public health demonstrate how impacts can cascade within and across sectors (see Key Message 1) and how risk management depends on understanding these interactions (see Key Message 3). The 2016 Climate and Health Assessment identified the impacts of climate-related extreme events on critical infrastructure as a major threat to public health, but it also emphasized the influence of non-climatic factors such as inequalities in income and education as well as individual behavioral choices on health outcomes (Ch. 14: Human Health, KM 1).[67]

More frequent and severe heat waves in many parts of the United States would increase stresses on electric power, increasing the risk of cascading failures within the electric power network that could propagate into other sectors (Ch. 4: Energy, KM 1).[74] Hot weather increases demand for electricity, mostly for residential air conditioning, while reducing transmission efficiency and pushing power infrastructure closer to its operating tolerances (Ch. 4: Energy, KM 1).[75] The Northeast blackout in August 2003, which affected the Northeast and the Canadian province of Ontario, is a familiar example of a cascading network failure that has been well documented (Figure 17.5) (see also Ch. 11: Urban, KM 3). In 2003, a single electrical line warmed on a hot day and sagged into vegetation, tripping out of service. Redirected power overloaded other lines, causing them to trip as well. The disruption cascaded through the network until at the peak of the outage it affected an estimated 50 million people in the Northeast and Canada's Ontario province.[76] Depending on the location, the outage lasted several hours to up to two days, resulting in economic losses of $4–$10 billion due to disruption of businesses and industries.[76]

In the decade following the blackout, despite improvements in reliability and vegetation control standards, weather-related outages actually increased, accounting for 80% of major outages reported; about 20% of weather-related outages cause cascading failures.[77] In addition, today's grid is increasingly large, complex, and heavily loaded, which some researchers suggest increases the potential for blackouts.[78,79] Conversely, others suggest that tighter integration with communications and information technology (IT) infrastructure will improve resilience.[80]

Box 17.5: Cascading Failures: Electricity, Public Health, and the 2003 Northeast Blackout, *continued*

Given the challenges facing today's grid, lessons from the 2003 blackout can still help the public health sector plan for and manage complex consequences of disruptions to interacting infrastructures.[81] Power outages compromise other critical infrastructures, including telecommunications, IT infrastructure, transportation systems, and water and wastewater treatment. In 2003, these disruptions had a broad range of implications for public health, including reduced access to medical equipment and pharmacies, isolation in multistory buildings, slow emergency response times, hospital closures, and temporary loss of disease surveillance systems.[82,83] These impacts translated into health consequences; one study estimated that the event caused 90 excess deaths during August.[83] Maintaining a resilient healthcare infrastructure system therefore depends on being able to successfully adapt, respond, and recover when supporting infrastructure systems are disrupted (see Key Message 3).[84] This reflects the importance of emergency response and disaster risk reduction planning at the community level as well as consideration of the health implications of urban design and infrastructure planning.[67]



Northeast Blackout

Figure 17.5: During the August 2003 blackout, an estimated 50 million people in Canada and the northeastern United States lost power, with cascading impacts on public health and critical infrastructure. These images show (clockwise from upper left): nighttime satellite imagery of the area before the outage; the same view during the blackout; people walking on the Manhattan Bridge; and passengers being evacuated from a subway train on the Manhattan Bridge during the outage. Image credits: (top) NOAA; (bottom left) Jack Szwergold (CC BY-NC 2.0); (bottom right) Eric Skiff (CC BY-SA 2.0).

Key Message 4

Advancing Knowledge

Predicting the responses of complex, interdependent systems will depend on developing meaningful models of multiple, diverse systems, including human systems, and methods for characterizing uncertainty.

Although it is clear that climate-related and non-climate stressors impact multiple natural, built, and social systems simultaneously, thereby altering societal risks, the tools available for predicting these dynamics lag those that predict the dynamics of individual systems. There are many existing modeling efforts that explore complex natural systems, including climate models and numerical weather forecasting models. Although these models are applied to scenarios driven by social and policy decisions, the models themselves rarely incorporate the feedback relationships to social systems and policy contexts.[85,86,87,88] Engineering and resource management models that explicitly incorporate societal economic decisions and represent built systems at a very high resolution have not traditionally been linked to climate projections. Some integrated human–earth system models are explicitly designed to identify system linkages but frequently lack key features or sufficient resolution of the inherent dynamics of the natural environment.[89,90] These and other intersectoral models are also used to create scenarios of how combined natural–human systems might evolve (for example, the Shared Socioeconomic Pathways [SSPs]) (see Scenario Products section of App. 3).[53] Such scenarios can be useful for exploring the range of possible outcomes of larger trends, but the results should not be considered predictive. There is a large gap, therefore, in the multisector and multiscale tools and frameworks that are available to describe how different human systems interact with one another and with the earth system and how those interactions affect the total system response to the many stressors they are subject to, including climate-related stressors.[91] However, increasing recognition of this gap has given rise to a number of innovative research projects that seek to directly link climate scenarios or earth system models to high-resolution models of built infrastructure and human systems (e.g., Allen et al. 2016; Voisin et al. 2016; Ke et al. 2016; Zhou et al. 2017, 2018; Tidwell et al. 2016[92,93,94,95,96,97]).

The responses of interacting systems to both climate-related and non-climate stressors exhibit deep uncertainty, especially when interactions with societal decisions are included. Deep uncertainty arises when there is a lack of clarity about the appropriate models to apply, the relative probability of various scenarios, and the desirability of alternative outcomes.[98] Risk management decisions must therefore be made in the face of these uncertainties (see Key Message 2). An important research challenge is therefore advancing scientific methods and tools that can be applied in climate research, risk assessment, and risk management for complex, interdependent systems under deep uncertainty.[99]

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Opening Image Credit

Landslide in California: © gece33/E+/Getty Images.

Traceable Accounts

Process Description

The scope of this chapter was developed to fill a gap in previous National Climate Assessments (NCAs), notably the risks that emerge from interactions among sectors. Previous NCAs have touched on this subject, for example the energy, water, and land use chapter in the Third National Climate Assessment (NCA3). However, these assessments never included a chapter specifically focused on a general treatment of this topic. Emerging scientific research is highlighting the links between sectors and the potential complexity and implications of these interactions, from complex system dynamics such as cascading failures to management approaches and approaches to risk. These concepts were then incorporated into a detailed terms of reference for the chapter, outlining the scope and the general content to be included in the document.

The author team for this chapter was constructed to bring together the necessary diverse experience, expertise, and perspectives. Our authors brought expertise and experience in multiscale, multisector research and modeling, with a focus in specific sectors or sectoral combinations including critical infrastructure, energy–water–land interactions, and ecosystems. The authors also had expertise in complex systems science and previous experience in assessment processes.

The chapter was developed through technical discussions, a literature review, and expert deliberation by chapter authors through email and phone discussions. The team evaluated the state of the science on the analysis of sectoral interdependencies, compounding stressors, and complex system science. Case studies were drawn from a range of sources intended to represent the key themes in the chapter.

Key Message 1

Interactions Among Sectors

The sectors and systems exposed to climate (for example, energy, water, and agriculture) interact with and depend on one another and other systems less directly exposed to climate (such as the financial sector). In addition, these interacting systems are not only exposed to climate-related stressors such as floods, droughts, and heat waves, they are also subject to a range of non-climate factors, from population movements to economic fluctuations to urban expansion. These interactions can lead to complex behaviors and outcomes that are difficult to predict. It is not possible to fully understand the implications of climate change on the United States without considering the interactions among sectors and their consequences. (*High Confidence*)

Description of evidence base

A suite of examples across this assessment and within this chapter demonstrate the interactions between systems and the potentially important implications of these linkages. Examples in this chapter include Hurricane Harvey; the 2003 Northeast blackout; energy–water–land systems in California and throughout the nation; forest systems facing influences from wildfires, drought, and pine bark beetles; and the implications of the reintroduction of wolves in Yellowstone. Each of these examples is supported by its own evidence base; the linkages between systems and the importance of non-climate influences is self-evident from these examples. Beyond these examples, a small set of recent literature has begun to explore ways to more systematically quantify the implications of including sectoral interdependencies in climate risk assessment (e.g., Harrison et al. 2016[8]).

In addition to literature specific to risk assessment in the context of climate change, there is a long history of research on complex systems[11] that raises the potential for a range of dynamics that might emerge from sectoral interdependencies and compounding stressors. This includes research spanning disciplines from meteorology[12] to ecology[13] to paleontology[14] to computer science.[15] This literature supports the conclusion that more complex dynamics may occur when multiple systems interact with one another.

Major uncertainties

The interactions between sectors and systems relevant to climate risk assessment are self-evident, and there are clear examples of unanticipated dynamics emerging from these interactions in the past. Yet our understanding is limited regarding the precise nature of complex system behavior in the context of climate risk assessment and its ultimate influence on the outcomes of such assessments. As noted in Key Message 4, the available tools and frameworks are simply not sufficient at this point to identify key risks emerging from intersectoral interdependencies and compounding stressors.

Description of confidence and likelihood

We have *high confidence* in this message, because there is high agreement and extensive evidence that a range of critical intersectoral interdependencies and compounding stressors are present and relevant to climate risk assessment. At the same time, the precise impact of these on system dynamics is not well understood.

Key Message 2

Multisector Risk Assessment

Climate change risk assessment benefits from a multisector perspective, encompassing interactions among sectors and both climate and non-climate stressors. Because such interactions and their consequences can be challenging to identify in advance, effectively assessing multisector risks requires tools and approaches that integrate diverse evidence and that consider a wide range of possible outcomes. *(High Confidence)*

Description of evidence base

Recent climate change assessments (e.g., Oppenheimer et al. 2014, Houser et al. 2015[45,46]) emphasize that a multisector perspective expands the scope of relevant risks and uncertainties associated with climate change impacts. Assessing these risks requires attention to multiple interacting sectors, geographic regions, and stressors, such as 1) interactions in the management of water, land, and energy (see Box 17.3), or 2) spatial compounding of impacts if, for example, multiple infrastructure systems fail within a city (see Box 17.1). Risk assessment also requires attention to indirect and long-distance climate change impacts, for instance resulting from human migration or conflict.[45,100] Analyses of historical events (see Box 17.5), evaluations of statistical risk (e.g., Carleton and Hsiang 2016[101]), and process-based modeling projections are some of the methods demonstrating these complex interactions across sectors, scales, and stressors.

Different tools and approaches are required to assess multisector risks. Approaches can be applied to integrate diverse evidence, combining quantitative and qualitative results and drawing from the natural and social sciences and other forms of analysis.[47,49,51] For instance, models and expert judgment have been used together to inform our understanding of future sea level rise,[52] and scenarios can also be used to explore preparedness across possible futures.[53,54,55]

Major uncertainties

For interdependent systems affected by multiple stressors, the number and complexity of possible interactions are greater, presenting deeper uncertainties. It is often difficult or impossible to represent all relevant processes and interactions in analyses of risks, especially quantitatively. For example, quantitative projections can evaluate probabilities of well-understood sectoral interactions but will be limited by processes or parameters that are poorly known or unknowable. This is why the integration of diverse evidence and attention to deeper uncertainties are important in multisector risk assessment.

Description of confidence and likelihood

We have *high confidence* in this Key Message because there is high agreement that a multisector perspective alters risk assessment, as is reflected in recent climate change assessments. However, the evidence basis for multisector evaluations is emerging.

Key Message 3

Management of Interacting Systems

The joint management of interacting systems can enhance the resilience of communities, industries, and ecosystems to climate-related stressors. For example, during drought events, river operations can be managed to balance water demand for drinking water, navigation, and electricity production. Such integrated approaches can help avoid missed opportunities or unanticipated tradeoffs associated with the implementation of management responses to climate-related stressors. *(High Confidence)*

Description of evidence base

Recent literature has documented that the management of interacting infrastructure systems is a key factor influencing their resilience to climate and other stressors. A range of studies have argued that the complexity of institutional arrangements in mature, democratic economies like the United States poses challenges to the pursuit of climate adaptation objectives and sustainability more broadly.[72,102,103,104,105] The complexity associated with interacting systems of systems poses significant challenges to integrated management.[105] The allocation of authority and responsibility for system management across multiple levels of government as well as between public and private sectors often contributes to decision-making by one actor being enabled or constrained by other actors.[72,103]

The interdependencies among systems reflect the potential value in the development of more integrated management strategies.[72] This concept of integrated management is reflected in existing literatures, particularly those associated with integrated water resources management [106,107,108,109] and integrated infrastructure planning.[110,111,112] Such studies often address integration within sectors or systems, with less consideration for integration between or among systems. This has the potential to lead to missed opportunities for improving management practice.[72] However, assessments of energy,[113] urban infrastructure,[75] and coupled energy–water–land[114] systems conducted as part of NCA3[44] identified a range of interdependencies across multiple sectors (see Dawson 2015[115]).

A range of strategies have been proposed for enhancing the capacity to manage system interdependencies and climate change risk. Significant effort has been invested in understanding and modeling system dynamics to enhance capabilities for risk and vulnerability assessment. These efforts have largely focused on physical infrastructure systems, infrastructure networks, and the potential for cascading failures.[116,117,118,119] Such capabilities help to identify what can be monitored in complex systems to enhance situational awareness, anticipate disruptions, and increase resilience.[71,120,121]

There is ample evidence of comanagement of interdependent systems, often as a function of resource assurance and/or contingency planning. For example, the use of water for electricity generation (hydropower or cooling in thermal generation) involves regulatory constraints around water use as well as operational decision-making regarding water management.[72,114,122,123,124,125] These interactions have been a major focus of studies addressing the climate–water–energy nexus. Meanwhile, emergency managers as well as agricultural, commercial, and industrial supply chains often develop contingency plans in the event of disruptions of transportation, telecommunications, water, and/or electricity.[81,126,127,128,129]

A key element of such planning is to build redundancy and flexibility into system operations.[73] Evidence suggests that adding flexibility or robustness to systems or transforming systems such that they interact or behave in fundamentally different ways can increase construction, maintenance, or procurement costs.[82,130,131] However, a number of studies exploring the valuation of resilience actions and investments have concluded that the benefits of resilience interventions can be significantly greater than the costs, provided the long-term mitigating effects of the intervention are factored in.[132,133,134]

Given the complexity of governance systems, the responsibility for the design and implementation of such strategies for integrated management rests on a broad range of actors. Over the latter part of the 20th century, the privatization of infrastructure, including energy, telecommunications, and water, transferred infrastructure management, responsibility, and risk to the private sector.[135] Nevertheless, local, state, and federal governments continue to have critical roles in regulation, risk assessment, and research and development. In addition, many institutions, organizations, and individuals either have infrastructure dependencies or influence the dynamics, operations, investment, and performance of infrastructure.[136] The increasing interconnectedness of both infrastructure and the people who use and manage that infrastructure is leading to both new challenges and opportunities for comanaging these systems, particularly in urban areas.[137,138,139]

A growing literature is identifying opportunities to enhance consideration of human health and other benefits in the design of urban landscapes and infrastructure.[67,140,141,142,143]

Major uncertainties

The dominant uncertainties associated with the management of climate risks and system interdependencies include understanding indirect effects and feedbacks between systems, particularly with respect to predicting system responses. Technological change could have significant implications for the resilience, interconnectedness, and responses of systems to climate-related stressors and other disturbances. Such change could increase the complexity of integrated management with implications that could be positive or negative with respect to vulnerability. In addition, the future evolution of governance and regulatory dimensions of infrastructures systems, as well as consumer choices and behavior, are associated with irreducible uncertainty, largely because they involve choices yet to be made.

Description of confidence and likelihood

There is high agreement and extensive evidence that institutional arrangements and governance are critical to the management of systems and their interdependencies. This finding is reflected in scientific assessments, modeling studies, and observations of system responses and performance, as well as in theories emerging from complex systems science. Furthermore, a history of management practice associated with water, energy, transportation, telecommunications, food, and health systems that spans decades to centuries provides evidence for the importance of system interdependencies. Thus, there is *high confidence* in this message.

Key Message 4

Advancing Knowledge

Predicting the responses of complex, interdependent systems will depend on developing meaningful models of multiple, diverse systems, including human systems, and methods for characterizing uncertainty. *(High Confidence)*

Description of evidence base

This Key Message is based on an understanding of a range of analyses and modeling tools described throughout the chapter.

Major uncertainties

Because the Key Message is the authors' assessment of the overall state of development of research tools and models, and the subsequent importance of developing research tools, the concept of major uncertainties is not entirely appropriate. This is a matter of the authors' judgment, not calculation or assessment of underlying probabilities.

Description of confidence and likelihood

See above. No likelihood statement is appropriate, and the *high confidence* is based on the authors' assessment of the underlying literature and development of methods and modeling tools.

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