Assessing Risk to the National Critical Functions as a Result of Climate Change

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About This Report

On January 27, 2021, President Joseph R. Biden, Jr., signed Executive Order (EO) 14008, “Tackling the Climate Crisis at Home and Abroad.” EO 14008 describes the threat that the climate crisis poses to the United States and to the world and the roles of various federal agencies in addressing it. It directs the Secretary of Homeland Security to “consider the implications of climate change in the Arctic, along our Nation’s borders, and to National Critical Functions” (§ 103[e]). The National Critical Functions (NCFs) represent “the functions of government and the private sector so vital to the United States that their disruption, corruption, or dysfunction would have a debilitating effect on security, national economic security, national public health or safety, or any combination thereof” (Cybersecurity and Infrastructure Security Agency [CISA], undated c, p. 1).

To fulfill the objectives of the EO, CISA asked the Homeland Security Operational Analysis Center (HSOAC) to (1) develop a risk management framework for integrating climate-driven changes to the strategic operating environment, building on the NCF risk architecture to identify, understand, and manage climate-driven effects on the NCFs;1 (2) identify the NCFs facing the greatest vulnerability to climate change and, as a result, facing disruption or degradation in the future; and (3) complete a full climate change risk assessment for the NCFs identified as being most vulnerable.

This report describes these three activities, presenting the risk management framework as an ongoing capacity for assessing climate-related risk moving forward and highlighting the results of the climate risk assessment that identified NCFs at risk due to climate change. The findings should be of interest to CISA and other federal agencies and partners managing risk to U.S. critical infrastructure.

This research was sponsored by CISA and conducted within the Strategy, Policy, and Operations Program of the HSOAC federally funded research and development center (FFRDC).

About the Homeland Security Operational Analysis Center

The Homeland Security Act of 2002 (Section 305 of Public Law 107-296, as codified at 6 U.S.C. § 185) authorizes the Secretary of Homeland Security, acting through the Under Secretary for Science and Technology, to establish one or more FFRDCs to provide independent analysis of homeland security issues. The RAND Corporation operates HSOAC as an FFRDC for the U.S. Department of Homeland Security (DHS) under contract HSHQDC-16-D-00007.

The HSOAC FFRDC provides the government with independent and objective analyses and advice in core areas important to the department in support of policy development, decisionmaking, alternative approaches, and new ideas on issues of significance. The HSOAC FFRDC also works with and supports other federal, state, local, tribal, and public- and private-sector organizations that make up the homeland security enterprise. The HSOAC FFRDC’s research is undertaken by mutual consent with DHS and is organized as a set of discrete tasks. This report presents the results of research and analysis conducted under task order 70RCSA21FR0000052, Assessing Risk to the National Critical Functions as a Result of Climate Change.

The results presented in this report do not necessarily reflect official DHS opinion or policy.

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1 The NCF risk architecture “break[s] down each NCF into its sub-functions and lower-level activities to enable CISA to quickly evaluate, identify, and assess both operational and strategic risks to the Nation’s infrastructure” (CISA, undated c, p. 2).
For more information on HSOAC, see www.rand.org/hsoac. For more information on this publication, see www.rand.org/t/RRA1645-7.

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Summary

Issue

On January 27, 2021, President Joseph R. Biden, Jr., signed Executive Order (EO) 14008, “Tackling the Climate Crisis at Home and Abroad,” which describes the threat that the climate crisis poses to the United States. The EO also directs various federal agencies, including the U.S. Department of Homeland Security, to assess climate change’s implications for multiple domains. The EO directs the Secretary of Homeland Security to “consider the implications of climate change in the Arctic, along our Nation’s borders, and to National Critical Functions” (§ 103[e]). The National Critical Functions (NCFs) represent “the functions of government and the private sector so vital to the United States that their disruption, corruption, or dysfunction would have a debilitating effect on security, national economic security, national public health or safety, or any combination thereof” (Cybersecurity and Infrastructure Security Agency [CISA], undated c, p. 1).

To address this request, CISA asked the Homeland Security Operational Analysis Center, a federally funded research and development center operated by the RAND Corporation, to develop a risk management framework to assess and manage the risk that climate change poses to the NCFs and to use the framework to assess 27 priority NCFs. The framework is intended to be compatible with and integrate into existing CISA risk management efforts, to support an initial risk assessment of climate-related risk to the NCFs, and to provide a repeatable capacity for ongoing assessment of climate-related risk moving forward. The framework is intended to provide CISA with an ongoing capability to assess climate-related risk. This report details the risk assessment portions of the risk management framework.

Approach

The risk management framework employs a five-step process: (1) identify higher-vulnerability NCFs; (2) identify and characterize climate drivers; (3) identify impact pathways; (4) assess risk to each NCF; and (5) identify mitigation strategies to reduce risk. We assessed risk based on a scale that CISA uses that ranges from a rating of 1 (no disruption or normal operations) to 5 (critical disruption on a national scale). We note that a risk rating of 3 (moderate disruption), although it still allows normal functioning on a national scale, could include a potentially significant disruption on a local or regional level, so the risk of moderate disruption to an NCF should be regarded as highly significant. For example, according to these criteria, the disruption caused by Hurricane Katrina in 2005 would be characterized as a moderate one. Although several NCFs, such as those related to the provision of power and water, failed at the local and regional levels as a result of impacts from the storm, at a national level, these NCFs continued to function. Accordingly, we stress that the risk of moderate disruption to an NCF at the national level should be regarded as highly significant and includes the potential for major disruptions or failure of NCFs at a local or regional level and for significant economic loss, health and safety impacts, and other consequences.

Using this risk rating scale and projected changes in eight climate drivers identified in our analysis (drought, extreme cold, extreme heat, flooding, sea-level rise, severe storm systems, tropical cyclones and hurricanes, and wildfire), we examined how NCFs could be affected by and at risk from climate change in three future time periods (by 2030, by 2050, and by 2100) and two future scenarios of greenhouse gas emissions.
Key Findings

All 27 NCFs analyzed for this report are expected to experience at least minimal disruption from climate change by 2100 under a scenario based on current greenhouse gas emissions (Table S.1).¹ These 27 NCFs were assessed as facing the most-significant risk of disruption, degradation, or failure in the future due to climate change. Because climate-related hazards and NCFs are distributed in time and space across the country, a complete national-scale failure of a single NCF is unlikely as a result of climate change; however, many regional-scale disruptions and failures (assessed as moderate disruption on the risk scale) are likely. For a list of all 55 NCFs, see the appendix.

By 2030, the NCFs at greatest risk are Provide Public Safety and Supply Water. These NCFs could face significant disruptions on the regional or local level due to climate change. Provide Public Safety governs responsibilities to support the community against such threats as hurricanes and wildfire, which, as of 2021, were already straining response capabilities. Similarly, Supply Water faces risk of moderate disruption by 2030 due to long-term drought, flooding, and wildfire.

Flooding, sea-level rise, and tropical cyclones and hurricanes pose the greatest risk of disruption to the NCFs. Although there are important regional distinctions in how and where climate drivers are anticipated to change, these three climate drivers were assessed as posing the greatest risk of disruption to the NCFs at the national level. Nearly all 27 NCFs are anticipated to be at risk of moderate disruption or greater by 2100 from sea-level rise; three-quarters of the 27 NCFs are anticipated to be at risk of moderate disruption from flooding; and more than two-thirds of the 27 NCFs are anticipated to be at risk of moderate disruption from tropical cyclones and hurricanes. Other drivers presenting risk to the NCFs are drought, extreme cold, extreme heat, severe storm systems, and wildfire.

Because of the interconnected nature of U.S. infrastructure, risk to one NCF can cause cascading risk to others. Failure in the Distribute Electricity NCF has the highest potential for cascading risk in dependent NCFs, with more than 20 of the 27 NCFs requiring electricity to ensure normal operations. Disruption or failure of this NCF has potential for significant cascading and immediate effects on other NCFs, including those supporting food production, medical care, and water supply.

Implications and Considerations

CISA should consider prioritizing specific NCFs for further assessment, communication, and risk mitigation. Specifically, Provide Public Safety and Supply Water are expected to be at risk of moderate disruption by 2030, and 11 of the 27 NCFs are assessed as being at risk of moderate disruption by 2050. CISA should consider prioritizing these NCFs for further assessment, including developing more-detailed assessments at the local and regional levels and assessing the mechanisms by which climate drivers could disrupt these NCFs. CISA should also consider prioritizing these NCFs for communications and outreach to stakeholders and the general public. Finally, CISA should prioritize the development of risk mitigation strategies for these NCFs, which was already anticipated by CISA’s request to the center to develop mitigation strategies in the next phase of this project.

The consequences of NCF disruption should be factored into future assessments. Regional disruption of an NCF can create national-level consequences, including significant threats to health and safety, eco-

¹ The U.S. Global Change Research Program (USGCRP) defines climate change as changes in average weather conditions that persist over multiple decades or longer. Climate change encompasses both increases and decreases in temperature, as well as shifts in precipitation, changing risk of certain types of severe weather events, and changes to other features of the climate system. (USGCRP, undated a)
TABLE S.1
National Risk Ratings and Strength of Evidence for 27 Assessed National Critical Functions

<table>
<thead>
<tr>
<th>NCF, by Risk Rating</th>
<th>Current Emissions</th>
<th>High Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2030</td>
<td>2050</td>
</tr>
<tr>
<td>Provide Public Safety</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Supply Water</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Develop and Maintain Public Works and Services</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Distribute Electricity</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Enforce Law</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Manage Hazardous Materials</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Manage Wastewater</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Prepare for and Manage Emergencies</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Provide Medical Care</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Transmit Electricity</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Transport Cargo and Passengers by Air</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Generate Electricity</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Maintain Supply Chains</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Manufacture Equipment</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Produce and Provide Agricultural Products and Services</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Produce Chemicals</td>
<td>2</td>
<td>2</td>
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<tr>
<td>Provide Housing</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Educate and Train</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Transport Cargo and Passengers by Vessel</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Provide and Maintain Infrastructure</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Exploration and Extraction of Fuels</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Provide Insurance Services</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Transport Cargo and Passengers by Rail</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Transport Cargo and Passengers by Road</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Transport Passengers by Mass Transit</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Produce and Provide Human and Animal Food Products and Services</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Support Community Health</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

NOTE: The list groups NCFs by risk rating, in descending order of risk. Multiple NCFs with the same ratings are listed alphabetically within their rating groups. The shade of gray indicates the strength of evidence for that NCF: dark gray = strong evidence base in peer-reviewed scientific literature with consistent findings; medium gray = moderate evidence base with several sources but limited documentation; and light gray = inconclusive or suggestive evidence base. 1 = no disruption or normal operations. 2 = minimal disruption. 3 = moderate disruption. These definitions are based on those used in the Fourth National Climate Assessment.

Economic loss, and risks to national security. CISA should consider conducting a more-complete analysis of the consequences of various levels of disruption examined in this report to inform the prioritization of future risk mitigation activities.
CISA should continue to prioritize risk communication about the NCFs. This report illustrates the challenge in conveying risk information about the NCFs, which are difficult to disrupt at a national scale but which nonetheless create severe life, safety, and economic impacts when disrupted at the local or regional level. Effectively communicating risk from climate change and climate drivers to the NCFs should be a key priority.

CISA should continue to update assessment of the risk that climate change poses to the NCFs over time. Projecting risk from climate change in 2050 and 2100 is inherently subject to error and unpredictability. Projections will only be refined over time as better information becomes available and as changes to the climate manifest in the real world and demonstrate NCFs’ resilience, or lack thereof. Future climate risk assessments should consider risk at subnational scales and might more directly incorporate NCF interdependencies. Such analyses would provide insight into which regions of the country are at higher risk and which NCFs or subfunctions within NCFs might increase risk to other critical infrastructure functions.
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CHAPTER ONE

Introduction

On January 27, 2021, President Joseph R. Biden, Jr., signed Executive Order (EO) 14008, “Tackling the Climate Crisis at Home and Abroad.” EO 14008 describes the threat that the climate crisis poses to the United States and to the world and the roles of various federal agencies in addressing this threat. The EO directs the Secretary of Homeland Security to “consider the implications of climate change in the Arctic, along our Nation’s borders, and to National Critical Functions” (§ 103[e]).

The National Critical Functions (NCFs) represent “the functions of government and the private sector so vital to the United States that their disruption, corruption, or dysfunction would have a debilitating effect on security, national economic security, national public health or safety, or any combination thereof” (Cybersecurity and Infrastructure Security Agency [CISA], undated c, p. 1). CISA developed the NCFs in 2019 to enable more-robust situational awareness of U.S. critical infrastructure. NCFs represent an evolution in CISA’s critical infrastructure risk management framework to improve the analysis of crosscutting risks and associated dependencies that could have cascading effects within and across sectors. Of these crosscutting risks, climate change creates both risks and opportunities for ensuring the security and resilience of critical infrastructure systems as evaluated through the lens of the NCFs.

To fulfill the objectives of the EO, CISA asked the Homeland Security Operational Analysis Center (HSOAC), a federally funded research and development (R&D) center operated by the RAND Corporation, to develop a risk management framework to assess and manage the risk that climate change poses to the NCFs and to use the framework to assess 27 priority NCFs. The framework is intended to be compatible with and integrate into existing CISA risk management efforts, support an initial assessment of climate-related risk to the NCFs, and provide a repeatable capacity for ongoing assessment of climate-related risk moving forward. The framework also provides CISA with an ongoing capability to assess climate-related risk.

This task builds on HSOAC’s prior work in assessing risk to the NCFs from coronavirus disease 2019 (COVID-19). In March 2020, CISA tasked HSOAC with assessing risk that the spread of COVID-19 posed to the 55 NCFs, developing a system to actively monitor risk to the NCFs, and identifying options for mitigating such risk.

Because climate change represents an entirely separate and distinct set of threats and hazards from COVID-19, this study builds on HSOAC’s experience working with the NCFs but differs in several ways. The study requires the development of an updated risk assessment framework; identification of new and distinct risk drivers related to climate change; and characterization of alternative means of mitigating risk to the NCFs that might not have been relevant for COVID-19. Unlike COVID-19, which presents an immediate, near-term threat to the NCFs and thus required forward-looking assessments covering the next 60 days, the risk of climate change covers a much wider time frame and thus requires both short-term and significantly longer-term analyses corresponding to time periods commonly used in national climate assessments (e.g., by 2030, by 2050, or by 2100).
Study Objectives

To achieve the aims of the EO described above, this report presents a climate change risk management framework and the results of a climate risk assessment to address the following objectives:

- Develop a climate risk management framework that can help analysts identify, assess, and manage the risks that climate change poses to the NCFs.
- Identify which NCFs are at most risk as a result of climate change.
- Determine how CISA, the U.S. Department of Homeland Security (DHS), other parts of the U.S. government, and other NCF stakeholders might effectively mitigate this risk.
- Synchronize this work with the extensive body of climate science, U.S. government, external efforts related to climate change, and efforts initiated by EO 14008.

Scope of This Report

To meet the study objectives, we carried out a series of research tasks, which are described in detail later in this report:

- developed a risk management framework for assessing risk that climate change poses to the NCFs (Chapter Two)
- identified key climate drivers and authoritative sources of climate-related data for CISA analyses (Chapter Three)
- assessed risk that climate change poses to the NCFs (Chapters Four and Five).

HSOAC also supported CISA in summarizing the findings from this study for an annual update response to EO 14008 and will, after completing this report, carry out additional work to provide investment decision support related to mitigation and adaptation activities for NCFs at risk from climate change. These activities are not detailed in this report.

Organization of This Report

The remainder of this report is organized as follows:

- Chapter Two details the risk management framework and its underlying methods.
- Chapter Three presents the analysis of future changes in climate drivers.
- Chapter Four describes the high-level findings of the climate risk assessment on a subset of NCFs, and Chapter Five presents an NCF-level summary of the risk that climate change poses to each NCF assessed in this analysis.
- Chapter Six provides an assessment of cascading risk posed by climate change across the NCFs.
- Chapter Seven details the implications of our findings and identifies areas for future work.
- The appendix contains the findings from our initial screening to identify higher-vulnerability NCFs to include in this analysis.
Methods

This chapter details the methods we employed to carry out the climate risk assessment detailed in this report. These methods support four principal activities: (1) developing a risk management framework, (2) screening higher-vulnerability NCFs, (3) identifying and characterizing climate drivers, and (4) assessing climate risk to the NCFs. Each of these activities is outlined in this chapter.

Developing a Risk Management Framework

DHS broadly and CISA specifically have employed a variety of risk management frameworks to manage homeland security risks and protect U.S. critical infrastructure (CISA, 2013; Risk Steering Committee, 2010). CISA also uses tailored risk assessment and management approaches to track risk to the 55 NCFs, including the NCF risk register and NCF risk architecture (CISA, 2020). With these existing approaches, as well as emerging efforts within CISA and prior work by HSOAC (Lauland et al., forthcoming), we developed a risk management framework to assess and manage the risk that climate change poses to the NCFs. The framework is intended to be compatible with and integrate into existing CISA risk management efforts, support an initial risk assessment of climate change risk to the NCFs, and provide CISA with the capacity for ongoing assessment of climate change risk moving forward. Figure 2.1 presents the five steps of the risk management framework:

1. Perform a screening exercise to determine which of the 55 NCFs have sufficient exposure and vulnerability to climate change to merit inclusion in the risk assessment described in this report.
2. Identify climate drivers that span the range of climate-related hazards that could degrade or disrupt NCFs over the course of the 21st century.
3. Define the climate driver impact pathways, including the mechanisms by which the climate drivers pose a threat to NCFs, such as physical exposure or workforce vulnerability, and the consequences of climate drivers’ effects on an NCF, such as operational failure.
4. Assign a rating to the risk that a climate driver poses to an NCF, based on the characterization of impact mechanisms and consequences.
5. Identify potential risk mitigation strategies that can be used to reduce risk to an NCF, and evaluate the potential feasibility and efficacy of those strategies.

The methods underlying steps 1 through 4 are detailed in the subsequent sections. The two-sided arrow between steps 4 and 5 indicates the iterative nature of ongoing risk assessment and risk mitigation actions. Step 5 (risk mitigation) will be developed and carried out after this report is complete. These steps generally align with risk management frameworks that CISA and DHS use, with the exception of the implementation of risk mitigation actions and risk communication activities. Although they are not explicitly covered in this framework, decision support matrices and communication products related to the implementation of risk mitigation strategies will also be developed as a part of step 5.
Screening Higher-Vulnerability National Critical Functions

Because of the consolidated timeline required to meet the objectives of EO 14008 and the complexity of assessing risk to the NCFs, we developed and performed a screening exercise to identify the subset of NCFs that might experience significant disruption or degradation from future climate change and therefore would merit a full risk assessment for this study. To screen the NCFs and identify those at higher vulnerability, we assessed all 55 NCFs based on their relative levels of inherent vulnerability to climate change and the robustness of available evidence in the scientific literature and among prior scientific climate assessments conducted by U.S. federal agencies and national laboratories.

HSOAC subject-matter experts assigned each NCF a rating of low, medium, or high vulnerability to climate change. These ratings were determined through a scan of relevant literature, with a focus on widely cited publications on the effects that climate change has on critical infrastructure, such as those included in climate assessments (Reidmiller et al., 2018), peer-reviewed scientific literature that assesses infrastructure’s sensitivities or vulnerabilities to climate change (Henry and Pratson, 2016), and other relevant federal or national-scale reports (Brown et al., 2015):

- A high vulnerability rating indicates that an NCF has been documented to be vulnerable to multiple climate drivers (e.g., drought, extreme heat) via multiple mechanisms of impact that affect its performance (e.g., decline in inputs, infrastructure damage).
- A medium rating indicates that an NCF has been documented to be vulnerable to a single or specific set of drivers via a limited set of mechanisms (e.g., only a subfunction of the NCF).
- A low rating indicates that an NCF does not already experience or is not anticipated to experience declines in NCF performance due to climate change through any climate drivers or mechanisms of impact.
Methods

The strength of the available evidence base to support each assessment was also rated as either low, medium, or high. HSOAC subject-matter experts examined the body of available evidence of the effects of climate change broadly, rather than by specific climate driver:

- A high evidence rating was given when a robust set of literature was available and multiple subfunctions or aspects of the NCF were the subject of significant research and reporting.
- A medium evidence rating was given when only a limited number of studies were available but were sufficiently generalizable to the regional or national scale.
- A low evidence base rating was given when very few to no peer-reviewed or widely cited reports were available to support the assessment or when any available documentation represented only narrow case studies that were not generalizable to the regional or national scale.

The NCF vulnerability and evidence base ratings were reviewed for interrater consistency and adjusted as needed, then peer-reviewed by a separate group of HSOAC subject-matter experts. Chapter Four details the higher-vulnerability NCFs, and the appendix contains the full summary results of this analysis.

Identifying and Characterizing Climate Drivers

Climate change constitutes a broad variety of future changes to our global climate. Although many definitions exist, the federal government has defined climate change as

changes in average weather conditions that persist over multiple decades or longer. Climate change encompasses both increases and decreases in temperature, as well as shifts in precipitation, changing risk of certain types of severe weather events, and changes to other features of the climate system. (U.S. Global Change Research Program [USGCRP], undated a)

To characterize these future changes, we first identified a set of climate-related hazards projected to change in the future. In doing so, we focused on those changes in climate phenomena and climate-related hazards that had direct impacts on NCFs, such as extreme events, rather than those that were indirect, such as atmospheric concentrations of carbon dioxide.

Relying on categories used in other federal climate change efforts that reflect authoritative sources of future climate changes, specifically the Fourth National Climate Assessment (NCA4),\(^1\) we identified a set of eight climate drivers, shown in Table 2.1, that represent seven groupings of extreme events plus sea-level rise. For the purposes of this report, we refer to these climate-related hazards as climate drivers.

These extreme events often have a set duration and are distinct from longer-term trends in climate variables. We did not consider these longer-term trends in variables, such as average daily temperature or average daily precipitation, although shifts in such variables are recognized as underlying causes of more-extreme events. For example, warmer temperatures and reduced precipitation can produce an increased incidence of drought. Instead, the climate drivers, as framed, focus on those changes likely to be directly responsible for future degradation or disruption of NCFs. Sea-level rise is conceptualized as a slower-moving climate driver but one that has direct and lasting impacts on NCFs. Although drought can occur over long periods of time, it is generally considered an extreme event. Additionally, the set of drivers developed for this risk assessment does not include the secondary effects of climate-related hazards, such as landslides or debris flows. Finally,

\(^1\) As of this writing, the Fifth National Climate Assessment is currently being carried out and so was unavailable at the time of analysis.
part of the reason we selected these drivers is that sufficient evidence exists about each to articulate future changes across different climate change scenarios and future time periods from a consistent evidence base.

To characterize future changes in these drivers, we defined three future time periods commonly used in regional and national climate assessments:

- near term (by 2030), representing projected changes over the next eight years
- medium term (by 2050), representing projected changes over approximately 30 years
- long term (by 2100), representing projected changes over approximately 80 years.

Additionally, because changes in the future cannot be predicted with certainty, this assessment relied on two future scenarios to characterize some of the uncertainty in future climate changes by 2100. Projected changes in future climate drivers were defined by two scenarios of future greenhouse gas (GHG) emissions:

- A current-emissions scenario that reflects global mean temperature change, given the current global GHG emission levels and recent international commitments to emission reductions. This is equivalent to the scenarios involving Representative Concentration Pathway (RCP) 4.5 to 6.0, or a global warming of approximately 3 degrees Celsius (5.4 degrees Fahrenheit) by the end of the century (Thomson et al., 2011). RCP4.5 was used in NCA4 as a low-emissions scenario. However, as noted in the latest Intergovernmental Panel on Climate Change (IPCC) assessment report (IPCC, 2021), current data suggest that this scenario is reflective of the planet’s current emission trajectory, so one assumes that there is a reasonable likelihood that emissions will be at least as high as RCP4.5. Lower-emissions scenarios have been modeled, but they have seen little use in impact assessments in the United States.

- A high-emissions scenario that reflects the global mean temperature change in the event of a significant increase in future GHG emissions or a higher climate sensitivity that results in higher magnitudes of climate change per unit of emissions. This is equivalent to RCP8.5, or a global warming of approximately 5 degrees Celsius (9 degrees Fahrenheit) by the end of the century (Riahi et al., 2011). As reflected in the latest IPCC assessment report (IPCC, 2021), current data suggest that this scenario is highly unlikely given observed progress in reducing emissions from developed countries and current understanding of
climate sensitivity. However, it remains plausible because of the potential for significant feedbacks in the climate system.

To characterize the projected degree of change for each climate driver, time period, and climate scenario at the national scale, we relied on consensus-based descriptions and information on future change contained in NCA4. NCA4 represents a nationally consistent consensus-based climate assessment intended to support research and adaptation for the United States. It also includes consistent historical baselines, future time periods, climate scenarios, and data sets necessary for ensuring a consistent basis for risk ratings.

We first examined national-level changes for each climate driver both quantitatively, when possible, and qualitatively based on information on specific climate drivers in NCA4 Volume I, as well as with the supplementary NCA4 viewer that contains the underlying downscaled global climate model data analysis based on the localized constructed analogs (LOCA) data set (USGCRP, undated b; Wuebbles et al., 2017). As needed, we referred to NCA4 Volume II or other scientific publications to refine estimates or descriptions of projected changes. Initially, we summarized the national-level changes for each driver, time period, and future climate scenario. Using the LOCA data sets for available climate variables, we noted any regional nuances. If sufficient information was not available in NCA4 to describe future climate changes across all time periods, we consulted other widely cited and nationally relevant scientific publications, consulting only those publications published within the past ten years. These summary descriptions for each driver, time period, and climate scenario are contained in Chapter Three.

Although these descriptions are intended for direct use in the risk assessment, we summarized these changes in a high-level table of the projected degree and direction of change at the national level to support CISA climate risk assessments and communication of climate changes. Each of the summary descriptions was characterized by degree of change as high, medium, low, or no degree of change and by direction as increase or decrease. These ratings did not distinguish between frequency, magnitude, or duration and were assigned for each driver, future time period, and climate scenario:

- We assigned a high degree of change if either of these conditions was true:
  - expected climate changes reflected significant increases or decreases over time
  - quantitative values indicated an increase or decrease of at least 20 percent.

  For example, a high degree of change was used to characterize the following:

  High temperature extremes are expected to increase by about 6 degrees Fahrenheit by late century. The frequency in the number of days with extreme temperatures (above 90 degrees Fahrenheit) is projected to increase by about 40–60% across the United States.

- We assigned a medium degree of change if either of these conditions was true:
  - expected climate changes reflected significant increases or decreases over time but with the most-significant increases or decreases occurring in other time periods
  - quantitative values indicated an increase or decrease of less than 20 percent.

  For example, a medium degree of change was used to characterize changes by 2050: “Significant increases in the potential for large wildfires are likely across the Western United States through the end of the 21st century. These increases are anticipated to be greater by the end of the century.”

- We assigned a low degree of change if expected climate changes did not differ much from recent changes in the historical record but changes were expected. For example, a low degree of change was used to
characterize the following: “Projected changes in global mean tropical cyclone and hurricane wind speeds and precipitation rates will likely increase, and the frequency of tropical cyclones and hurricanes may remain the same as seen in the historic record.” We assigned no degree of change if changes in climate drivers were not expected. For example, no degree of change was used to characterize the following: “Cold waves are generally less frequent, as observed in recent years, but no changes are expected from the baseline period.”

We based assignments to each category on NCA4 language about the degree of change qualitatively or, for climate drivers with quantitative information, quantitative changes. To assess each driver, we relied on those values or descriptions of change for each driver as published in NCA4. In some cases, changes in average values for a specific metric were available, but, in many cases, NCA4 presents its own summary of how a driver is anticipated to change. Examples of these descriptions are described in the rating definitions above. When possible, we relied on quantitative changes from the underlying LOCA data set made available as part of NCA4 resources. These data sets rely on average values for various metrics, and we used those metrics described in NCA4 for each driver. We assigned the direction of change based on the direction of expected changes—if a climate driver was projected to increase in frequency, magnitude, or duration, we assigned an increase. If a climate driver was projected to decrease in frequency, magnitude, or duration, we assigned a decrease. We present the ratings in Chapter Three.

Assessing Climate Risk to the National Critical Functions

We assessed the risk to each NCF based on projected changes in the climate drivers and their expected impact on the NCF. We assessed risk for each NCF across the three future time periods and both climate scenarios, as depicted in Figure 2.2. Risk assessments relied on available evidence of a given climate driver’s expected impact on an NCF, the degree of change in a given climate driver, and our judgment of the degree of risk this produced. We made these risk assessments at the national level. In addition, HSOAC subject-matter experts peer-reviewed the risk assessments, and we cross-checked the assessments to ensure consistency across analysts. Additionally, the HSOAC team held multiple sessions calibrating risk ratings to discuss differences in ratings among similar NCFs and ensure analyst concordance on risk ratings. This process drew from prior HSOAC work on risk assessment with the NCFs (Lauland et al., forthcoming).

![FIGURE 2.2](image)

An Overview of the Components of a Climate Risk Assessment

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2 By average value, we mean the average value of the range of future climate projections that could characterize future change for a given climate driver. For example, the LOCA data set includes 32 global climate models, each of which contains a projection of future change.
In addition to the details described under “Risk Ratings” later in this chapter, we made some key assumptions in assessing risk to the NCFs. We assumed that there were no major changes to the NCFs and the environment in which they operate (e.g., no climate adaptation strategies are undertaken, no major population shifts occur), outside of normal operational changes, into the future. Additionally, in our risk ratings, we did not consider interdependencies between NCFs. Instead, we conducted a separate interdependency analysis (see Chapter Six).

**National Critical Function Subfunctions**

Each NCF consists of between two and nine subfunctions that define the key systems within it. For example, Educate and Train is made up of two subfunctions:

- Provide Formal Education
- Provide Workforce Training.

Transport Cargo and Passengers by Rail is made up of six subfunctions:

- Provide Rail Systems
- Provide Intermodal Transport of Freight
- Transport Cargo via Rail
- Transport Passengers by Rail
- Maintain Rail Workforce
- Govern Rail Transport Operations.

CISA developed these subfunctions as part of the NCF risk architecture and provided that information to us. At CISA’s request, these subfunctions served as the basis for NCF risk ratings. Specifically, we rated risk for each subfunction–driver combination across the three time periods and two future scenarios, resulting in 96 to 432 risk ratings for each NCF.

We then summarized subfunction risk ratings at the NCF level. To do this, we calculated the maximum risk rating across all subfunctions for each driver, time period, and future scenario. For example, if, for the current-emissions scenario for 2030 for sea-level rise, one subfunction was assigned a rating of 1 and the second subfunction was assigned a 3, the NCF-level risk for sea-level rise for 2030 under the current-emissions scenario would be a 3. The risk rating scale is described under “Risk Ratings” later in this chapter. We used this type of aggregation to capture the highest underlying risk to an NCF, rather than an average of ratings. For NCFs with nine subfunctions, for example, seven of them could be relatively insensitive to climate change (e.g., subfunctions related to human resources or communication), but two could be at high risk, with disruption or failure of either of these two affecting the NCF at large.

Although this process provided a high level of granularity for risk ratings within an NCF, it also meant that risk ratings depended on how NCFs are characterized by their subfunctions. For example, the subfunctions for Support Community Health focus on the systems and functions that provide community health (operations, emergency response, communications) but not on the health of the community itself. As a result, risk to this NCF focuses on the impact that climate change will have on these types of functions.

**Impact Pathways**

In assessing risk, HSOAC analysts considered the impact pathways for each driver–NCF subfunction pair (the various mechanisms by which a climate driver can disrupt an NCF), as well as the consequences a driver might have on that NCF. Pathways include direct impacts from a climate driver, such as physical damage to
An asset that reduces its performance or requires investment to restore performance, as well as the resulting consequences from a climate driver (i.e., the unwanted effects on an NCF, such as degradation in operations).

An example impact pathway that depicts one effect that flooding would have on Supply Water is shown in Figure 2.3. This illustrates that flooding can directly affect a drinking water system when floodwaters bring contaminants into drinking water sources. For a drinking water provider, this would affect operations by requiring additional treatment or requiring the operator to switch to an emergency or backup water source. For drinking water consumers, contamination of water sources could also mean a degradation of drinking water quality.

We characterized and briefly described the impact pathways for each climate driver and each NCF, drawing from published scientific literature on NCF operations in the face of extreme events and climate change. Characterizing these types of impact pathways for climate drivers and NCFs provided an understanding of how severe the impacts of climate change could be on an NCF and was a key input to HSOAC analyst risk assessments. Chapter Five contains summary descriptions of how climate drivers are anticipated to affect each NCF.

As a part of this analysis, we also identified the mechanisms of impact that characterize how climate change causes a risk of disruption to each of the 27 assessed NCFs. We categorized these mechanisms into four groupings:

- **physical damage or disruption**: The effects of climate change, or a specific climate driver, cause physical damage to facilities or equipment necessary for the functioning of the NCF. This mechanism also includes cases in which a climate driver might disrupt but not necessarily damage infrastructure (e.g., high temperatures that ground airplanes).
- **input or resource constraint**: The effects of climate change, or a specific climate driver, cause an interruption in the supply of inputs to the NCF, preventing the NCF from functioning. These could be raw materials, or they could be goods or services produced by others, including those produced or delivered by other NCFs, such as water, power, and communication.
- **workforce shortage**: The effects of climate change, or a specific climate driver, create a shortage of workers needed to operate the NCF. This includes conditions in which the climate driver makes such work unpleasant or dangerous. Note that we did not consider interdependencies among NCFs, so workforce shortage includes only those conditions that prevent sufficient numbers of workers from being able to work. If roads are inundated and workers unable to travel, we considered that an interdependency with Transport Cargo and Passengers by Road.
- **demand change**: The climate driver causes changes in the demand for the NCF, resulting in the NCF not being able to fully meet the demand. This could be an increase in demand that goes beyond what the NCF can supply, a decrease in demand affects the viability or efficiency of the NCF, or volatile fluctuations encompassing both increases and decreases.

**FIGURE 2.3**
An Example Impact Pathway for the Supply Water National Critical Function

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Consequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flooding</td>
<td>• Additional water treatment is required.</td>
</tr>
<tr>
<td></td>
<td>• Consumers must rely on an emergency water source.</td>
</tr>
<tr>
<td></td>
<td>• Drinking water quality is degraded.</td>
</tr>
</tbody>
</table>
Mechanisms relevant to each assessed NCF are identified in that NCF’s summary table, or scorecard, in Chapter Five.

Risk Ratings

We assigned risk ratings on a scale of 1 to 5, as shown in Table 2.2, based on the amount of anticipated disruption at the national scale, with 1 being no disruption or normal operations and 5 being critical. Analysts were also able to assign an unknown rating if sufficient evidence was not available to assess risk for a given subfunction–driver combination. Risk rating definitions are based on CISA’s operational-level framework and, although they were tailored to the context of this risk assessment, were developed to ensure alignment with other CISA NCF risk assessments. Using this scale, we determined a risk rating for each driver–subfunction combination across all three time periods and two climate scenarios. For each NCF, risk ratings are provided in Chapter Five for those drivers and subfunctions that were assessed at a risk of minimal disruption or greater.

The risk levels of minimal and moderate disruption (ratings of 2 and 3) imply significant effects locally and regionally:

- Moderate disruption indicates that an NCF is at risk of not meeting operational needs in potentially large portions of or key locations in the country.
- Minimal disruption indicates that an NCF is at risk of being affected by climate change, which could stress resources and operations, even though it is likely to meet operational needs.

Table 2.3 provides an example of the interpretation of these ratings for Transport Cargo and Passengers by Air.

**TABLE 2.2**

<table>
<thead>
<tr>
<th>Risk Rating</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unknown or insufficient evidence</td>
<td>A driver’s effect on this NCF or subfunction is unknown, or there was insufficient evidence to make a risk assessment.</td>
</tr>
<tr>
<td>1 No disruption or normal operations</td>
<td>The NCF or subfunction was anticipated to meet all routine operational needs.</td>
</tr>
<tr>
<td>2 Minimal disruption</td>
<td>Climate change is expected to affect the NCF or subfunction, but the function is expected to meet routine operational needs.</td>
</tr>
<tr>
<td>3 Moderate disruption</td>
<td>The NCF or subfunction is anticipated to meet all routine operational needs in most but not all of the country.</td>
</tr>
<tr>
<td>4 Major disruption</td>
<td>The NCF or subfunction is anticipated to be unable to meet routine operational needs in most of the country.</td>
</tr>
<tr>
<td>5 Critical</td>
<td>The NCF or subfunction is anticipated to be unable to meet any of its routine operational needs across the country.</td>
</tr>
</tbody>
</table>

3 Unpublished framework provided to the HSOAC research team by CISA staff.
### TABLE 2.3
An Example Interpretation of Risk Ratings for the Transport Cargo and Passengers by Air

<table>
<thead>
<tr>
<th>Risk Rating</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 No disruption or normal</td>
<td>Air transportation continues to function as it does today, with occasional delays due to weather and operational problems.</td>
</tr>
<tr>
<td>operations</td>
<td></td>
</tr>
<tr>
<td>2 Minimal disruption</td>
<td>A few airports in flood-prone regions experience longer periods in which they cannot operate safely, but cargo and passengers can be moved through alternative airports.</td>
</tr>
<tr>
<td>3 Moderate disruption</td>
<td>Some airports close temporarily or permanently because of sea-level rise; flight delays and cancellations due to extreme heat and storms (and the damage they cause to airport infrastructure) become far more frequent.</td>
</tr>
<tr>
<td>4 Major disruption</td>
<td>Most commercial air travel is not viable; some airlines cease to operate, and a significant number of airports close permanently.</td>
</tr>
<tr>
<td>5 Critical</td>
<td>Air travel and freight movements by air are essentially halted, although they might be available at very high prices.</td>
</tr>
</tbody>
</table>
CHAPTER THREE

Climate Drivers

This chapter presents the findings of our analysis of changes in climate drivers over the three time periods and two climate scenarios considered in this work. As described previously, climate drivers are conceptualized as the climate-related hazards that drive risk to the NCFs from climate change. Table 3.1 depicts the qualitative summary of national-scale projected degree of change in each of the eight climate drivers. To maintain consistency with authoritative sources that describe both historical and future changes in these drivers, changes are reported in climate drivers relative to the historical climatology utilized in the Climate Science Special Report volume of NCA4 for 1976 through 2005. As shown in this table, nearly all climate drivers are expected to experience some degree of increase in intensity, magnitude, or duration by 2050. Five of the drivers—drought, extreme heat, flooding, sea-level rise, and wildfire—are projected to experience a high degree of increase by 2100. Only extreme heat is projected to see a high degree of increase by 2050 (under the high-emissions scenario). Extreme cold is the only climate driver expected to decrease into the future.

A broad consensus and scientific basis exist around future climate changes, but climate models on regional to global scales have not fully characterized all future climate changes. As a result, Table 3.2 provides a low, medium, or high rating for confidence in the projected future trend based on the evidence basis in climate science for anticipated future changes for each climate driver:

- We assigned a low rating if either of these conditions was true:
  - The literature provided a limited understanding of physical processes.
  - Significant inconsistencies existed among models.
- We assigned a medium rating if either of these conditions was true:
  - The literature provided a moderate understanding of physical processes.
  - There was published variation in model results.
- We assigned a high rating if either of these conditions was true:
  - A high degree of understanding of physical processes was exhibited in the literature.
  - Consistency was evident in modeling.

As shown in the table, only severe storm systems had a low degree of confidence in the future trend.

In the following sections, future national trends in each of the eight climate drivers are described, noting differences between future time periods, climate scenarios, and any regional nuances. Additionally, each section contains a description of the confidence in future trends.
Assessing Risk to the National Critical Functions as a Result of Climate Change

Drought

In the near term, the declines in surface soil moisture that have occurred as average temperatures have warmed are expected to continue. In both the current- and high-emissions scenarios, this is expected to lead to continued incidence of drought, similar to that experienced in the past five to ten years (Easterling et al., 2018).

Changes in hydrological drought, which is governed predominantly by precipitation (including snowpack), will be uneven across the United States, with projections indicating that the western and southwestern portions of the United States are likely to experience increases in hydrological drought in both scenarios through the 21st century. Agricultural drought, which is caused by temperature in addition to precipitation, is likely to occur across the United States as soil moisture declines, with the incidence of extreme drought increasing as well. Drought incidence is likely to increase across emission scenarios and from 2050 to 2100,
which is similar to projections of hydrological drought (Wuebbles et al., 2017). IPCC's Sixth Assessment Report (AR6) suggests more-intense agricultural drought conditions by 2050 under the high-emissions scenario (IPCC, 2021).

Confidence in the projected trend in droughts is high because there is a solid understanding of the physical processes underlying droughts and there is consistency in observations and modeling of future drought conditions under climate change. Current climate science has understood the dynamics that produce droughts relatively well, with NCA4 citing a very high confidence in the projected changes in hydrological drought by the end of the century. For agricultural drought, global climate model representation of land surface processes and the models' ability to represent soil moisture at the root zone of crops varies, but models consistently show drying of soil moisture across the United States (Wuebbles et al., 2017).

NCA4 focuses on the underlying science describing projected changes in drought incidence for those regions that have historically experienced and are increasingly prone to drought—the western United States. Although droughts have occurred in portions of the eastern United States, these are generally less severe and much shorter in duration than those in the western United States. The future anticipated change in the eastern United States is, therefore, lower than that shown for national-scale changes (Wuebbles et al., 2017).

**Extreme Cold**

Unlike other climate drivers, the trend in extremely cold temperatures is expected to decline in the next century. In both the current- and high-emissions scenarios, cold waves are expected to be generally less frequently observed than they have been in recent years (Wuebbles et al., 2017). The frequency and intensity of cold waves and low temperature extremes are expected to decrease by 2050 as temperatures warm across the United States. In the current-emissions scenario, cold-wave temperatures are expected to warm by at least 4 to 6 degrees Fahrenheit on average across the United States by 2050 (USGCRP, undated b; Wuebbles et al., 2017). In the high-emissions scenario, cold-wave temperatures are expected to warm by at least 6 to 8 degrees Fahrenheit on average across the United States by 2100 (USGCRP, undated b; Wuebbles et al., 2017). The current-emissions scenario projects cold-wave temperatures to warm by at least 6 to 8 degrees Fahrenheit on average across the United States by 2100 (USGCRP, undated b; Wuebbles et al., 2017). In the high-emissions scenario, cold-wave temperatures are expected to warm by at least 10 to 14 degrees Fahrenheit by 2100 (USGCRP, undated b; Wuebbles et al., 2017).

Confidence in the projected trend in extremely cold temperatures is high. A large and robust body of work describes and attributes temperature changes to climate change. Numerous data sets exist to examine specific regional to national-scale changes in extreme temperatures. Although more work has been done on high temperature extremes, the same data and models support analyses of warming cold temperatures (Wuebbles et al., 2017). Although recent extreme cold events have shown the potential for significant impacts from extreme cold, future climate projections do not indicate a high likelihood of similar events in the future. In general, global climate models do not capture the Arctic polar vortex with consistency and are not in agreement on how it will shape future extreme cold events. Additionally, most experts on extreme cold agree that the general trend is that, "on average, winters are warmer and cold extremes are less likely than they were a century ago" (Lindsey, 2021).

Some regional differences in the trend in extreme cold are expected as well. Across the available metrics in NCA4 to track changes in extreme cold (such as a projected change in the number of days below freezing or the coldest five-day one-in-ten-year event), compared with national average changes in extreme cold events, the Northeast and Great Lakes are expected to see greater declines in the number of extreme cold events, and the southern half of the United States is projected to see lower declines in the number of extreme cold events (USGCRP, undated b; Wuebbles et al., 2017).
Extreme Heat

In the near term, under both the current- and high-emissions scenarios, high temperature extremes and heat waves are projected to increase (Easterling et al., 2018). Changes by 2030 are expected to be minimal, with extreme heat consistent with that experienced in the past five to ten years (Easterling et al., 2018). High temperature extremes are expected to increase, by 2050, by about 4 degrees Fahrenheit under the current-emissions scenario and by about 6 degrees under the high-emissions scenario. The frequency of extreme temperature days (above 90 degrees Fahrenheit) is also projected to rise by 2050. In the current-emissions scenario, these days are projected to increase by 20 to 40 percent; in the high-emissions scenario, the increase is projected to be 40 to 60 percent across the United States (USGCRP, undated b; Wuebbles et al., 2017).

Extremely high temperatures and heat waves are expected to become more frequent and intense by 2100. By 2100, high temperatures are expected to increase by 6 degrees Fahrenheit across the United States in the current-emissions scenario. The number of extreme heat days are also projected to rise by between 40 to 60 percent under the current-emissions scenario. Under the high-emissions scenario, high temperatures are expected to increase by 10 degrees or more by 2100, and the number of extreme heat days is projected to increase by about 60 to 80 percent across the country (USGCRP, undated b; Wuebbles et al., 2017).

Confidence in this increased trend is high because there is a high understanding of the physical processes and consistency in observations and modeling of extreme heat under climate change. A large and robust body of work describes and attributes changes in temperatures to climate change. Numerous data sets exist to examine specific regional to national-scale changes in extreme temperatures (Wuebbles et al., 2017), which indicates that the confidence in the projected trends is high.

Across the available metrics in NCA4 to track changes in extreme heat (such as projected change in the number of days above 90 degrees Fahrenheit or the warmest five-day one-in-ten-year event), compared with national average changes in extreme heat events, the Northeast and Pacific Northwest are expected to warm less and the southern half of the United States is projected to warm more (USGCRP, undated b; Wuebbles et al., 2017). At the national scale, urban areas are likelier to experience extreme heat events because of the urban heat-island effect (IPCC, 2021). Additionally, extreme heat events can be magnified in regions with high humidity, such as the southeastern and midwestern United States. The combination of heat and humidity is known as the wet-bulb temperature, and wet-bulb temperatures above 79 degrees Fahrenheit can affect human health (Raymond, Matthews, and Horton, 2020). Finally, heat is regional, and some regions could be more vulnerable to less-extreme heat days (e.g., 90 degrees Fahrenheit instead of 105 degrees Fahrenheit) because of the prevalence or absence of air-conditioning or other existing adaptations to extreme heat.

Flooding

Flooding is expected to increase in intensity and frequency over the next century under both the current-emissions and high-emissions scenario. In both current- and high-emissions scenarios, the near-term (by 2030) observed changes in the frequency and intensity of extreme precipitation events are projected to continue in most parts of the United States, contributing to the occurrence of severe flood events, similar to what has been experienced in the past five to ten years (Easterling et al., 2018).

Projections of future precipitation under the current-emissions scenario show that increases in the frequency of flood-inducing extreme precipitation events (specifically, those events with a return period of more than five years) could be 50- to 100-percent more than historical averages by the end of the century. This suggests a slightly smaller magnitude in these changes by midcentury. Similarly, under the high-emissions scenario, the increase in frequency of extreme precipitation events that cause flooding could be 200- to 300-percent by the end of the century, indicating that flooding by 2050 could also be higher (IPCC, 2021).
Model projections under the current-emissions scenario indicate an 8- to 10-percent increase in the size of precipitation events with a 20-year return period, which could translate to a slight but noticeable increase in the incidence of flooding by midcentury (Wuebbles et al., 2017). In the high-emissions scenario, events with return periods of 20 years are projected to increase frequency by a moderate amount by 2050 (Wuebbles et al., 2017).

By 2100, increases in the frequency of extreme precipitation events that cause flooding could be 50 to 100-percent more than historical averages under current emissions (IPCC, 2021), and 200 to 300-percent above historical averages under the high-emissions scenario. The size of 20-year return period events is projected to increase by 10 to 13 percent under the current-emissions scenario and by 16 to 21 percent under the high-emissions scenario by 2100 (Wuebbles et al., 2017).

There is a significant volume of research of historical and recent trends in extreme precipitation and flooding supporting the near-term flooding projections. NCA4 describes and cites clear trends in future precipitation extremes, and its authors attribute these changes to a strong body of evidence that ties increases in extreme precipitation to increased water vapor due to warmer temperatures (Easterling et al., 2018; Wuebbles et al., 2017). Although the evidence on general trends in precipitation is strong, limitations in this body of research do exist. In particular, there are limitations in global climate models’ ability to capture the magnitude of future extreme precipitation events, as well as limitations in the forecasting of future flood occurrence as a result of changing precipitation (in part, because of uncertainties about future land use).

Finally, regional differences are expected in projected changes in flooding. Projected changes in extreme precipitation, combined with studies on changes in historical flood incidence and changing flood risk, suggest that the Northeast could experience greater increases in flooding than national averages in the future (Mallakpour and Villarini, 2015; Slater and Villarini, 2016; Wuebbles et al., 2017).

Sea-Level Rise

Coastal inundation from sea-level rise and tidal events is projected to become more frequent in the next century. By 2030, U.S. coastal communities are projected to continue to experience coastal flooding from rising sea levels and tidal events similar to observed events in the past five to ten years (Easterling et al., 2018). This projection is the same under the current- and high-emissions scenarios.

However, by 2050, global mean sea levels could rise by 1.7 to 2 ft. under the current-emissions scenario and by 1.7 to 3 ft. under the high-emissions scenario (Wuebbles et al., 2017). Under the current- and high-emissions scenarios, by 2100, global mean sea levels could increase, respectively, by 2.5 to 4.5 feet and 2.5 to 5.8 feet (Wuebbles et al., 2017). During these periods, sea-level rise will affect the U.S. coastline, resulting in inundation of facilities within affected areas, coastal erosion and permanent inundation, heightened wave impacts, coastal flooding, and saltwater intrusion into coastal freshwater (surface water and groundwater) (Wuebbles et al., 2017).

There is a high degree of confidence in sea-level rise projections. Scientists are more readily able to detect and project sea-level rise than they are other climate drivers. According to NCA4, this is due, in part, to the fact that “the trend signal for sea level change tends to be large relative to natural variability” (Wuebbles et al., 2017, § 12.2).

Some regional differences in sea-level rise are likely. According to NCA4, although rates of change in the Northeast are projected to be slightly higher than along the southern Atlantic coastline, estimated differences between the two are not likely to be significant. However, projected relative sea-level change is amplified in the Gulf Coast compared with that along the rest of the Atlantic coastline and slightly lower in the Pacific Northwest (Wuebbles et al., 2017).
Severe Storm Systems

Convective storm systems (including thunderstorms and tornadoes), extreme winter storms, and atmospheric rivers are expected to change only slightly from historical climatology over the next century. In the short term, the incidence of severe thunderstorms, tornadoes, hail, strong wind events, and other nontropical extreme weather is similar to observations for the past five to ten years. By 2030, potential increases in the frequency and intensity of nor’easters and other extreme winter storms are similar to those seen in the past five to ten years (Easterling et al., 2018). This is projected to be the case in both the current- and high-emissions scenarios.

The 2050 and 2100 projections are also similar in the current- and high-emissions scenarios. An increase in the frequency of the environments that produce severe thunderstorms is likely throughout the mid- to late 21st century. Global climate models also suggest the possibility of increases in winter storm frequency and intensity in the same time period. The frequency and severity of atmospheric rivers are likely to increase throughout the 21st century with warming global temperatures (Wuebbles et al., 2017). In the high-emissions scenario, some estimates suggest that a large increase in the number of days with atmospheric rivers could occur by the end of the 21st century (Gao et al., 2015; Wuebbles et al., 2017).

Additionally, the confidence in projections of the future trend of severe storm systems is the lowest of all the climate drivers. There is a limited understanding of physical processes and significant inconsistencies among models predicting changes in severe storm systems. Limitations in both the consistency and accuracy of historical data and the ability of global and regional climate models to capture the dynamics that produce severe storms contribute to lower confidence in the projections of changes of convective storms. However, a small body of work supports similar findings in future trends. The complexity of the dynamics that lead to winter storm events, combined with a limited understanding of the effects that greater arctic warming has on winter weather across the United States, limits the conclusiveness of future projections for winter storms. Studies on atmospheric rivers, however, are more conclusive (Wuebbles et al., 2017).

Each of the subcategories of storm types within this category—winter storms, convective storms, and atmospheric rivers—has a regional footprint, with atmospheric rivers occurring in the western United States; severe winter storms throughout the Midwest, intermountain West, and Northeast; and convective storms occurring throughout the United States, although less frequently along the continental Pacific coastline. Even with these regional differences, national projections of aggregate changes in severe storms are appropriate for the majority of regions. Projected changes, however, are anticipated to be elevated for convective storms in the midwestern and southern United States by 2100 (Diffenbaugh, Scherer, and Trapp, 2013; Wuebbles et al., 2017).

Tropical Cyclones and Hurricanes

In both the current- and high-emissions scenarios, no change in hurricane activity is expected to be observed by 2030. These storms will continue to affect the eastern United States, and hurricane seasons are expected to be similar to those of the past five to ten years (Easterling et al., 2018).

Tropical cyclone and hurricane activity is projected to increase in the next century. In the medium and long terms, the projected changes in global mean tropical cyclone and hurricane wind speeds and precipitation rates will likely increase in both current- and high-emissions scenarios. Hurricane frequency will likely remain the same as seen in the historical record in the current-emissions scenario. However, hurricane frequency could increase under the high-emissions scenario. Increases in storm intensity and frequency are likelier to be seen by 2100, with more-moderate changes expected by 2050 (IPCC, 2013; Wuebbles et al., 2017).
However, confidence in projections of this trend is lower than confidence in projections of the changes of other climate drivers. The literature reveals a moderate understanding of physical processes and variation in model results of future storms. The IPCC, based on available science and examination of AR6 projections (IPCC, 2021), suggest a medium to high confidence rating for projections of changes in global tropical cyclone rainfall rates and intensities. Other studies, and the NCA4, have confirmed a medium confidence in projections of changes in global mean tropical cyclones (Knutson, Sirutis, et al., 2015; Wuebbles et al., 2017). For the Atlantic basin, research shows that uncertainty in these future changes in storm frequency and intensity is higher than at the global scale (Knutson, Camargo, et al., 2020).

The regions that will be most affected by changes in hurricane activity will remain those that have been most affected historically. Specifically, future simulations of Saffir–Simpson category 4 and 5 hurricanes show the majority of hurricane landfalls and hurricane tracks affecting the Atlantic coastline and the Gulf Coast. Remnants of tropical cyclones can make their way further inland and contribute to significant flooding and storm-related damage (Villarini et al., 2014). However, research on anticipated changes in tropical remnants into the future, as well as their plausible regions of impact, is limited.

Wildfire

In the near term, the conditions likely to trigger wildfire, including low soil moisture, declines in precipitation, and warming temperatures, which have contributed to the increased incidence of very large wildfires since the 1980s, are expected to continue. In both the current- and high-emissions scenarios, the trend in these conditions is expected to result in the occurrence of wildfire at levels similar to those of the past five to ten years (Easterling et al., 2018).

Significant increases in the potential for large wildfires are likely across the western United States through the end of the 21st century. These increases are anticipated to be greater by 2100 and increase between the current-emissions and high-emissions scenarios. Projections of future wildfires in the southeast and Alaska also suggest increases (Stavros et al., 2014; Wuebbles et al., 2017). AR6 suggests an increase in the incidence of conditions that can lead to wildfire by 2050 under the high-emissions scenario (IPCC, 2021).

Confidence in the increasing trend in wildfire is high because of sufficient understanding of the physical processes involved in wildfire and because of consistency in observations and modeling of how wildfire will progress under climate change. The climatic factors that contribute to wildfire risk—drought, temperature, and vapor pressure—are well-understood climatic variables. Their relationship to wildfire risk is also well understood. A substantial body of evidence supports an increased risk of wildfire occurrence in the future. However, the literature notes variability in local ecosystems and land management practices that are difficult to fully consider in future projections (Wuebbles et al., 2017).

Some regional differences in wildfire risk are expected as climate change progresses through the century. NCA4 focuses on the underlying science describing projected changes in wildfire incidence for those regions that have historically experienced and are prone to wildfire—the western United States and Alaska. Although wildfires have occurred in portions of the eastern United States, these are generally less severe than those in the West. As a result, the future anticipated change in the eastern United States is less than that for the western United States (Wuebbles et al., 2017).
CHAPTER FOUR

Synthesis of Results and High-Level Findings

This chapter presents a synthesis of our high-level findings on climate change and the NCFs that we identified as being most vulnerable to climate change. First, we present the results of the screening process described in Chapter Two to identify the NCFs at higher vulnerability to climate change. We next provide the results of our analysis of the eight climate drivers described in Chapter Three and which of those drivers present the most risk to the NCFs. Finally, we present high-level, crosscutting findings about our risk assessment of the NCFs identified as having higher vulnerability. In Chapter Five, we present detailed results at the NCF level for each of the 27 higher-vulnerability NCFs.

The Higher-Vulnerability National Critical Functions

We identified 27 medium- to high-vulnerability NCFs for a full climate risk assessment. These NCFs are shown in Table 4.1, and those not included are listed in the appendix. These 27 higher-vulnerability NCFs focus on critical infrastructure, health and safety functions, and food- and supply chain–related functions. Notably, all NCFs in the distribution category were included in this assessment (CISA, 2020). NCFs that were not screened into this application of the framework included the NCFs in the connection category, finance, material transport and storage, and civil infrastructure and organization (CISA, 2020). Table A.1 in the appendix lists all the NCFs and their functional groups.

We note that the inclusion of these 27 NCFs does not imply that NCFs at lower levels of assessed vulnerability are not at risk due to climate change. Future applications of the risk management framework should consider the full set of NCFs, and such applications could be expanded or reproduced as more evidence is available for the 28 NCFs not included in this assessment. Because of the complex nature of the NCFs and the impact pathways by which climate change could affect them, NCFs deemed at lower levels of vulnerability in this screening could still be at risk due to climate change.

Key Takeaways on Climate Drivers for National Critical Functions

Climate change is increasing the frequency, magnitude, and duration of many of the climate drivers that pose a risk to U.S. critical infrastructure systems. Although there are important regional distinctions in how and where climate drivers are anticipated to change, at the national scale, a subset of climate drivers is anticipated to pose the greatest risk of disruption to the higher-vulnerability NCFs: flooding, extreme heat, sea-level rise, and tropical cyclones and hurricanes.

Extreme Heat

Extreme heat is anticipated to cause a risk of moderate disruptions to about half of the assessed NCFs by 2100 under the high-emissions scenario (this is about one-third of the 27 NCFs under the current-emissions
Assessing Risk to the National Critical Functions as a Result of Climate Change

More than three-quarters of the 27 NCFs assessed are anticipated to be at a risk of moderate disruption by 2100 in the high-emissions scenario and nearly two-thirds in the current-emissions scenario. Flooding due to riverine and flash flooding from extreme rainfall events can cause significant disruption to infrastructure scenario), including Distribute Electricity, Develop and Maintain Public Works and Services, and Transport Passengers by Mass Transit.

Flooding

More than three-quarters of the 27 NCFs assessed are anticipated to be at a risk of moderate disruption by 2100 in the high-emissions scenario and nearly two-thirds in the current-emissions scenario. Flooding due to riverine and flash flooding from extreme rainfall events can cause significant disruption to infrastructure

### Table 4.1
The 27 Higher-Vulnerability National Critical Functions

<table>
<thead>
<tr>
<th>NCF</th>
<th>Our Vulnerability Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribute Electricity</td>
<td>High</td>
</tr>
<tr>
<td>Maintain Supply Chains</td>
<td>High</td>
</tr>
<tr>
<td>Transmit Electricity</td>
<td>High</td>
</tr>
<tr>
<td>Develop and Maintain Public Works and Services</td>
<td>High</td>
</tr>
<tr>
<td>Prepare for and Manage Emergencies</td>
<td>High</td>
</tr>
<tr>
<td>Provide and Maintain Infrastructure</td>
<td>High</td>
</tr>
<tr>
<td>Support Community Health</td>
<td>High</td>
</tr>
<tr>
<td>Generate Electricity</td>
<td>High</td>
</tr>
<tr>
<td>Produce and Provide Agricultural Products and Services</td>
<td>High</td>
</tr>
<tr>
<td>Supply Water</td>
<td>High</td>
</tr>
<tr>
<td>Transport Cargo and Passengers by Air</td>
<td>Medium</td>
</tr>
<tr>
<td>Transport Cargo and Passengers by Rail</td>
<td>Medium</td>
</tr>
<tr>
<td>Transport Cargo and Passengers by Road</td>
<td>Medium</td>
</tr>
<tr>
<td>Transport Cargo and Passengers by Vessel</td>
<td>Medium</td>
</tr>
<tr>
<td>Transport Passengers by Mass Transit</td>
<td>Medium</td>
</tr>
<tr>
<td>Educate and Train</td>
<td>Medium</td>
</tr>
<tr>
<td>Manage Hazardous Materials</td>
<td>Medium</td>
</tr>
<tr>
<td>Manage Wastewater</td>
<td>Medium</td>
</tr>
<tr>
<td>Provide Insurance Services</td>
<td>Medium</td>
</tr>
<tr>
<td>Provide Medical Care</td>
<td>Medium</td>
</tr>
<tr>
<td>Provide Public Safety</td>
<td>Medium</td>
</tr>
<tr>
<td>Exploration and Extraction of Fuels</td>
<td>Medium</td>
</tr>
<tr>
<td>Manufacture Equipment</td>
<td>Medium</td>
</tr>
<tr>
<td>Produce and Provide Human and Animal Food Products and Services</td>
<td>Medium</td>
</tr>
<tr>
<td>Produce Chemicals</td>
<td>Medium</td>
</tr>
<tr>
<td>Provide Housing</td>
<td>Medium</td>
</tr>
<tr>
<td>Enforce Law</td>
<td>Medium</td>
</tr>
</tbody>
</table>
systems from direct damage caused by floodwaters or debris, loss of access to assets, or cascading effects within and among infrastructure systems. Because flooding is so pervasive across much of the United States, this climate driver is likely to affect all regions of the country. For example, for Transmit Electricity, protecting the transmission system during a flooding event is difficult for substations in floodplains. Industry-standard substation site design is to avoid significant impacts from flooding at the historical 100-year floodplain plus 1 ft. As flooding events become more commonplace in the next 70 years, floodwaters will surpass the historical 100-year floodplain more often, resulting in disruptions in transmission (Agrawal, 2020; Boggess, Becker, and Mitchell, 2014; Doherty and Dewey, 1925; Wuebbles et al., 2017).

Sea-Level Rise

Sea-level rise, which can temporarily or permanently inundate facilities, infrastructure assets, or key components of infrastructure systems, is expected to affect the majority of assessed NCFs by 2050 and all assessed NCFs by 2100 under the high-emissions scenario. These effects are compounded by the relatively high concentration of major urban areas and infrastructure assets in coastal zones. In the case of Manage Wastewater, for example, the treatment and collection of wastewater and stormwater, as well as the construction and maintenance of wastewater facilities, are at risk from sea-level rise across all future time periods and scenarios assessed. In coastal regions of the United States, sea-level rise has already affected the management of stormwater and wastewater by magnifying nuisance flooding in coastal cities and temporarily or permanently inundating components of the wastewater management system. Wastewater treatment plants are at particular risk along coastal zones because their typical location at low elevation and along coastal waterways where they discharge treated wastewater. One study suggested that the inundation of wastewater treatment plants could result in five times as many households losing wastewater services as those at direct risk of flooding from sea-level rise (Hummel, Berry, and Stacey, 2018).

Tropical Cyclones and Hurricanes

More than two-thirds of the 27 NCFs assessed are anticipated at risk of moderate disruption caused by a tropical cyclone or hurricane by 2050 and by 2100 under the high-emissions scenario and by 2100 under the current-emissions scenario. Tropical cyclones and hurricanes and their associated weather effects, such as storm surge and waves, high winds, and extreme rainfall, have a legacy of severe and lasting damage to regions of the United States. The Gulf Coast and Atlantic coastline are anticipated to be most significantly affected. For example, for Maintain Supply Chains, hurricanes and tropical storms can affect supply chain operations by imposing temporary costs on consumers and producers through these storms’ effects at coastal ports, temporarily delaying the delivery of goods, increasing logistical costs, destroying inventory, and disrupting the distribution of raw materials (Friedt, 2021; Friedt and Crispin, 2021; Sytsma, 2020).

Drought, Extreme Cold, Severe Storm Systems, and Wildfire

Other climate drivers will affect subsets of NCFs:

- Drought is projected to cause a risk of moderate disruption to about one-quarter of the assessed NCFs by 2100 under the high-emissions scenario, including Generate Electricity and Supply Water.
• Extreme cold is anticipated to heighten risk of only a minimal disruption for the assessed NCFs, most notably Provide and Maintain Infrastructure.¹
• Severe storm systems are expected to increase risk of moderate disruptions to about one-third of the assessed NCFs by 2100 under the high-emissions scenario (although to only two in the current-emissions scenario), including Provide Medical Care and Provide Housing.
• Wildfire is expected to increase risk of moderate disruptions to 12 of the 27 higher-vulnerability NCFs by 2100 under the high-emissions scenario (or seven of the 27 NCFs under the current-emissions scenario), including Provide Public Safety and Supply Water.

Across the United States, climate changes across the eight climate drivers have important regional footprints on NCFs due to both the geographic distribution of NCFs and the regional and local dynamics of climate change. For example, sea-level rise has direct effects on NCFs with infrastructure assets along coastlines, and drought is likelier to occur and be severer in the western United States. Similarly, each NCF has its own unique regional distribution. Some NCFs, such as Educate and Train, are distributed by population across the United States, while other NCFs, such as Exploration and Extraction of Fuels, are distributed by resource availability.

When we combined these two dimensions, regional hotspots emerged in the picture of the future risk that climate change poses to the 27 higher-vulnerability NCFs. Figure 4.1 shows those regions where NCFs were at risk of moderate or greater disruption from each climate driver within any of the three time periods or two climate scenarios and where analysts noted that there might be hotspots above national risk ratings. Our delineations of regions 1 through 10 are based on the standard federal regions that CISA and many other U.S. federal agencies and offices use (CISA, undated b). For the 27 higher-vulnerability NCFs, we found the following:

- NCFs with physical infrastructure along the Atlantic coastline (regions 1 through 4) are at heightened risk due to flooding, sea-level rise, and hurricanes.
- NCFs with physical infrastructure in the Great Lakes area (region 5) are at heightened risk due to flooding and severe storms.
- NCFs with physical infrastructure in the south, southwest, and mountain west (regions 4, 6, 8, and 9) are at heightened risk from extreme heat.
- NCFs with physical infrastructure in region 9 are at heightened risk from the most climate drivers, including the unique challenges of facing drought and flooding.

Key Takeaways on Climate Risk for National Critical Functions

A summary of the results of the climate risk assessment of the 27 higher-vulnerability NCFs is shown in Table 4.2. This table depicts risk due to climate change across three future time periods—by 2030, by 2050, and by 2100—for the current-emissions and high-emissions scenarios. For Provide and Maintain Infrastructure, this table shows that, in 2030, the risk to this NCF is rated as 1 (no disruption); the NCF is not expected to be affected by climate change. In 2050, the risk to this NCF is assessed at a rating of 2 (minimal disruption);

¹ Although recent extreme cold events have shown NCFs’ vulnerability to extreme cold, future climate projections do not indicate a high likelihood of similar events in the future. In general, global climate models do not consistently capture the Arctic polar vortex and are not in agreement about how it might shape future extreme cold events. Additionally, most experts on extreme cold agree that the general trend is that, “on average, winters are warmer and cold extremes are less likely than they were a century ago” (Lindsey, 2021).
FIGURE 4.1
The Eight Climate Drivers Most Likely to Affect the Assessed National Critical Functions, by Region
### TABLE 4.2
National Risk Ratings and Strength of Evidence for 27 Assessed National Critical Functions

<table>
<thead>
<tr>
<th>NCF, by Risk Rating</th>
<th>Current Emissions</th>
<th>High Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2030</td>
<td>2050</td>
</tr>
<tr>
<td>Provide Public Safety</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Supply Water</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Develop and Maintain Public Works and Services</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Distribute Electricity</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Enforce Law</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Manage Hazardous Materials</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Manage Wastewater</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Prepare for and Manage Emergencies</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Provide Medical Care</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Transmit Electricity</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Transport Cargo and Passengers by Air</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Generate Electricity</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Maintain Supply Chains</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Manufacture Equipment</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Produce and Provide Agricultural Products and Services</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Produce Chemicals</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Provide Housing</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Educate and Train</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Transport Cargo and Passengers by Vessel</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Provide and Maintain Infrastructure</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Exploration and Extraction of Fuels</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Provide Insurance Services</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Transport Cargo and Passengers by Rail</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Transport Cargo and Passengers by Road</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Transport Passengers by Mass Transit</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Produce and Provide Human and Animal Food Products and Services</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Support Community Health</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

**NOTE:** The list groups NCFs by risk rating, in descending order of risk. Multiple NCFs with the same ratings are listed alphabetically within their rating groups. The shade of gray indicates the strength of evidence for that NCF: dark gray = strong evidence base in peer-reviewed scientific literature with consistent findings; medium gray = moderate evidence base with several sources but limited documentation; and light gray = inconclusive or suggestive evidence base. 1 = no disruption or normal operations, 2 = minimal disruption, 3 = moderate disruption. These definitions are based on those used in NCA4.
the NCF is expected to be affected by climate change but to operate relatively normally. And the risk to this NCF by 2100 is assessed at 3 (moderate disruption); the NCF is expected to be affected by climate change, with operations affected at local to regional scales.

The risk ratings shown in Table 4.2 are aggregated across all eight climate drivers. We aggregated risk ratings by using the maximum risk score across all climate drivers and subfunctions of NCFs. For example, if the risk to an NCF from sea-level rise was rated as 3, flooding was rated as 2, and all other drivers were rated as 1, the risk rating is summarized in Table 4.2 as a 3. The process for aggregating across NCF subfunctions is described in Chapter Two. The colors in Table 4.2 reflect the numerical risk ratings. The strength of evidence of the impacts of climate change on each NCF is also shown in Table 4.2. The implications of these ratings on research needs are discussed in Chapter Seven.

Key takeaways from the risk assessment presented in Table 4.2 include the following:

- All of the 27 higher-vulnerability NCFs were judged to be at risk of at least a minimal disruption from climate change by 2100.
- Nearly all of the assessed NCFs are anticipated to be at risk of moderate disruption or greater by 2100 in the high-emissions scenario.
- Two NCFs already face a risk of moderate disruption by 2030—Supply Water, because of drought, and Provide Public Safety, because of the effects of wildfire.

As depicted in Table 4.2, no assessed NCFs are anticipated to be at risk of a major or critical disruption due to climate change. Such a disruption would mean that an NCF is unable to meet operational needs across most of the country or across the entire country, respectively. However, the finding that an NCF is at risk of moderate disruption should not be interpreted as suggesting that the consequences of that disruption will be insignificant. A moderate disruption is defined in the risk management framework applied in this work as an NCF meeting routine operational needs in most of the country. According to these criteria, the disruption caused to NCFs by a major historical weather event, such as Hurricane Katrina in 2005, would be characterized as moderate disruption. Although several NCFs, such as those related to the provision of power and water, failed at the local and regional levels as a result of storm effects (e.g., 5 million people lost power) (BearingPoint, 2006), at a national level, these NCFs continued to function. Accordingly, for purposes of our analysis, the risk of moderate disruption to an NCF at the national level should be regarded as highly significant and includes the potential for major disruption or failure of an NCF at the local or regional level and for significant economic loss, health and safety impacts, and other consequences. Major disruption (an NCF not being expected to meet routine operational needs in most of the country) and critical disruption (an NCF not being expected to meet any of its routine operational needs in most of the country) would be expected to be less likely given both the nature of the NCFs and the geospatial distribution of climate changes.

For purposes of this analysis, the assessed NCFs are discussed in three groups in the sections that follow:

- First, we discuss the NCFs at risk of moderate disruption by 2030, which includes two NCFs: Supply Water and Provide Public Safety.
- Second, we discuss NCFs at risk of moderate disruption by 2100 under the current-emissions scenario, which include 21 of the 27 assessed NCFs.
- Finally, we discuss NCFs at risk of only minimal disruption by 2100.
National Critical Functions at Risk of Moderate Disruption by 2030

Two NCFs were assessed to be at risk of moderate disruption due to climate change by 2030: Provide Public Safety and Supply Water.

We assessed Provide Public Safety to be at risk of moderate disruption across all time periods and in both scenarios. The primary drivers of risk are climate events that have the potential to cause widespread destruction and threaten lives, such as flooding, storms, and wildfire. These events increase the need for public safety personnel to fight fires, conduct rescues, deliver emergency medical care, and maintain order. Public safety must also assist in evacuations and support displaced people. Wildfire poses a risk of moderate disruption in 2030. Wildfire frequency and intensity are already far higher than they were a decade ago, with simultaneous fires limiting agencies’ ability to provide mutual support, having insufficient personnel and equipment to combat fires effectively (Applebaum et al., 2016; Reidmiller et al., 2018).

We also assessed Supply Water to be at risk of moderate disruption across all time periods and in both scenarios. In some regions, this NCF is already experiencing moderate disruption due to the effects that drought, flooding, and wildfire have on NCF operations. Drought can limit the amount of raw water available from groundwater and surface water sources. Wildfire requires massive amounts of water to fight and can contaminate water by creating large volumes of debris or it can damage infrastructure, and flooding can both degrade water quality and damage water infrastructure. As these three climate drivers increase in frequency and magnitude, this NCF is at continued risk of disruption, particularly because of drought and wildfire in the western United States (Office of Water, 2014; U.S. Environmental Protection Agency [EPA], undated a; Washington State Department of Health, 2019).

National Critical Functions at Risk of Moderate Disruption by 2100

We assessed 21 NCFs to be at risk of moderate disruption by 2100 in the current-emissions scenario. These 21 NCFs represent a mix of NCFs with substantial physical infrastructure footprints. The NCFs at risk of moderate disruption by 2100 include all three NCFs related to electricity (Distribute Electricity, Transmit Electricity, and Generate Electricity), all three related to supply chains and manufacturing (Maintain Supply Chains, Manufacture Equipment, and Produce Chemicals), and four of the five transportation-related NCFs (Transport Cargo and Passengers by Air, Transport Cargo and Passengers by Road, Transport Cargo and Passengers by Vessel, and Transport Passengers by Mass Transit). NCFs also assessed at this risk level include those NCFs involved in service provision, such as Provide Medical Care, Prepare for and Manage Emergencies, Educate and Train, and Enforce Law.

The three electricity-related NCFs (Distribute Electricity, Transmit Electricity, and Generate Electricity) are at risk from flooding, sea-level rise, and tropical cyclones and hurricanes. These drivers threaten the equipment at distribution and transmission substations that serve as key nodes for distributing electricity throughout the power grid network. Extreme heat threatens distribution, transmission, and generation equipment that is not rated for safe operation above certain design thresholds. Relevant design standards for these assets were not created with consideration of future changes in extreme heat. The increased severity of droughts and extreme heat threaten conventional fossil fuel power plants that rely on water for cooling equipment and have components rated for lower temperatures. Power plants in historical 100-year floodplains and in low-lying coastal zones are threatened by increased prevalence of flooding and sea-level rise, accounting for more than 25 gigawatts, or approximately 2 percent, of national power plant operating capacity (Agrawal, 2020; Doherty and Dewey, 1925; Nateghi, 2018; U.S. Department of Energy [DOE], 2015; Wuebbles et al., 2017).

We assessed Manage Hazardous Materials as being at risk of moderate disruption by 2100 in both climate scenarios. The primary climate drivers of risk for this NCF are flooding and sea-level rise, particularly at
legacy sites that are already vulnerable and could experience catastrophic failure under future conditions. Flooding and severe storms, especially with corrosive saltwater, can damage liners and leachate systems, infiltrate above-ground components, destroy monitoring and control systems, and disturb underwater confined areas and earthen caps, often in proximity to population centers and other critical infrastructure. Approximately half of the Superfund sites are at risk of flooding from 3 ft. of sea-level rise, and 15 percent are at risk from wildfire (Office of Solid Waste and Emergency Response, 2014; Office of Superfund Remediation and Technology, 2014; U.S. Government Accountability Office [GAO], 2019).2

Provide Medical Care is anticipated to be affected by climate change through two mechanisms:

- The first mechanism is the direct threat posed to the operation of health care facilities because climate drivers can damage or destroy facilities, render them inoperable by disrupting utilities, or necessitate their evacuation to safeguard people from approaching threats. This has the potential to disrupt the provision of medical care in certain parts of the country when such events occur.
- The second mechanism is increased injuries stemming from flooding, storms, and wildfire and increased diseases caused by those climate drivers, as well as drought, extreme cold, and extreme heat. Disasters also disrupt normal health care, exacerbating chronic conditions and increasing mental stress. Together, this causes an increase in the demand for medical care, which creates a strain on health care providers and institutions (Anderson et al., 2017; Guenther and Balbus, 2014; Reidmiller et al., 2018).

Four transportation-related NCFs (Transport Cargo and Passengers by Air, Transport Cargo and Passengers by Road, Transport Cargo and Passengers by Vessel, and Transport Passengers by Mass Transit) are considered at risk of moderate disruption for different reasons. Of these, air transportation is at greatest risk because key airports are in metropolitan areas expected to continue to experience effects due to sea-level rise.3 Mass transit is at risk of disruption, given the increasing disruption that severe storms and extreme heat can create for individual systems, as well as the lack of substitutability at the local level.4 Maritime transportation is at risk due to the exposure to tropical cyclones and hurricane along the Gulf and Atlantic coastlines, and roadway transportation is vulnerable to sea-level rise, both tropical and nontropical storms, and debris flows from wildfire.

We assessed Provide Housing to be at risk of moderate disruption. Climate change could stress U.S. housing stock through flooding caused by sea-level rise, severe storms, and wildfire, any of which can damage structures or render them uninhabitable. By 2100, approximately 2.4 million residential properties, valued at

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2 As described in Chapter Three, by 2050, global mean sea levels could rise by 1.7 to 2 ft. under the current-emissions scenario and by 1.7 to 3 ft. under the high-emissions scenario. Under the current- and high-emissions scenarios, global mean sea levels could increase by 2.5 to 4.5 ft. and 2.5 to 5.8 ft. by 2100, respectively.

3 One analysis suggested that, under the current-emissions scenario, 14 airports would experience route disruptions due to sea-level rise in 2100. Under the high-emissions scenario, the number increases to 29, which includes six airports with more than ten route disruptions annually. Four of the six are large- or medium-hub airports: two in the New York region and one each in New Orleans and Oakland, California. Eight of the 13 origin–destination pairs that result in the most delay propagation begin or end at New York-area airports, suggesting that delays in the New York area can produce delays throughout the air travel system. In addition, glacial melt might lead to increased volcanic activity and changes to the jet stream, which can have negative impacts on flight operations due to decreased visibility and clear-air turbulence. See C. Cooper et al., 2018; Miller et al., 2020; and Yesudian and Dawson, 2021.

4 Heavy rain can cause landslides that damage tracks and facilities. High winds can topple trees and blow other debris onto tracks and roads and disrupt communications. Storms can produce bridge scour, which can weaken bridges, and strong-enough storms can cause severe bridge damage. Electrical train control, monitoring, and communication systems for rail systems can overheat and malfunction. Overhead catenary wires can fail in extreme heat, leading to loss of power. Heat can cause tracks to buckle, which can lead to derailments, and agencies generally issue “slow orders” as a precaution. See Hodges, 2011.
more than $1 trillion, will be at risk of chronic flooding. The number of owned and rented housing units in areas at risk from sea-level rise have already begun to alter the mortgage, leasing, financing, and insurance markets, and these impacts are anticipated to grow. For example, banks have begun disproportionately shifting their debts in floodplains to government-backed mortgage enterprises. An estimated $16 billion in home value has already been lost along the East and Gulf Coasts.5

National Critical Functions at Risk of Only Minimal Disruption by 2100

We assessed two NCFs as having no risk of disruption due to climate change in 2030 and a risk of only a minimal disruption by 2100. These are Support Community Health and Produce and Provide Human and Animal Food Products and Services. We assessed a third NCF—Transport Cargo and Passengers by Rail—as being at risk of only minimal disruption across all future time periods.

Support Community Health is assessed at risk of only minimal disruption by 2100 from all drivers except for extreme cold, which is assessed as posing no risk of disruption. Climate drivers are expected to increase the incidence of many diseases. Increased storms and floods will cause injuries and diseases in victims. Extreme cold causes an increase in hypothermia, particularly among poor and elderly who cannot or do not sufficiently heat their homes. Extreme heat causes increases in heart, lung, and kidney problems; fetal health problems; insect populations and therefore vector-borne illnesses; water-related illnesses, such as toxic algae bloom; ozone levels; and airborne allergens. Wildfire adversely affects air quality through smoke and an increase in particulate-matter levels. Drought increases the frequency and severity of dust storms, which, in turn, increase respiratory diseases, and affects the availability, safety, and nutrient content of food. Thus, climate change will negatively affect the health of the community. This in turn will affect support of community health by increasing the need for services, such as disease surveillance, lab testing, community outreach efforts, and supporting emergency response, but should not cause a disruption in those services (Anderson et al., 2017; Levy et al., 2016; Reidmiller et al., 2018).

Produce and Provide Human and Animal Food Products and Services is at risk of only minimal disruption by climate drivers, including drought, extreme cold, extreme heat, and flooding, by 2100. Climate change threatens the production of human and animal food products and services primarily through damage to infrastructure for storage and processing but also by disruption of inputs of primary agricultural commodities (Wuebbles et al., 2017). Climate change’s effects on crop growth and harvesting are accounted for in the risk ratings for Produce and Provide Agricultural Products and Services.

5 By 2050, under current policies, half a million homes—valued at $241 billion—will probably flood once per year. Approximately 150,000 homes will be subject to disruptive flooding (more than 26 times per year) by 2030, a number that will double by 2050. The top 20 cities account for 75 percent of overall exposure, so the NCF must operate at an urban rather than regional scale. Hotspots for risk include Florida, New Jersey, and New York, which might have disrupted financial mechanisms, whereas wealth necessary for maintenance and sustainment might be most affected in Maryland, Massachusetts, and Texas. Both factors could lead to negative feedback loops and spread into the broader housing market. See Aurand et al., 2021; Buchanan et al., 2020; Dahl et al., 2018; and Flavelle, 2021.
CHAPTER FIVE

National Critical Function–Level Findings

In this chapter, we present individual risk assessments for each of the NCFs identified as having higher vulnerability and selected for inclusion in our analysis. We list the NCFs in descending order of risk, like in Table 4.2 in Chapter Four. For each NCF, we provide a scorecard that presents a summary of our findings and a synopsis of key aspects of our analysis. The CISA definition for each NCF is also included (CISA, 2020). We provide the national-level risk rating for each NCF and for any of its subfunctions that we assessed as at risk of minimal disruption or greater. Each scorecard also shows what we assessed the risk to the NCF to be from any climate driver that we assessed as posing a risk of minimal disruption or greater. We do not show subfunctions and drivers that we assessed as having no disruption or normal operations across all future time periods and both climate scenarios included in the study. Our methodology for assessing risk and the risk rating scale are described in more detail in Chapter Two. Table 5.1 presents the risk rating scale again for easy reference.

TABLE 5.1
Risk Rating Scale

<table>
<thead>
<tr>
<th>Risk Rating</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unknown or insufficient evidence</td>
<td>A driver’s effect on this NCF or subfunction is unknown, or there was insufficient evidence to make a risk assessment.</td>
</tr>
<tr>
<td>1 No disruption or normal operations</td>
<td>The NCF or subfunction was anticipated to meet all routine operational needs.</td>
</tr>
<tr>
<td>2 Minimal disruption</td>
<td>Climate change is expected to affect the NCF or subfunction, but the function is expected to meet routine operational needs.</td>
</tr>
<tr>
<td>3 Moderate disruption</td>
<td>The NCF or subfunction is anticipated to meet all routine operational needs in most but not all of the country.</td>
</tr>
<tr>
<td>4 Major disruption</td>
<td>The NCF or subfunction is anticipated to be unable to meet routine operational needs in most of the country.</td>
</tr>
<tr>
<td>5 Critical</td>
<td>The NCF or subfunction is anticipated to be unable to meet any of its routine operational needs across the country.</td>
</tr>
</tbody>
</table>
Synopsis

Supply Water is intrinsically tied to climate, even in regions dependent on imported water. Centuries of water management around the globe have focused on efforts to capture, store, and transport water to overcome short-term fluctuations in precipitation, streamflow, and snowmelt, as well as inter- and intra-annual changes in water demand due to the single or combined effects of other climate (e.g., temperature), physical (e.g., crop water demand) or socioeconomic variables (e.g., urban growth and development). Managing water under short-term climate variability has been a long-term focus of water management. However, infrastructure and operations have been designed based on historical patterns of raw water availability and water demand. These patterns shift in time and space because of climate change, challenging long-held formulas, design criteria, and approaches for water infrastructure, operations, and management (Milly et al., 2008). The infrastructure assets that support water systems are also vulnerable to extreme events, such as drought, flooding, and wildfire, that are projected to increase in occurrence and severity in the future. Long-term degradation that has occurred in the condition and capacity of infrastructure assets exacerbates this vulnerability (American Society of Civil Engineers [ASCE], 2021b). Additionally, management paradigms for groundwater resources are still in development in many parts of the United States, as are those for conjunc-
tive management of groundwater and surface water, thus further increasing these systems’ vulnerability to climate change.\(^1\)

These factors, along with projected changes in climate drivers to which Supply Water is vulnerable, such as drought, flooding, and wildfire, suggest that Supply Water is at risk of moderate disruption due to climate change across all future time periods and both climate scenarios. A moderate disruption could mean significant regional disruption or failure for this NCF, such that the provision of water for residential, agricultural, or industrial use is temporarily or permanently degraded. Such an impact could have both public health and economic implications. These impacts could include providing drinking water that does not comply with Safe Drinking Water Act (SDWA) (Public Law 93-523, 1974) standards, fallowing of agricultural land because of lack of water supply, or ceasing of industrial operations if water shortages occur.

### Subfunctions

Six of the nine subfunctions for Supply Water are at risk of minimal or moderate disruption due to climate change. These are primarily the subfunctions with a significant number of infrastructure assets that are exposed to climate drivers (Provide Potable Water, Provide Building and Facility Water, and Provide Fire Protection) or those subfunctions dependent on the natural availability of water that is projected to change in the future (Provide Agricultural Water, Provide Industrial Water, and Provide Raw Water).

Of the former, Provide Fire Protection is at risk from extreme heat and wildfire. Provide Fire Protection is sensitive to the number and magnitude of wildfires, and, as these events increase in both of those dimensions over time, the response capabilities will be limited compared with the firefighting needs. This subfunction is also sensitive to extreme heat, which could create even more-dangerous conditions for the firefighting and emergency management workforce (Applebaum et al., 2016). Provide Potable Water has a different dynamic. This subfunction is at risk of moderate disruption because of flooding across all future time periods. The delivery of water and the maintenance of water quality to federal SDWA standards is vulnerable to flooding because physical assets can be inundated or damaged, disrupting the movement of water within water systems or within or around treatment plants and contaminating water sources (Office of Water, 2014). This could limit the safe treatment and delivery of potable water if assets are unable to operate, if inundation results in contamination of water sources that no longer meet source water quality standards, or if floodwaters leach into the treated distribution system following damage (Washington State Department of Health, 2019). The effects of flooding could temporarily disrupt operations, particularly as flood risk increases (EPA, undated a).

The provision of agricultural, industrial, and raw water is at risk of disruption primarily because of projected increases in drought intensity in the future. These dynamics are discussed in the next section.

### Climate Drivers

Supply Water is at risk of moderate disruption across all future time periods and both climate scenarios because of drought, flooding, and wildfire. The availability of water supply is highly vulnerable to drought because drought can significantly reduce the amount of water available from surface and groundwater sources (Johnson et al., 2018). These effects could disrupt water availability on seasonal to multiyear, or even

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\(^1\) Conjunctive management is the integrated management of ground and surface water resources, to enhance security of water supply and environmental sustainability . . . . Unlike conjunctive water use, which refers simply to the combined use of surface and groundwater to improve reliability of water supply, conjunctive management focuses on the monitoring and coordination in the use of the two water sources. Conjunctive management of water resources can bring a range of benefits that include reducing vulnerability . . . . and improving water security . . . . (Lautze et al., 2018, p. 3)
multidecadal, scales. Because droughts are more confidently predicted to occur in the western United States, which includes portions of the Southwest and southern Great Plains, and with more frequency and severity, the risk in these regions might be higher (Johnson et al., 2018). Other regions notably affected by drought include the southeastern United States, as well as Hawaii, the Pacific Islands, and the Caribbean, which could still be vulnerable to shorter-duration and less-severe drought than that seen in the western United States. The effects that flooding and wildfire could have on this NCF are described in the sections on the subfunctions for which they pose the greatest risk (Provide Potable Water and Provide Fire Protection, respectively).

Sea-level rise, hurricanes, and extreme heat pose the risk of moderate disruption to Supply Water by 2100 in the current-emissions scenario and by 2050 and by 2100 in the high-emissions scenario. Sea-level rise poses risk of infrastructure damage for this NCF, like flooding does, as described previously. Additionally, the availability of raw water is vulnerable to coastal inundation from sea-level rise because coastal groundwater or freshwater surface water resources can be permanently degraded as it becomes more saline over time, temporarily or permanently reducing water availability, particularly as sea-level rise increases in the future (EPA, undated a). Although this is already occurring in some locations in the United States, this risk is greater in the future. Hurricanes and tropical cyclones threaten to damage infrastructure assets and disrupt operations (Florida Health, 2014). The maintenance of water availability is at risk from extreme heat due to heightened water needs across water uses during extreme heat events, as well as increased pan evaporation rates that can affect raw water availability (Johnson et al., 2018).2

Cascading Risk
Supply Water is critically dependent on the following NCFs:3

- Distribute Electricity
- Develop and Maintain Public Works and Services
- Manage Hazardous Materials
- Produce Chemicals
- Maintain Supply Chains
- Operate Government.

Water utilities are highly dependent on other NCFs to ensure normal operations (Wasley, Jacobs, and Weiss, 2020). Distribute Electricity is critical to the normal operations of a water utility because power is needed for many treatment plant functions and the movement of water in and around the conveyance and distribution system, at least in part. The development and maintenance of infrastructure (Develop and Maintain Public Works and Services) is necessary to protect the life cycle of assets, as well as their proper functioning over time. The management of hazardous waste produced in water treatment plants is regulated, and the waste must be disposed of properly, necessitating the functioning of the Manage Hazardous Materials NCF (Krogmann et al., 1999). The production of chemicals and the supply chains that deliver chemicals and other inputs are necessary for proper treatment of drinking water to SDWA standards. Because the majority of water agencies are public, Operate Government is also a necessary condition for this NCF to function.

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2 Pan evaporation is “the evaporation rate of water from a small dish located at the ground-surface” (Roderick, Hobbins, and Farquhar, 2009, abstract).

3 Critically dependent NCF was defined as an NCF that, if disrupted or in failure, would severely disrupt a given NCF and for which a given NCF could not recover until the upstream NCF was sufficiently operational. Upstream was defined as providing a key input to a downstream NCF.
Other Factors Driving Risk
Underlying the risk ratings for Supply Water are key factors that contribute to the adaptive capacity of water systems across the United States. The condition and capacity of infrastructure are critical to shaping the risk profile for water supply because they determine how a facility and its assets will operate in the face of extreme events and climate change (Ceres, undated). Throughout the United States, infrastructure assets are often degraded or need significant investment to ensure that they perform sufficiently into the future (ASCE, 2021b). Lack of resources and adaptive capacity among small and rural water agencies, utilities, and providers exacerbates this problem and contributes to an uneven distribution of climate risk across the United States (Godden, Ison, and Wallis, 2011; Wescoat, Headington, and Theobald, 2007). Additionally, long-term risk in the water sector more broadly could affect credit ratings in the future and suppliers’ ability to issue bonds (Ceres, 2010; Moody’s, 2021).

Strength of Evidence
Evidence of climate change’s effects on water systems and water availability is already the subject of significant research and reporting in the United States. NCA4 notes that “water security in the United States is increasingly in jeopardy.” The report also notes that limited surface water storage, deteriorating infrastructure, and long-term depletion of groundwater resources contribute to water systems’ climate vulnerability. In addition to water being a significant focus of national, regional, and international climate assessments, it is the subject of significant research that provides a broad base of evidence for understanding climate change’s current and projected impacts on water systems. Although a wide body of evidence exists for most of the subfunctions for Supply Water on which to base our risk ratings, less information is available on climate change’s effects on Manufacture Parts and Supplies and the direct effects on the processes that lead to the development of water infrastructure. There is a growing body of work on climate change’s effect on the financial systems and processes that support Supply Water and underlie the Govern Water subfunction (Ceres, undated; Morrison et al., 2009), but additional research in this space could help water suppliers across the United States better understand climate change’s implications for their investment decisions.
Provide Public Safety

Scorecard

National Risk Assessment

SUMMARY: The provision of public safety, in the form of police, fire, and emergency medical services (EMS) in addition to other support functions, is at risk of moderate disruption from climate change by 2030 primarily because of extreme weather events that create threats to lives and property and damage to infrastructure, which creates an increase in the demand for public safety services.

1 = no disruption or normal operations. 2 = minimal disruption. 3 = moderate disruption. The table includes only drivers and subfunctions with risk ratings of 2 or higher.

Provide Public Safety: “Provide public services—to include police, fire, and emergency medical services—to ensure the safety and security of communities, businesses, and populations” (CISA, 2020, p. 6).

<table>
<thead>
<tr>
<th>Current Emissions</th>
<th>High Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>2030</td>
<td>2050</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

Highest-Risk Climate Drivers

<table>
<thead>
<tr>
<th>MECHANISM OF IMPACT</th>
<th>Current Emissions</th>
<th>High Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2030</td>
<td>2050</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

Highest-Vulnerability Subfunctions

<table>
<thead>
<tr>
<th>CASCADING RISKS</th>
<th>Current Emissions</th>
<th>High Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2030</td>
<td>2050</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

Synopsis

Climate change is anticipated to lead to an increase in the frequency and severity of extreme weather events, which, in turn, has the potential to increase demand for public safety services (Anderson et al., 2017; Reidmiller et al., 2018; Silverman et al., 2010). Tropical cyclones and hurricanes, severe storm systems, and floods, exacerbated by sea-level rise, have the capacity to cause widespread damage or destruction to homes, businesses, and other facilities. Cold weather can cause injuries and deaths from traffic accidents, as well as from hypothermia, particularly among the poor and elderly, who often have inadequate heat. Extreme hot weather can cause increase in heat-related illnesses, including heart, lung, and kidney problems, as well as issues with fetal health. Some studies have also shown that hotter weather is correlated with an increase in crime and terror attacks; less clear are whether there is a causal relationship and what the magnitude of that
Together, the effects of climate change are expected to increase the need for law enforcement to maintain order, fire services to suppress fires and provide rescue, and EMS to provide prehospital care—service providers who will also need to help conduct evacuations and support displaced people. During large disasters, emergency management personnel will need to coordinate with public health, while restoration of damaged utilities will require support from public works (Calma, 2021).

By 2030, Provide Public Safety is expected to be at risk of moderate disruption from climate change in both the current- and high-emissions scenarios. These ratings are due chiefly to an expected increase in the frequency, intensity, and duration of wildfires: Public safety needs in this area are already not being fully met in some parts of the country because of the current wildfire situation (as discussed in “Subfunctions” next). In the current-emissions scenario, by 2050, the frequency, intensity, and duration of nearly all of the climate drivers (except flooding) are expected to increase, leading to an increase in the demand for this NCF, which we assess will cause moderate disruption, resulting in the inability to meet operational needs in some parts of the country. In the high-emissions scenario, the frequency, intensity, and duration of flooding are also expected to increase by 2050, adding to the risk of moderate disruption of this NCF.

Subfunctions
All of the subfunctions for this NCF—Contribute to Law Enforcement, Provide Fire and Rescue Services, Provide EMS, Provide Public Works Support, Provide Emergency Management, and Support Public Health Services—are expected to be at risk due to the increase in demand associated with natural disasters, as well as the increase in disease associated with changes in the climate drivers. Especially of concern is the ability to combat wildfire; in the 2021 fire season, firefighting capacity was often deemed to be insufficient, resulting in slower suppression and consequently larger fires (Phillips, 2021; Quinton, 2021). Thus, the subfunction Provide Fire and Rescue Services can be considered to already be suffering moderate disruption in the case of wildfire.

Climate Drivers
Nearly all climate drivers will have at least a minor impact on the provision of public safety. This is because severe storm systems, tropical cyclones and hurricanes, and wildfire have the potential to threaten or cause physical damage and injuries. Those climate drivers, along with drought and extreme heat, also have effects on population health and are all expected to increase.

The one exception is extreme cold. Extreme cold does create health problems in the community, particularly in elderly and in economically vulnerable populations, which could increase the need for rescue and EMS. However, the overall projection is that extreme cold events are not expected to increase over current levels, so the impact on this NCF is not expected to change.

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4 See also the discussion of the Enforce Law NCF for more information about the relationship between crime, instability, and climate.
Cascading Risk

Provide Public Safety is critically dependent on the following NCFs:\textsuperscript{5}

- Provide Wireless Access Network Services
- Provide Wireline Access Network Services
- Provide Satellite Access Network Services
- Provide Positioning, Navigation, and Timing Services
- Distribute Electricity
- Transport Cargo and Passengers by Road
- Supply Water
- Operate Government.

Communication infrastructure is critical to the dispatch of public safety services. Therefore, wireless, wire-line, and satellite access network services are required, along with electricity and Global Positioning System location services. The ability to transport by road is necessary not only to ensure that personnel can get to their workplaces but also to allow those personnel to get to where their services are needed. Given water’s role in suppressing fires, a functioning water supply is required to support this NCF. Finally, because public safety services, especially police and fire, are government functions, an operating government is required for public safety operations.

Other Factors Driving Risk

The credibility and legitimacy of law enforcement depend on public trust in the institutions. Degradation in the functioning of institutions, real or perceived, would be a significant factor driving a potential increase in risk.

Strength of Evidence

Evidence on climate change’s effect on natural disasters is well established and has been recognized by government agencies (Anderson et al., 2017; Reidmiller et al., 2018). However, although the need for public safety services has been shown to increase in disasters, such as major floods and wildfire, the magnitude of climate’s effect on increased workload of public safety services is not as well documented for other climate drivers.

\textsuperscript{5} Critically dependent NCF was defined as an NCF that, if disrupted or in failure, would severely disrupt a given NCF and for which a given NCF could not recover until the upstream NCF was sufficiently operational. Upstream was defined as providing a key input to a downstream NCF.
Distribute Electricity

Scorecard

National Risk Assessment

SUMMARY: Distribute Electricity is at risk of moderate disruption by 2050 due to the effects that flooding, hurricanes, and extreme heat are anticipated to have on distribution substations, utility poles, and power conductors. 

1 = no disruption or normal operations.
2 = minimal disruption. 3 = moderate disruption. The table includes only drivers and subfunctions with risk ratings of 2 or higher.

Distribute Electricity: “Maintain and operate medium- to low-voltage system to reliably supply consumer demand for electricity from the bulk electric power network” (CISA, 2020, p. 3).

<table>
<thead>
<tr>
<th>Highest-Risk Climate Drivers</th>
<th>Current Emissions</th>
<th>High Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2030</td>
<td>2050</td>
</tr>
<tr>
<td>Extreme cold</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Extreme heat</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Flooding</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Sea-level rise</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Severe storm systems</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Tropical cyclones and hurricanes</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Wildfire</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Highest-Vulnerability Subfunctions</th>
<th>Current Emissions</th>
<th>High Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2030</td>
<td>2050</td>
</tr>
<tr>
<td>Operate Distribution System</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Provide Access</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Maintain System</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Provide Electrical Protection for System</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Secure System</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Provide Customer Service</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Synopsis

Distribute Electricity is at risk of moderate disruption by 2050 due to the effects that flooding, hurricanes, and extreme heat are anticipated to have on distribution substations, utility poles, and power conductors. Electricity distribution is vulnerable to most climate drivers because of the sheer breadth of infrastructure assets that are exposed to climate change, as well as legacy design and maintenance standards that are based on historical climatology and unequipped for more-frequent and -intense climate disasters. For example, flooding from extreme precipitation on the West and East Coasts and regions with dense riverine systems, sea-level rise on the West and East Coasts, and hurricanes along the Gulf Coast are already contributing to unprecedented flooding impacts on electricity distribution infrastructure throughout the United States. Notable examples include repeated flooding events in the Virginia coastal region (Virginia Secretary of Natural Resources, undated) and Hurricane Harvey in Houston, Texas (Dullo et al., 2021; Gangrade et al., 2019; Qiang, 2019). Many distribution substation components are not rated for the extreme heat projections that

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6 Recall that these analyses assume static, business-as-usual operations, with no attempt to adapt for or mitigate climate change. Routine maintenance and equipment replacement cycles might ensure that the NCF is protected in the future, but this was not considered for this analysis.
much of the western and southeastern United States are likely to experience in the coming century (Burillo et al., 2019). Although these climate change-driven disruptions will have cascading impacts on NCFs and sectors that rely on power on a regional basis, the interconnected redundancies that exist throughout the U.S. power grid increase the system’s resilience to national cascading failures of the Distribute Electricity NCF (Abi-Samra, 2017). However, the increased intensity and frequency of these events are likely to stress the maintenance and response operations put in place to mitigate vulnerabilities and increase the occurrence of longer, sustained power outages.

Additionally, we identified Distribute Electricity as the NCF with the most downstream NCFs depending on it to ensure normal operations. Distribute Electricity NCF assets, such as substations, which serve as nodal points for the broader distribution network, are therefore vital points susceptible to cascading failure. A substation failure can cause power outages throughout the entire power distribution network, resulting in power outages for all interconnected critical infrastructure assets. Substations have components that were not designed for the climate risks of the next century (Anshari Munir, Al Mustafa, and Siagian, 2019).

Subfunctions
All but one Distribute Electricity subfunction, Operate in Market, faces a risk of minimal disruption or greater due to climate change. Extreme weather events that degrade distribution lines and substation infrastructure can lead to significant interruptions to the operation of power distribution, resulting in the inability to provide power access to all customers, an increase in frequency of system maintenance, and the disruption of distribution security. For Distribute Electricity subfunctions, such as Operate Distribution System, Provide Access, Maintain System, Secure System, and Provide Electrical Protection for System, climate change could frequently hamper the ability to provide uninterrupted power, resulting in a risk of moderate disruption. These subfunctions are directly exposed to climate change hazards. Subfunctions that rely on human capital are likely to be less affected by their indirect exposure to climate change, although climate change could cause minor issues through 2100 that reduce the ability to provide consistent and high-quality customer service, suggesting a risk of minimal disruption by 2100.

Climate Drivers
All climate drivers except for drought pose risks to electricity distribution (Zuloaga and Vittal, 2021). Primarily because of the codes and standards for electricity distribution equipment and components and system design practices, distribution infrastructure is susceptible to climate drivers that increase the frequency of flooding, high wind, and heavy precipitation events (Boggess, Becker, and Mitchell, 2014) and increase extreme temperature volatility (Anshari Munir, Al Mustafa, and Siagian, 2019; Keane, Schwarz, and Thernherr, 2013). Judging from historical impacts and projected exposure of critical power distribution assets, we projected that hurricanes, sea-level rise, and extreme heat would pose the largest risk to power distribution by 2100. Hurricanes and flooding cause major disruptions regionally on an acute temporal basis (Doherty and Dewey, 1925; Nateghi, 2018), but these effects rarely, if ever, affect the NCF on a national scale. For example, Hurricanes Katrina, Maria, and Harvey caused prolonged power outages due to heavy distribution substation and power line damage, but these outages largely occurred only within a hurricane’s locale. Extreme heat and sea-level rise pose more chronic risk to power distribution infrastructure (Burillo et al., 2019; Griggs and

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7 We added a subfunction to the table only if it received a risk rating greater than minimal disruption between 2030 and 2100. Operate in Market received a risk rating of minimal disruption for the entirety of the time frame considered.

8 For this study, we considered only the effects of primary hazards, not the cascading effects that could trigger secondary hazards. Droughts can trigger certain types of landslides, but, in this research, we did not capture those second-order effects.
Patsch, 2019; Wuebbles et al., 2017), but again, the effects are largely limited to the infrastructure within a region.

**Cascading Risk**
Distribute Electricity is critically dependent on the following NCFs: 9

- Transmit Electricity
- Generate Electricity
- Exploration and Extraction of Fuels
- Store Fuel and Maintain Reserves
- Fuel Refining and Processing Fuels.

In the NCF framework, electricity distribution is one part of three interconnected NCFs that compose bulk power delivery: Transmit Electricity, Generate Electricity, and Distribute Electricity. If any of them fails, they all fail (Vartanian et al., 2018). Electricity distribution infrastructure could cause cascades to other NCFs within a region, but cascading risk between regions due to climate drivers is much rarer because of climate disasters’ footprint and the redundancies present in distribution infrastructure systems across regions. Additionally, other NCFs—Exploration and Extraction of Fuels, Store Fuel and Maintain Reserves, and Fuel Refining and Processing Fuels—maintain the development of fuel resources that are critical inputs to the generation of electricity. Should any of the fuel NCFs fail, it would likely be exceptionally difficult to maintain continuous power delivery through electricity distribution (Murphy et al., 2020).

**Other Factors Driving Risk**
Distribute Electricity infrastructure that has not received adequate maintenance or is being used beyond its designed life poses significant risk to the continued operation of the uninterrupted-power system (Chen, Wang, and Ton, 2017). Furthermore, electricity utilities’ responses to distribution system restoration procedures are typically based on predefined priorities and are inefficient and too slow to respond to power outages, and the absence of situational awareness following an extreme event severely slows the electricity restoration process. Maintenance and extreme-event response delays can increase the time to recovery of power distribution systems and threaten the short- and long-term viability of uninterrupted power delivery. Dated codes and standards also pose a chronic threat to legacy systems and future design and construction of power distribution systems (Pudyastuti and Nugraha, 2018). Design standards that do not consider increased frequency and intensity of climate drivers increase the risk of perpetuated power outages in critical electricity distribution infrastructure.

**Strength of Evidence**
The body of existing literature and studies of climate risk to electricity distribution infrastructure is expansive and well studied. Previous studies have detailed risks to the NCF-related infrastructure by U.S. region (Glick and Christiansen, 2019; Wakiyama and Zusman, 2021), and complementary studies have analyzed climate risk to supporting infrastructure and components from other countries that can be used to assess and substantiate risk ratings (Rübbelke and Vögele, 2010; Tobin et al., 2018; Turner et al., 2017; Zamuda,

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9 Critically dependent NCF was defined as an NCF that, if disrupted or in failure, would severely disrupt a given NCF and for which a given NCF could not recover until the upstream NCF was sufficiently operational. Upstream was defined as providing a key input to a downstream NCF.
Mignone, et al., 2013). Because most modern systems rely on uninterrupted power supply (Federal Emergency Management Agency [FEMA], 2007), there is a general interest in studying how to maintain continuous power through all types and scales of climate disasters (Boggess, Becker, and Mitchell, 2014; Huang, Swain, and Hall, 2020; Saint, 2009).
Manage Hazardous Materials

Scorecard

SUMMARY: Manage Hazardous Materials is at risk of moderate disruption from climate change by 2050, primarily because of the anticipated impacts of flooding, sea-level rise, and tropical cyclones and hurricanes. 1 = no disruption or normal operations, 2 = minimal disruption, 3 = moderate disruption. The table includes only drivers and subfunctions with risk ratings of 2 or higher.

<table>
<thead>
<tr>
<th>Highest-Risk Climate Drivers</th>
<th>Current Emissions</th>
<th>High Emissions</th>
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<tbody>
<tr>
<td></td>
<td>2030</td>
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<tr>
<td>Extreme cold</td>
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<td>Extreme heat</td>
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<td>Flooding</td>
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<td>Sea-level rise</td>
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<td>Severe storm systems</td>
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<td>Tropical cyclones and hurricanes</td>
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<td>Wildfire</td>
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<table>
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<tr>
<th>Highest-Vulnerability Subfunctions</th>
<th>Current Emissions</th>
<th>High Emissions</th>
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<tbody>
<tr>
<td></td>
<td>2030</td>
<td>2050</td>
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<tr>
<td>Manage Use of Hazardous Materials</td>
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<td>Manage Transport of Hazardous Materials</td>
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<td>Manage Hazardous Materials</td>
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</table>

Synopsis

Manage Hazardous Materials intersects with chemicals, substances, and activities heavily regulated by EPA and other federal agencies. For this analysis, we focused on facilities and their contents under the Resource Conservation and Recovery Act (RCRA); the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA, or Superfund); and the Emergency Planning and Community Right-to-Know Act of 1986 (EPCRA). EPCRA is the statute responsible for the Toxics Release Inventory (TRI) Program,

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10 To our knowledge, CISA has not explicitly defined which regulations, materials, or sites are necessary to “safely identify, monitor, handle, store, transport, use, and dispose of hazardous materials (including chemical, biological, radioactive, nuclear, and explosive substances) under normal operations and in response to emergencies” (CISA, 2020, p. 4).

11 Future studies at an additional order of analytic magnitude could include the Atomic Energy Act of 1954 (Pub. L. 83-703) sites, Brownfields and Land Revitalization Programs properties (see EPA, undated b), prerogatory landfills, coal-ash storage ponds, medical waste disposal sites, Nuclear Regulatory Commission–regulated sites, underground storage tanks, and other substances (such as RCRA–excluded agricultural and radioactive wastes). In addition, a second order of analysis could include the environmental presence of chemicals under the Toxic Substances Control Act (Pub. L. 94-469, 1976) that could climate drivers could release—for example, asbestos or lead from building damage, or dioxin from wildfire. For more information, see Superfund Research Center, undated. Last, these efforts could be cross-coordinated within CISA to align with the Chemical Facility Anti-Terrorism Standards program, which has a different but complementary focus that “identifies and regulates [approximately 37,000] high-risk facilities to ensure [that] security measures are in place to reduce the risk that certain hazardous chemicals are weaponized by terrorists” (CISA, undated a). About 9 percent of these facilities are considered high-enough risk to be assigned risk ratings via a computational engine, with approximately 170 sites in the top tier. For more
which tracks industrial and federal facilities responsible for chemical-release and pollution-prevention activities for the air, water, and land domains, amounting to 21,393 locations in 2019 (EPA, 2021d). In contrast, there are more than 60,000 RCRA large- and small-quantity hazardous waste generators and 1,450 treatment, storage, and disposal facilities (EPA, 2021a). Finally, there are approximately 1,600 nonfederal CERCLA sites (properties known as Superfund sites, managed by agencies among the listed, unlisted, and proposed National Priorities List [NPL] sites) containing legacy hazardous wastes (EPA, 2021b).

Hazardous materials are used, transported, and managed throughout the United States by large and small, public and private entities in nearly every community. For example, 50 percent of the U.S. population lives within a mile of approximately 60,000 RCRA-regulated hazardous waste generators, and a three-mile radius captures 80 percent of the population in the United States (EPA, 2014). Since 1976, the management of hazardous material has historically addressed climatic and environmental variability through industry standards and engineered risk tolerances, although many legacy sites are likely more vulnerable and less documented. These safety mechanisms, if they exist, however, might not match projected changes in climate drivers to avoid moderate disruption by 2050 or by 2100. Indeed, for flooding, sea-level rise, and tropical cyclones and hurricanes, which contribute to risk of moderate disruption for this NCF by 2050 and by 2100, coastal communities have already experienced hazardous leaks, fires, or explosions close to populated areas, other critical infrastructure, and sensitive natural ecosystems (GAO, 2019; Hasemyer and Olsen, 2020; Office of Solid Waste and Emergency Response, 2014; Office of Water, 2014; Summers, Lamper, and Buck, 2021). The primary mechanism of impact of these climate drivers is physical damage from flooding, hurricanes, and sea-level rise to containment structures, the latter of which is further exaggerated by the corrosive effects of saltwater. In addition, because of limited funding and other resource constraints, the ability to remediate damage that climate drivers cause to hazardous waste facilities could be hampered.

Climate changes will primarily affect the Manage Use of Hazardous Materials and Manage Hazardous Materials subfunctions. Both subfunctions are typically located in built-up areas because such areas host transportation infrastructure, often in or adjacent to environmental justice communities (EPA, 2021f).12 The most concerning consequence is leakage of hazardous materials from storage and disposal containment systems or increased fugitive air emissions that create health and safety effects.13 Releases into the air, land, or water can include acute, short-term, or long-term effects to human health and the environment coming from ignitable, corrosive, reactive, or toxic hazards as classified in 40 CFR § 261.11(a)(2) and assessed by the U.S. Department of Health and Human Service’s Agency for Toxic Substances and Disease Registry (EPA, 2021c). The potential for economic loss might be high but is likely localized because of the probability, dissemination pattern, and consequence of hazardous material disruptions.

Subfunctions
The Manage Use of Hazardous Materials subfunction is at risk of moderate disruption largely from either inadequate storage requirements or processing sensitivities (for example, complex chemical engineering information, see CISA, undated a. RCRA “often refers to interchangeably to [sic] the law, regulations, and EPA policy and guidance” (Summers, Lamper, and Buck, 2021, p. 1)—and can include waste not legally defined as hazardous, totaling 454,256 across the United States. For more information on the intersection of RCRA sites and natural hazards, see Summers, Lamper, and Buck, 2021.

12 Executive Order 12898 set into motion environmental justice programs to address “disproportionately high and adverse human health or environmental effects of . . . programs, policies, and activities on minority populations and low-income populations” (Clinton, 1994, § 1-101).

13 A fugitive emission is an emission that “could not reasonably pass through a stack, chimney, vent, or other functionally-equivalent opening” (40 C.F.R. § 70.2).
plants could require a long, specialized recovery). Despite robust engineering safety standards for storage requirements, anticipated extreme conditions and events could exceed design criteria and built-in risk tolerances. Additionally, increased flooding in previously unexposed areas can cause an uncontrolled release of unsecured hazardous materials into the soil, groundwater, surface water, and sediment (Office of Water, 2014; Summers, Lamper, and Buck, 2021). In contrast, power disruptions associated with severe storm systems, tropical cyclones and hurricanes, and wildfire climate drivers can affect complex production processes' management systems or security features that are designed to prevent fugitive air emissions (Healthy Building Network, 2019; Office of Water, 2014; Office of Solid Waste and Emergency Response, 2014; Summers, Lamper, and Buck, 2021). For example, if higher temperatures volatilize or break down chemicals more easily, people can experience new sources of impact and exposure pathways (Healthy Building Network, 2019; Minovi, 2020; Office of Solid Waste and Emergency Response, 2014; Office of Water, 2014; Summers, Lamper, and Buck, 2021). Although it was beyond the scope of this effort, further analysis could look at preparedness plans for EPCRA's TRI sites or risk management plans under the 1990 Clean Air Act amendments (Pub. L. 101-549) for facilities that use extremely hazardous substances.

Manage Hazardous Materials is also at risk of moderate disruption, primarily because of the known vulnerabilities of RCRA facilities and those perhaps still unknown at legacy CERCLA sites. Many of the impact pathways are similar to those of the Manage Use of Hazardous Materials subfunction. In addition, containment vessels can fail with extreme heat or wildfire, remediation strategies might depend on the current range of temperatures and precipitation (leading to degradation under drought and extreme heat), or drought or flood could affect the monitoring of groundwater plumes (Sinha et al., 2020).

The Transport of Hazardous Materials subfunction has only a minimal risk of disruption, primarily because the bulk of activities are colocated in only a few regions. For example, the Gulf Coast produces and transports a large amount of hazardous material, and more than 4.3 million people live within 1.5 miles of 872 facilities within 50 miles of the coast. If flooding, sea-level rise, and hurricanes continue to and increasingly threaten current management capabilities and capacities, however, some of these facilities might relocate to other regions with sufficient markets or legacy infrastructure, or they might import from offshore sources, necessitating new and more-distant transportation procedures (perhaps of more midstream or specialty materials rather than bulk chemicals, as seen in the plastics industry) (Anenberg and Kalman, 2019; Minovi, 2020; Office of Solid Waste and Emergency Response, 2014; Office of Water, 2014; Summers, Lamper, and Buck, 2021). This could exacerbate worker stress and fatigue at transfer sites or require new training to mitigate vulnerabilities from a longer supply chain (National Clearinghouse for Worker Safety and Health Training, 2015; Summers, Lamper, and Buck, 2021).

Climate Drivers

We narrowly considered how climate drivers might directly affect the sources of hazardous materials and waste on their pathway to a receptor individual, not accounting for second-order transport and transformation of the materials and wastes. This focus aligns our effort with that of GAO, which found in 2019 in a screening of Superfund sites that available federal data on flooding, storm surge, wildfires, and sea level rise suggest that about 60 percent (945 of 1,571) of all nonfederal NPL sites are located in areas that may be impacted by one or more of these potential climate change effects. (GAO, 2019, p. 18)

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14 For more information on the distinction, see Balbus et al., 2013.

15 GAO provided several caveats about lacking site-specific information, including validated boundary information, and the definition of the climate change effects were somewhat different: “0.2 percent or higher annual chance of flooding or other
Flooding, sea-level rise, and tropical cyclones and hurricanes contribute to an anticipated risk of moderate disruption for this NCF by 2050 and by 2100 by overwhelming containment structures, damaging storage assets, and dispersing materials and wastes into floodwaters the soil. As of this writing, 713 nonfederal NPL sites (45 percent of the total under CERCLA) are in one of FEMA’s Special Flood Hazard Areas (the 100-year floodplain)—a number that is expected to grow as the exposure area increases to include more sites and adjacent populations (Dearen, Biesecker, and Kastanis, 2017; GAO, 2019). A further 110 and 183 nonfederal NPL sites (7 and 12 percent of the total, respectively) are exposed to sea-level rise and storm surge, respectively (GAO, 2019). In comparison, at present, 7 percent of RCRA sites are exposed to flooding, 3 percent to sea-level rise, and 10 percent to hurricanes. Comparable numbers for EPCRA’s TRI facilities were not readily available but could be obtained through further analysis. Water can damage liner and leachate systems for underground and aboveground components or infiltrate aboveground components, which, in turn, can require new monitoring and or characterizations of an impact area and use-limitation boundary. This can be especially true for sites capped with soil, clay, or concrete while hazardous materials remain in the ground. These climate drivers can cause additional physical damage to horizontal elements, such as pipe networks, and vertical elements, such as flares and monitoring equipment (Healthy Building Network, 2019; Office of Solid Waste and Emergency Response, 2014; Office of Water, 2014; Summers, Lamper, and Buck, 2021).

Wildfire is likely to be a growing threat, especially given facilities’ substantial exposure, and could ignite flammable materials or puncture storage envelopes (Minovi, 2020; Office of Water, 2014; Summers, Lamper, and Buck, 2021). For example, 234 nonfederal NPL sites (15 percent of the total) and 21 percent of RCRA facilities are considered at high wildfire hazard potential (GAO, 2019; Summers, Lamper, and Buck, 2021). In addition, wildfire has the potential to result in an uncontrolled release of either heat-sensitive or unsecured materials into the air, vastly expanding their potential effects beyond an immediate regulated site (Healthy Building Network, 2019; Office of Solid Waste and Emergency Response, 2014; Office of Water, 2014; Summers, Lamper, and Buck, 2021).

Other climate drivers are likely to be within the NCF’s management capabilities. Drought, extreme cold, extreme heat, and severe storms can disrupt chemical processing, damage containment strategies, alter the composition of fugitive air emissions, or render safety systems inoperable, largely through dependencies on the electrical grid or discharge bodies in the 2050 time frame (Knickmeyer, 2019; Office of Solid Waste and Emergency Response, 2014; Office of Water, 2014; Summers, Lamper, and Buck, 2021).

Cascading Risk
Manage Hazardous Materials is critically dependent on the following NCFs:18

- Distribute Electricity
- Produce Chemicals

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16 The highest-risk RCRA sites have a 75-percent Cumulative Resilience Screening Index score or higher. EPA developed the index to assess a baseline of current exposure to a selection of 12 natural hazards. For more information, see Summers, Lamper, and Buck, 2021.

17 Similar statistics could be produced for EPCRA’s TRI.

18 Critically dependent NCF was defined as an NCF that, if disrupted or in failure, would severely disrupt a given NCF and for which a given NCF could not recover until the upstream NCF was sufficiently operational. Upstream was defined as providing a key input to a downstream NCF.
• Transport Cargo and Passengers by Road
• Develop and Maintain Public Works and Services.

Hazardous materials must be used only by trained people using specialized equipment, and their use is tightly connected with the chemical industry. The materials are typically transported by roads, require regulated and monitored collection protocols, and often require electricity to manage and control (GAO, 2019; Hasemyer and Olsen, 2020; Office of Solid Waste and Emergency Response, 2014; Office of Water, 2014; Summers, Lamper, and Buck, 2021).

Other Factors Driving Risk
The management of hazardous materials is a highly regulated field, and the relative level of statute enforcement can vary by administrative and legislative institutional priorities. Given the historical and current locations of these materials’ use, transport, and disposal associated with economic development and land-use policy, they have had and are likely to continue to have disproportionate equity impacts on certain socioeconomically vulnerable and environmental justice populations that could be more sensitive to these effects or have less adaptive capacity (GAO, 2019; Hasemyer and Olsen, 2020; Office of Solid Waste and Emergency Response, 2014; Office of Water, 2014). These often statistically underrepresented and systematically excluded communities might have not only a higher likelihood of proximity to hazardous materials but also unique routes of exposure, such as children, indigenous communities, subsistence and sports fishing people, rural populations, farmers or farm workers, and urban poor (Gochfelt and Burger, 2011; Mascarenhas, Grattet, and Mege, 2021). The Manage Use of Hazardous Materials and Manage Transport of Hazardous Materials subfunctions depend on not only security-screened and specially licensed people, such as plant operators or truck drivers, who could be subject to periodic shortage but also scientists with advanced training who collect data and produce research critical to understanding contaminant presence, migration, and degradation, as well as their consequences (GAO, 2019; Hasemyer and Olsen, 2020; Office of Solid Waste and Emergency Response, 2014; Office of Water, 2014; Summers, Lamper, and Buck, 2021).

Strength of Evidence
The strength of evidence for Manage Hazardous Materials depends on climate driver rather than the subfunction. At present, management strategies for the climate drivers across the Manage Use of Hazardous Materials, Manage Transport of Hazardous Materials, and Manage Disposal of Hazardous Materials subfunctions are adequate, so little additional study has been required beyond the analysis of notable recent disasters, especially hurricanes in sea-level rise–prone regions. For example, flooding, sea-level rise, and tropical cyclones and hurricanes have strong evidence, with numerous government studies, independent engineering analyses, and peer-reviewed scientific studies (Anenberg and Kalman, 2019; ASCE, 2021d; Summers, Lamper, and Buck, 2021). There is moderate evidence for severe storm systems and wildfire, although the latter climate driver is rapidly receiving greater attention from analysts and researchers. The weakest evidence is for the consequence of drought, extreme cold, and extreme heat.
Transmit Electricity

Scorecard

National Risk Assessment

SUMMARY: Transmit Electricity is at risk of moderate disruption by 2050 due to the effects that flooding, hurricanes, and extreme heat are anticipated to have on transmission substations, transmission towers, and power conductors.

1 = no disruption or normal operations.
2 = minimal disruption. 3 = moderate disruption. The table includes only drivers and subfunctions with risk ratings of 2 or higher.

Transmit Electricity: “Maintain and operate high-voltage (>100-kilovolt) bulk electric system to reliably supply distribution network demand for electricity from generation resources” (CISA, 2020, p. 3).

<table>
<thead>
<tr>
<th>Climate Driver</th>
<th>2030</th>
<th>2050</th>
<th>2100</th>
<th>Current Emissions</th>
<th>2030</th>
<th>2050</th>
<th>2100</th>
<th>High Emissions</th>
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</thead>
<tbody>
<tr>
<td>Extreme cold</td>
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<tr>
<td>Extreme heat</td>
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<td>Severe storms</td>
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<td>Tropical cyclones and hurricanes</td>
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Highest-Risk Climate Drivers

MECHANISMS OF IMPACT

- Physical damage or disruption
- Input or resource constraint
- Workforce shortage
- Demand change

The shade of gray indicates the strength of evidence for that NCF: dark gray = strong evidence and medium gray = moderate evidence. We also found strong evidence for drought.

Highest-Vulnerability Subfunctions

CASCADING RISKS

- Upstream linkages: 5
- Downstream linkages: 3

Upstream and downstream linkages are detailed in Chapter Six.

Synopsis

Transmit Electricity faces a risk of moderate disruption from four of the eight climate drivers and a risk of minimal disruption from three of the eight climate drivers by 2100. This is due in part to the NCF’s broad national footprint, which exposes it to climate divers where they manifest in each region and to legacy design and maintenance standards that were not created for more-frequent and -intense climate disasters. Flooding from heavy precipitation on the West and East Coasts and in regions with dense riverine systems, sea-level rise on the East Coast, and hurricanes in the Gulf Coast are already having unprecedented impacts on electricity transmission infrastructure (Dullo et al., 2021; Gangrade et al., 2019; Qiang, 2019). Critical transmission substation components are not rated for the extreme heat that much of the western and southeastern United States are projected to experience through 2100 (Burillo et al., 2019). Although these climate change–driven disruptions will have cascading impacts on NCFs and sectors that rely on power on a regional basis, redundancies throughout the U.S. power grid increase the system’s resilience to national cascading failures of the NCF (Abi-Samra, 2017). However, the increased intensity and frequency of climate change–driven extreme events are likely to stress maintenance and response operations put in place to mitigate vulnerabilities and lead to longer, sustained power outages. The increased intensity and frequency of extreme events are likely to cause greater regional disruptions in the NCF through 2100, resulting in a risk of moderate disruption.
Additionally, the interconnected nature of the assets in this NCF and in upstream and downstream NCFs creates the potential for significant cascading risk across the system. Transmit Electricity NCF assets, such as substations, are nodal points for the broader transmission network and therefore can create the risk of cascading failures. Substations have components that were not designed for the climate risks through 2100 (Anshari Munir, Al Mustafa, and Siagian, 2019).

Subfunctions
All but one Transmit Electricity subfunction, Operate in Market, face at least a risk of moderate disruption by 2050 as a result of climate change. Extreme weather that degrades or destroys transmission power lines and substation infrastructure can lead to significant power transmission interruptions, resulting in the inability to provide access to power for all customers (Nateghi, 2018), an increase in frequency of system maintenance (Fant et al., 2020), and the disruption of electricity transmission security (Agrawal, 2020; DOE, 2015). Power outages often lead to regional economic loss, although prolonged outages can also propagate economic losses nationally or globally (Shuai et al., 2018; Y. Zhang and Lam, 2016). For Transmit Electricity subfunctions, such as Operate Infrastructure, Provide Access, Maintain System, Secure System, and Provide Electrical Protection, climate change could frequently disrupt the ability to provide uninterrupted power. Each of these subfunctions has infrastructure that is directly exposed to weather. As extreme weather conditions continue to increase in frequency and intensity, the risk of these subfunctions failing also increases. Therefore, each of these subfunctions is likely to experience moderate disruption by the end of 2100 due to climate change. The other subfunction, Operate in Market, relies on decentralized systems, human resources, and infrastructure that have redundancies that increase the subfunction’s resilience to climate change.

Climate Drivers
All the identified climate drivers other than drought pose risk to Transmit Electricity (Zuloaga and Vittal, 2021). Transmission infrastructure is susceptible to climate drivers that increase the frequency of flooding, high wind, and heavy precipitation events (Boggess, Becker, and Mitchell, 2014) and the volatility of extreme temperatures (Anshari Munir, Al Mustafa, and Siagian, 2019; Keane, Schwarz, and Thernherr, 2013). As a result of electricity distribution equipment codes and standards and system design practices, Transmit Electricity infrastructure is susceptible to extreme temperature changes and flooding. However, because they have a more centralized power delivery function, transmission systems are often hardened more than downstream distribution equipment, reducing their vulnerability. Given historical impacts and projected exposure of critical power distribution assets, hurricanes, sea-level rise, and extreme heat are projected to pose the largest risk to power transmission by 2100. Hurricanes and flooding cause major disruptions regionally on an acute temporal basis (Doherty and Dewey, 1925; Nateghi, 2018), but these effects rarely, if ever, affect the NCF on a national scale. Extreme heat and sea-level rise pose more chronic risk to power transmission infrastructure (Burilloy et al., 2019; Griggs and Patsch, 2019; Wuebbles et al., 2017), but again, the effects are largely limited to the infrastructure within each region. Electricity transmission infrastructure can cause cascading effects to other NCFs within a region, but cascading risk between regions due to climate drivers is much rarer because of the footprint of climate disasters and the redundancies present in transmission infrastructure systems across regions.

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19 We added a subfunction to the table only if it received a risk rating greater than minimal disruption between 2030 and 2100. Operate in Market received a risk rating of minimal disruption for the entirety of the time frame considered.
Cascading Risk
Transmit Electricity is critically dependent on the following NCFs:20

- Generate Electricity
- Exploration and Extraction of Fuels
- Store Fuel and Maintain Reserves
- Fuel Refining and Processing Fuels
- Maintain Supply Chains.

Within the NCF framework, electricity transmission is one part of three interconnected NCFs that compose bulk power delivery. If Transmit Electricity, Generate Electricity, or Distribute Electricity fails, the other two NCFs will also fail (Vartanian et al., 2018). Additionally, other NCFs maintain the development of fuel resources (Exploration and Extraction of Fuels, Store Fuel and Maintain Reserves, and Fuel Refining and Processing Fuels) that are critical inputs to the generation of electricity. Should any of these fuel NCFs fail, it would likely be exceptionally difficult to maintain continuous power delivery through electricity transmission (Murphy et al., 2020).

Other Factors Driving Risk
Transmission infrastructure that has not been adequately maintained or is being used beyond its designed life poses significant risk to the continued operation of the uninterrupted-power system (Chen, Wang, and Ton, 2017). Furthermore, electricity utilities’ responses to transmission system restoration procedures are typically based on predefined priorities and are inefficient and unsatisfactory, and the absence of situational awareness following a hazard severely slows the restoration process. Additionally, transmission infrastructure restoration is often more labor- and capital-intensive, with the locations of the damage often more remote and harder to access than those of distribution infrastructure. Maintenance and disaster response delays can increase the time to recovery of power distribution systems and threaten the short- and long-term viability of uninterrupted power delivery. Dated codes and standards also pose a chronic threat to legacy systems and to the future design and construction of power distribution systems (Pudyastuti and Nugraha, 2018). Design standards that do not consider increased frequency and intensity of climate disasters can increase the risk of perpetuated power outages in critical electricity transmission infrastructure.

Strength of Evidence
The body of existing literature and studies of climate risk to electricity transmission infrastructure is expansive and well studied. Some studies have detailed risks to the NCF-related infrastructure by region of the United States (Glick and Christiansen, 2019; Wakiyama and Zusman, 2021), and complementary studies have analyzed climate risk to supporting infrastructure and components from other countries that can be used to assess and substantiate risk ratings (Rübbelke and Vögele, 2010; Tobin et al., 2018; Turner et al., 2017; Zamuda, Mignone, et al., 2013). Because most modern systems rely on uninterrupted power supply (FEMA, 2007), there is a general interest in studying how to maintain continuous power through all types and scales of climate disasters (Huang, Swain, and Hall, 2020; Boggess, Becker, and Mitchell, 2014; Saint, 2009).

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20 Critically dependent NCF was defined as an NCF that, if disrupted or in failure, would severely disrupt a given NCF and for which a given NCF could not recover until the upstream NCF was sufficiently operational. Upstream was defined as providing a key input to a downstream NCF.
Transport Cargo and Passengers by Air

**Scorecard**

**National Risk Assessment**

SUMMARY: Transport Cargo and Passengers by Air is at risk of moderate disruption from climate change by 2050, primarily because of the effects that flooding, sea-level rise, tropical cyclones and hurricanes, severe storm systems, and heat are anticipated to have on physical airport infrastructure and aircraft operations.

1 = no disruption or normal operations. 2 = minimal disruption. 3 = moderate disruption. The table includes only drivers and subfunctions with risk ratings of 2 or higher.

**Highest-Risk Climate Drivers**

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<td></td>
<td>2030</td>
<td>2050</td>
</tr>
<tr>
<td>Extreme heat</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Flooding</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Sea-level rise</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Severe storm systems</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Tropical cyclones and hurricanes</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Wildfire</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Highest-Vulnerability Subfunctions</th>
<th>Current Emissions</th>
<th>High Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obtain and Maintain Knowledgeable Workforce</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Manage Transport Operations</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Provide Diverse Energy Sources</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

**Synopsis**

Air transportation is vulnerable to climate change for multiple reasons. Inclement weather is already the main cause of flight delays and cancellations (Burbidge, 2018), and increasing storm activity can make this worse. Extreme heat can reduce the allowable weight that aircraft can carry, and more high-temperature days could mean that aircraft will carry fewer goods and passengers safely. Finally, sea-level rise will affect the infrastructure of some coastal airports, both through inundation and storm surge. Overall, this NCF is anticipated to face a risk of minimal disruption in 2030 due to existing storm patterns, and that risk rises to moderate disruption by 2050 as flooding, hurricane intensity, and wildfire risk increase.

The aviation system is also highly interconnected. Although the United States has thousands of airports, more than 85 percent of enplanements take place at just 61 airports, and delays and cancellations can cascade through the aviation system even if climate drivers affect only a few airports. The New York region is over-represented in air travel delay propagation; eight of the 13 origin–destination pairs that result in the highest amount of delay propagation begin or end at New York–area airports (Miller et al., 2020). This suggests that delays in the New York region, which is particularly vulnerable to sea-level rise (Wright and Hogan, 2008), can cascade throughout the air travel system.
Subfunctions
The primary subfunctions disrupted by climate change are Manage Transport Operations and Provide Diverse Energy Sources. Manage Transport Operations is affected through the possible effects that both physical damage to airport infrastructure and inclement weather (particularly snow, freezing temperatures, and heavy rain and wind) can have on airport and airline operations (Burbidge, 2018), as well as extreme heat’s consequences for aircrafts’ ability to transport their usual cargo and passenger loads (Coffel, Thompson, and Horton, 2017). Extreme heat can also damage runways (Burbidge, 2018). This subfunction is rated minimal disruption by 2030, as many of these disruptions already occur on a regular basis. Provide Diverse Energy Sources is a downstream impact from Distribute Electricity; lack of electricity would severely affect airport and airline operations. This suggests a risk of minimal disruption by 2030 and a moderate disruption by 2050 because electricity disruptions are expected to worsen by 2050.

A less affected subfunction is Obtain and Maintain Knowledgeable Workforce. Although climate change might not directly affect the ability to attract and retain the skilled workers required to operate the air transportation system, it could affect workers’ ability to function outdoors when temperatures are too hot to work safely (National Institute for Occupational Safety and Health [NIOSH], 2016). This suggests a risk of minimal disruption by 2100 due to temperatures halting outdoor work. This effect would vary among airports depending on the future combination of heat and humidity.

Climate Drivers
Air transportation is at risk mainly from sea-level rise, hurricanes (and, to a lesser extent, nontropical severe storms), flooding, and extreme heat. Sea-level rise could render some airports temporarily or permanently unusable, depending on the amount of inundation. According to one study, the country has about 200 airports located 10 m or less above sea level, although only a handful of these are large- or medium-hub airports. (Although our analysis focused on the U.S. air transportation system, the study suggested that international flights could be affected by sea-level rise at major airports in other countries [Yesudian and Dawson, 2021]). However, two of those airports are in the New York area, and disruptions in the New York area can affect the national aviation system by propagating delays (Miller et al., 2020). For safety reasons, aircraft are required to maintain additional separation when flying in intense precipitation (Burbidge, 2018), and, according to one study, 13 large- and medium-hub airports have at least one runway “within the reach of moderate to high storm surge” (Thompson, 2016, p. 107). Heavy precipitation and high winds can damage landside airport infrastructure, and flooding can damage both aboveground and underground infrastructure (Burbidge, 2018).

Extreme heat also poses risks to air transportation. Aircraft have temperature thresholds for safe takeoff that are affected by elevation, runway length, and aircraft type. Studies have projected that weight-restriction days will increase up to 50 to 100 days per year at four major airports in the United States by 2070 (Coffel and Horton, 2015) and that 10 to 30 percent of flights taking off during maximum daily temperature might require weight restrictions (Coffel, Thompson, and Horton, 2017). The number of weight-restricted days is projected to increase every decade, so effects will be greater by 2100 than by 2050. Effects will be greatest at airports with short runways or at high elevations (Coffel and Horton, 2015). Extreme heat can also damage tarmac, lead to increased cooling requirements for buildings, and create fire hazards if the flash point for aviation fuel is exceeded (Burbidge, 2018; Thompson, 2016).

Given that weather is the leading cause of flight delay, an increase in the number of convective storms (storms with thunder and lightning) would seem to increase delays and thus disrupt airline operations. For this reason, we have rated this at risk of moderate disruption by 2050. However, we also note that there has
been very little study of this risk, so defining more-precise effects (such as increased delay or safety hazards) is difficult.\textsuperscript{21}

Cascading Risk

Transport Cargo and Passengers by Air is critically dependent on the following NCFs:\textsuperscript{22}

- Transport Cargo and Passengers by Road
- Distribute Electricity
- Provide Positioning, Navigation, and Timing Services
- Provide Satellite Access Network Services
- Fuel Refining and Processing Fuels.

Transportation by air requires roadway transportation for access of both goods and people (staff and passengers) to airports (National Academies of Sciences, Engineering, and Medicine, 2008; U.S. Department of Transportation [DOT], undated). Aircraft are powered largely by petroleum products (jet fuel and aviation gas) (Holladay, Abdullah, and Heyne, 2020), and airport operations require electricity. The air traffic control system, which ensures safe movement of aircraft in flight, relies on both positioning, navigation, and timing (PNT) and satellite-based services (Wallischeck, 2016).

Other Factors Driving Risk

Underlying the risk ratings for Transport Cargo and Passengers by Air are key factors that contribute to the risk ratings. Although this NCF depends heavily on physical infrastructure, airport runways are generally well maintained, and the major issue with landside infrastructure is lack of sufficient capacity rather than disrepair (Miller et al., 2020). If airport infrastructure were to be degraded in the future, this NCF would be at an elevated risk because most metropolitan regions have only one or two major airports. Airports are not readily substitutable, inexpensive, or easy to build. In addition, regional economic development drives demand for both passenger travel and air cargo. Because airports generally depend financially on user fees from air transportation (rather than tax revenues), a decrease in air travel demand due to a stagnating regional economy can lead to a loss of revenue, which would diminish an airport’s ability to fund its operations.

Strength of Evidence

There have been multiple analyses of the effect that sea-level rise and extreme heat have on airports and aircraft operations (Burbidge, 2018; Coffel and Horton, 2015; Coffel, Thompson, and Horton, 2017; Thompson, 2016; Wright and Hogan, 2008; Yesudian and Dawson, 2021). There is some literature on flooding, hurricanes, and other storms but very little analysis of the effects of drought, extreme cold, and wildfire. Several

\textsuperscript{21} An extensive 2022 review noted the type of disruption that would occur: “longer routes, steeper climbs and descents, and less efficient airspeeds—all adversely impacting emissions, flight times and costs, and forcing more aircraft into some portions of airspace, creating potential safety issues that must be mitigated” (Gratton et al., 2022, p. 213).

\textsuperscript{22} Critically dependent NCF was defined as an NCF that, if disrupted or in failure, would severely disrupt a given NCF and for which a given NCF could not recover until the upstream NCF was sufficiently operational. Upstream was defined as providing a key input to a downstream NCF.
studies have noted that, despite the predicted increase in the number of convective storms, there is almost no analysis of their effect on air transportation.\textsuperscript{23}

\textsuperscript{23} An extensive 2022 review noted the type of disruption that would occur: “longer routes, steeper climbs and descents, and less efficient airspeeds—all adversely impacting emissions, flight times and costs, and forcing more aircraft into some portions of airspace, creating potential safety issues that must be mitigated” (Gratton et al., 2022, p. 213). It also went on to say the following:

Whilst there is strong evidence of increasing clear air turbulence severity and contact incidence in the vicinity of the north polar jet stream, and to a lesser extent in the vicinity of other jet streams, there appears presently to be no published analysis of the safety or other operational implications of those encounters. (Gratton et al., 2022, p. 219)
# Develop and Maintain Public Works and Services

## Scorecard

### National Risk Assessment

**SUMMARY:** Develop and Maintain Public Works and Services is at risk of moderate disruption by 2100 for all climate drivers except extreme cold.

1 = no disruption or normal operations, 2 = minimal disruption, 3 = moderate disruption. The table includes only drivers and subfunctions with risk ratings of 2 or higher.

### Highest-Risk Climate Drivers

<table>
<thead>
<tr>
<th>MECHANISMS OF IMPACT</th>
<th>Drought</th>
<th>Extreme cold</th>
<th>Extreme heat</th>
<th>Flooding</th>
<th>Sea-level rise</th>
<th>Severe storm systems</th>
<th>Tropical cyclones and hurricanes</th>
<th>Wildfire</th>
</tr>
</thead>
<tbody>
<tr>
<td>◎ Physical damage or disruption</td>
<td>2 2 3</td>
<td>1 1 2</td>
<td>2 3 3</td>
<td>2 3 3</td>
<td>2 3 3</td>
<td>2 3 3</td>
<td>2 2 3</td>
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<tr>
<td>◎ Input or resource constraint</td>
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<td></td>
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<tr>
<td>◎ Workforce shortage</td>
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<td></td>
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<tr>
<td>□ Demand change</td>
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</tr>
</tbody>
</table>

The shade of gray indicates the strength of evidence for that NCF: medium gray = moderate evidence and light gray = little evidence.

### Highest-Vulnerability Subfunctions

<table>
<thead>
<tr>
<th>CASCAдинG RISKS</th>
<th>Transportation Construction and Maintenance</th>
<th>Utility Construction and Maintenance</th>
<th>Provide and Maintain Public Safety Buildings and Services</th>
<th>Manage Recreation Spaces and Facilities</th>
<th>Community Revitalization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upstream linkages: 8</td>
<td>2 3 3</td>
<td>2 3 3</td>
<td>1 2 3</td>
<td>1 2 3</td>
<td>1 2 3</td>
</tr>
<tr>
<td>Downstream linkages: 4</td>
<td>2 3 3</td>
<td>2 3 3</td>
<td>1 2 3</td>
<td>1 2 3</td>
<td>1 2 3</td>
</tr>
<tr>
<td>Upstream and downstream linkages are detailed in Chapter Six.</td>
<td></td>
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</tr>
</tbody>
</table>

### Synopsis

Public works and services are vital to providing adequate quality of life and supporting communities’ general well-being. The infrastructure needed to support public works and services, including transportation systems, utility systems, recreational spaces, and public safety buildings, is assessed to be at risk of disruption and damage from climate drivers. Historical incidents, such as flooding events in Rhode Island in 2010, which led to the closure of 98 roads and 28 bridges (Special Task Force on Climate Change and Energy, 2011), or the extreme heat and wildfire conditions in California in 2018, which led to contamination of municipal water sources (Chow, Karanfil, and Dahlgren, 2021), serve as examples to highlight the vulnerabilities of public works and services to exacerbating climate conditions. By 2100, climate drivers could result in risk of moderate disruptions for public works and services. The construction and maintenance of transportation systems, utilities, and buildings dedicated to public safety can be disrupted by climate drivers, including flooding, extreme heat, hurricanes, and severe storm systems. An increase in both the frequency and intensity of these events can result in unsafe working conditions for construction laborers and maintenance staff, creating workforce shortage, disruption to construction operations, and physical damage to equipment or
Assessing Risk to the National Critical Functions as a Result of Climate Change

For instance, the southern United States is vulnerable to extreme heat conditions in the future, which makes outdoor occupational hazards more dangerous because of heat illnesses (Applebaum et al., 2016). Additionally, infrastructure serving public works and services will require additional maintenance to address damage resulting from flooding, severe storm systems, hurricanes, and wildfire, as well as require adaptation to future climate conditions. For example, a study in which researchers reviewed stormwater infrastructure design standards in the United States indicated that stormwater infrastructure in 43 states was underdesigned for future precipitation conditions, making it more susceptible to flooding and therefore in greater need of ongoing maintenance as this infrastructure is affected over time (Lopez-Cantu and Samaras, 2018).

Subfunctions

Three out of the five subfunctions for Develop and Maintain Public Works and Services are at risk of moderate disruption by at least one of the climate drivers by 2100. Both Transportation Construction and Maintenance and Utility Construction and Maintenance are vital to public works and services, and both are vulnerable to drought, flooding, sea-level rise, tropical cyclones and hurricanes, and wildfire. Fixed-node transportation systems (e.g., airports and seaports) and fixed-route transportation systems (e.g., roads, buses, and subways) provide access for commuting, emergency vehicles, and other community services. Climate drivers’ effect on these systems differs by region and transportation mode. Existing transportation infrastructure in the United States is designed and managed based on historical climatology. As future climate conditions change, more-frequent disruptions and damage to transportation systems are likely (Transportation Research Board and National Research Council, 2008). For example, damage from Hurricanes Katrina, Rita, and Wilma in the Gulf Coast in 2005 resulted in $5.3 billion in repair and rebuild costs for highways and other transportation systems, as compared with $1.9 billion for the repair and rebuild costs for homes and property. Similarly, federal appropriations to DOT as a result of Hurricane Sandy in 2012 totaled $15.2 billion (Congressional Budget Office, 2016). Utility systems, which also serve as crucial infrastructure for public works and services, are susceptible to risk of moderate disruption from some of the same climate drivers. Recent examples include electrical power failures due to flooding from Hurricane Sandy in 2012, when it took ten days for electric utilities in New York and New Jersey to restore power for approximately 95 percent of their customers after outages peaked (Office of Cybersecurity, Energy Security, and Emergency Response, 2013); the power outage had considerable effects on public works and services including the evacuation of 300 patients from a New York City hospital (First Street Foundation, 2021). The severity of these effects will vary regionally; the Western Electricity Coordinating Council, for instance, estimated that costs to construct and repair electric grid infrastructure in areas with high population density were 1.59 times higher than in areas with low populations (Korbatov et al., 2017). Other examples include extreme heat conditions from the past two decades in the southwestern United States, leading to reductions in water storage for communities near the Colorado River, which poses challenges for water reservoir management (Runyon, 2021). In addition to transportation and utility systems, the construction and maintenance of public buildings (e.g., hospitals, police stations, local government offices) support public works and services but are at risk of disruption from climate drivers. In Los Angeles County, for instance, 34 percent of hospitals were identified as being in an area at high risk for wildfire in the future (Adelaine et al., 2017).

Other subfunctions for Develop and Maintain Public Works and Services, such as Manage Recreation Spaces and Facilities and Community Revitalization, are also at risk of potential disruption from climate drivers.

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24 The $5.3 billion cost value is adjusted for inflation from 2015 dollars ($4.5 billion) to 2021 dollars.
25 The $15.2 billion cost value is adjusted for inflation from 2015 dollars ($13 billion) to 2021 dollars.
drivers. Both physical components of recreational spaces, such as buildings, and nature and nature-based features can be damaged by drought, flooding, tropical cyclones and hurricanes, and wildfire. Examples include the 2020 wildfires in the western United States, which spread to 6,500 acres in Rocky Mountain National Park (Repanshek, 2020), and Hurricane Irma in 2017, which led to loss of vegetation cover and erosion of land mass on islands in Everglades National Park (Wingard et al., 2020).

Climate Drivers
Six out of the eight climate drivers (flooding, sea-level rise, tropical cyclones and hurricanes, severe storm systems, extreme heat, wildfire) are expected to pose the greatest risk of disruption of the development of public works and services by 2100. Disruptions will have varying regional effects; public works and services located on U.S. coastlines and the Gulf of Mexico are more vulnerable to flooding, sea-level rise, and tropical cyclones and hurricanes, whereas public works and services in regions that are expected to experience high heat conditions by 2100 will be more vulnerable to wildfire and extreme heat. Although drought and extreme cold can pose threats to some subfunctions, as evidenced by Winter Storm Uri in early 2021, when frozen pipelines and equipment disrupted water and power services to millions of homes and businesses in Texas (Campbell, 2021), their overall impact on this NCF is minimal or expected to decrease.

Cascading Risk
Develop and Maintain Public Works and Services is critically dependent on the following NCFs: 26
- Distribute Electricity
- Transport Cargo and Passengers by Air
- Transport Cargo and Passengers by Rail
- Transport Cargo and Passengers by Road
- Educate and Train
- Supply Water
- Provide and Maintain Infrastructure
- Operate Government.

Developing and maintaining public works and services are involved processes that require continual operation of both physical infrastructure (e.g., transportation, electric, and water supply) and nonphysical infrastructure (e.g., community governance, education and training of workforce). Disruption of these NCFs increases the risk of failure of public works and services.

Other Factors Driving Risk
Communities’ ability to develop climate resilience measures for infrastructure serving public works and services is a significant factor in mitigating disruption from climate drivers. Although climate drivers pose many threats to subfunctions of this NCF, communities’ ability to adapt and mitigate the risks will help avoid disruptions in the future. Investments in resilience measures to avoid disruptions can be financially significant, and some communities might lack the resources to make those investments. For instance, a tornado in 2011 made landfall in Joplin, Missouri, which destroyed a regional medical center. The medical center was

26 Critically dependent NCF was defined as an NCF that, if disrupted or in failure, would severely disrupt a given NCF and for which a given NCF could not recover until the upstream NCF was sufficiently operational. Upstream was defined as providing a key input to a downstream NCF.
subsequently rebuilt with windows rated to withstand winds up to 250 miles per hour; the cost of these windows was $70 more per square foot than that of conventional standard windows (Weiss and Weidman, 2013).

**Strength of Evidence**
Assessing potential risks and disruptions from climate drivers for specific subfunctions of this NCF, such as Transportation Construction and Maintenance and Utility Construction and Maintenance, is moderately documented through academic research reports, damage assessments from historical extreme weather events, and industry white papers. There is less evidence to indicate climate drivers’ effects on other subfunctions of this NCF, such as Manage Recreation Spaces and Facilities and Community Revitalization.
Manage Wastewater

Scorecard

**National Risk Assessment**

**SUMMARY:** Manage Wastewater is at risk of moderate disruption from climate change by 2050, primarily because of the effects that flooding and sea-level rise are anticipated to have on the conveyance and treatment of stormwater and wastewater and on the NCF’s capacity to construct and maintain assets. 2 = minimal disruption. 3 = moderate disruption. The table includes only drivers and subfunctions with risk ratings of 2 or higher.

Manage Wastewater: “Collect and treat industrial and residential wastewater to meet applicable public health and environmental standards prior to discharge into a receiving body” (CISA, 2020, p. 4).

<table>
<thead>
<tr>
<th>Current Emissions</th>
<th>High Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2030</strong></td>
<td><strong>2050</strong></td>
</tr>
<tr>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

**Highest-Risk Climate Drivers**

<table>
<thead>
<tr>
<th>MECHANISM OF IMPACT</th>
<th>2030</th>
<th>2050</th>
<th>2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drought</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Extreme cold</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Extreme heat</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Flooding</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Sea-level rise</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Severe storm systems</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Tropical cyclones and hurricanes</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Wildfire</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

The shade of gray indicates the strength of evidence for that NCF: dark gray = strong evidence.

**Highest-Vulnerability Subfunctions**

<table>
<thead>
<tr>
<th>CASCADING RISK</th>
<th>2030</th>
<th>2050</th>
<th>2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treat Wastewater</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Collect Wastewater</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Provide Facilities</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

Upstream and downstream linkages are detailed in Chapter Six.

**Synopsis**

Manage Wastewater is at risk of minimal to moderate disruption due to climate change across all time periods and scenarios assessed. The infrastructure that supports wastewater systems is vulnerable to extreme events, such as hurricanes and severe storms, as well as longer-term climate changes, such as drought and sea-level rise (Zouboulis and Tolkou, 2015). Wastewater and stormwater systems can be damaged or temporarily disrupted during these events, such as by the flooding of outlets or the increased incidence of combined sewer overflows, or demand can change and have implications for system operations, such as decreases in water use during drought that reduce flow rates in collection systems. These physical vulnerabilities, combined with long-term declines in the condition and capacity of existing wastewater infrastructure and projected changes in future climate, contribute to this NCF’s risk ratings (ASCE, 2021f). Further, these risk ratings indicate that entire regions of the country could be significantly disrupted in the future, resulting in degradation and pollution of receiving waters and the ecosystem services they support, the inability to meet Clean Water Act (Pub. L. 80-845, 1948) standards, or harm to human health from direct or indirect exposure to raw or poorly treated sewage (Mason, Ellis, and Hathaway, 2019; NIOSH, 2016; Olds et al., 2018).

In addition to these general dynamics, additional factors make certain aspects of this NCF at higher risk from climate change. Combined stormwater and wastewater systems, which are common throughout the Midwest and on the East Coast, also receive stormwater runoff. These systems are much more vulnerable to...
climate change than separate wastewater systems because of the additional exposure to extreme precipitation and flooding (Fortier and Mailhot, 2014). Distributed wastewater systems—namely, onsite wastewater treatment and septic systems—have additional vulnerabilities to climate change. Many of these systems are poorly maintained, leaky, and in regions vulnerable to sea-level rise or groundwater mounding and contamination, which can affect the quality of interconnected surface water and receiving coastal waters (J. Cooper, Loomis, and Amador, 2016).

Subfunctions
Risk assessments for each of the seven Manage Wastewater subfunctions showed that three—Treat Wastewater, Collect Wastewater, and Provide Facilities—are at risk of minimal to moderate disruption due to climate change. These subfunctions are highly dependent on infrastructure assets that are directly exposed to climate change drivers and not currently designed to withstand many of the projected changes, particularly for flooding, sea-level rise, and hurricanes. For example, for Provide Facilities, the construction and maintenance of wastewater infrastructure are vulnerable to severe storms, flooding, and sea-level rise, among other drivers, because physical assets can be inundated or damaged by these events, requiring more-frequent maintenance and construction of new or replacement facilities. These events could also temporarily limit worker access to sites. This NCF’s dependence on Distribute Electricity, as described in the “Cascading Risk” section later in this discussion, could result in discharge of untreated wastewater if power loss occurs because of these events.

The other four subfunctions—Govern Wastewater, Assure Secure Operations, Maintain Facility Infrastructure, and Provide HR [Human Resources] Services—were assessed as relatively insensitive and not at meaningful risk due to climate change. This assessment was generally due to these subfunctions’ ability to perform operations remotely, the lack of an infrastructure footprint required for operations, or the current capacity of management entities. For example, within the subfunction Assure Secure Operations, the management of wastewater—the plans, protocols, and processes in place for short- and long-term operations—has long been focused on protecting and managing water resources and the operations of wastewater systems in the face of weather events. Although climate change is projected to increase the frequency or magnitude of extreme heat events for most of the United States, these changes are unlikely to directly affect the ability to produce and manage plans, protocols, and processes of water management in the near to long term (Godden, Ison, and Wallis, 2011). One exception to this generalization is for local and, particularly, rural areas and small water providers around the United States. These entities might have a harder time addressing the challenges that enhanced climate risk poses and could become overwhelmed by the demands placed on them.

Climate Drivers
Flooding and sea-level rise pose a risk of moderate disruption to this NCF by midcentury under both emission scenarios. Both climate drivers constitute different sources of flooding, which can cause physical assets to be inundated or damaged, disrupting the movement of water within treatment systems and limiting treatment and discharge of effluent if assets cannot operate (Office of Water, 2014). In addition, because most wastewater treatment plants are located along waterways or coastlines, riverine flooding and sea-level rise could also temporarily or permanently damage discharge points or the treatment plants themselves (Hummel, Berry, and Stacey, 2018). These effects could halt operations or result in sewage spills that have implications for the environment and human health (Olds et al., 2018).

In addition to these climate drivers, wildfire, severe storms, and tropical cyclones and hurricanes pose risk of moderate disruption by 2100 under the current-emissions scenario and by 2050 and by 2100 under the high-emissions scenario. Severe storms and tropical cyclones and hurricanes result in similar impacts on
this NCF as flooding and sea-level rise with the added risks posed by high winds and storm surge. Wildfire can also result in direct physical damage to infrastructure or could generate debris that clogs storm-system inlets. If a wildfire is in direct proximity to a wastewater treatment plant, treatment plant operators might be unable to safely remain on site, limiting the treatment of wastewater if assets are damaged or if a treatment plant is unable to run without certified operators. Additionally, wildfire can result in widespread power outages that can shut down water systems.

The final climate drivers—drought, extreme cold, and extreme heat—are anticipated to drive risk of minimal disruption. For example, the collection of stormwater and wastewater is vulnerable to drought because changes in water-use behaviors can affect the quantity and quality of influent into the collection system. When the ratio of solids to liquids increases, this can lead to stagnation of waste streams and reactions that break down collection-system pipes (Chappelle et al., 2019). If low flow conditions in receiving waters occur because of drought, concentrations of pollutants could increase in water bodies, resulting in the exceedance of total maximum daily loads or other water quality thresholds and limiting wastewater treatment plants’ ability to discharge into receiving waters. However, because drought effects on wastewater collection systems are not as widespread or severe as those of other drivers, the risk that drought poses to this subfunction is not as significant.

Cascading Risk
Manage Wastewater is critically dependent on the following NCFs:27

- Distribute Electricity
- Develop and Maintain Public Works and Services
- Manage Hazardous Materials
- Produce Chemicals
- Maintain Supply Chains
- Operate Government.

Wastewater utilities are highly dependent on other NCFs to ensure normal operations (Wasley, Jacobs, and Weiss, 2020). Distribute Electricity is critical to the normal operations of a wastewater utility because power is needed for many treatment plant functions and the movement of water in and around the collection system, at least in part. The development and maintenance of infrastructure (Develop and Maintain Public Works and Services) are necessary to ensure asset life cycles and their proper functioning over time. The management of hazardous waste produced in wastewater treatment plants is regulated, necessitating the functioning of the Manage Hazardous Materials NCF (Silva, Matos, and Rosa, 2016). The production of chemicals and the supply chains that deliver chemicals and other inputs are necessary for proper treatment of waste streams. Because the majority of wastewater and stormwater agencies are public, Operate Government is also a necessary condition for this NCF to function.

Other Factors Driving Risk
Underlying the risk ratings for Manage Wastewater are key factors that contribute to the current adaptive capacity of wastewater systems across the United States. The condition and capacity of infrastructure are

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27 Critically dependent NCF was defined as an NCF that, if disrupted or in failure, would severely disrupt a given NCF and for which a given NCF could not recover until the upstream NCF was sufficiently operational. Upstream was defined as providing a key input to a downstream NCF.
critical to shaping the risk profile for wastewater because they determine how a facility and its assets will operate during and in the face of changes in climate. Generally speaking, wastewater infrastructure is aging and could benefit from significant investment, redesign, and adaptation (ASCE, 2021f). Because wastewater agencies manage the effluent from urban to industrial waste streams, as well as runoff, the dynamics of land use and population are crucial to determining the magnitude of additional demand placed on a wastewater agency. In some areas, population decline has left portions of wastewater systems in low to no use, leaving stranded assets and a management cost burden on utilities. These dynamics, combined with uneven resource availability among wastewater and stormwater agencies, contribute to an uneven distribution of climate risk across the United States (Mason, Ellis, and Hathaway, 2019).

Strength of Evidence
Evidence of climate change’s effects on U.S. wastewater systems is already apparent across many parts of the country, resulting in a wide body of existing evidence on past and projected impacts (Reidmiller et al., 2018). For example, in hurricane-affected regions, tropical cyclones and hurricanes have resulted in significant damage to wastewater infrastructure and wastewater treatment plants, in some cases leaving them inoperable for extended periods of time. For combined stormwater and wastewater systems, a large body of evidence and research supports the conclusion that combined sewer overflows have been increasing over time and could continue to do so in regions projected to experience increases in the frequency and magnitude of extreme precipitation events (Fortier and Mailhot, 2014; Zouboulis and Tolkou, 2015).
Prepare for and Manage Emergencies

Scorecard

National Risk Assessment

SUMMARY: Prepare for and Manage Emergencies is at risk of moderate disruption from climate change by 2050 because the increase in the frequency and severity of natural disasters will require emergency management agencies to coordinate the response to and recovery from disasters.

1 = no disruption or normal operations.
2 = minimal disruption. 3 = moderate disruption. The table includes only drivers and subfunctions with risk ratings of 2 or higher.

Prepare for and Manage Emergencies: “Organize and manage resources and responsibilities for dealing with all aspects of emergencies (prevent, protect, mitigate, respond, and recover), to be resilient to and reduce the harmful effects of all hazards” (CISA, 2020, p. 5).

<table>
<thead>
<tr>
<th>Highest-Risk Climate Drivers</th>
<th>Current Emissions</th>
<th>High Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2030</td>
<td>2050</td>
</tr>
<tr>
<td>Drought</td>
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<tr>
<td>Extreme heat</td>
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<tr>
<td>Flooding</td>
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<td>2</td>
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<tr>
<td>Sea-level rise</td>
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<tr>
<td>Severe storm systems</td>
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<tr>
<td>Tropical cyclones and hurricanes</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Wildfire</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

Highest-Vulnerability Subfunctions

Prepare for Emergencies 1 2 2 1 2 2
Manage Emergencies 2 3 3 2 3 3
Protect Against Threats and Hazards 1 2 2 1 2 2
Mitigate Impacts of Threats and Hazards 1 2 2 1 2 2
Respond to Incidents 2 3 3 2 3 3
Recover from Incidents 2 3 3 2 3 3

Synopsis

Prepare for and Manage Emergencies is at risk of moderate disruption from climate change by 2050 because of the increase in the frequency and severity of natural disasters that will require emergency management agencies to coordinate disaster response and recovery. Climate change is expected to increase the frequency and severity of extreme weather events, which will, in turn, increase demand to prepare for emergencies and manage response and recovery when disasters occur (Reidmiller et al., 2018). Storms and floods have the capacity to cause widespread damage and destruction to homes, businesses, and other facilities. Cold weather can lead to injuries and deaths from traffic accidents, as well as from hypothermia, particularly among the poor and elderly, who often have inadequate heat. Extreme hot weather can lead to an increase in heat-related illnesses, including heart, lung, and kidney problems. Wildfire can threaten homes, businesses, and other facilities, necessitating fire suppression, evacuation, and rescue. Drought can lead to an increase in the number and severity of dust storms, which, in turn, increase respiratory disease (Anderson et al., 2017).

Overall, this NCF is anticipated to face a risk of minimal disruption in 2030 due to climate change for both the current- and high-emissions scenarios. By 2050, in the current-emissions scenario, there will be
increases in the frequency, intensity, and duration of nearly all of the climate drivers other than flooding, leading to moderate disruption as demand for this NCF increases and resulting in the inability to meet operational needs in some parts of the country. By 2050, this NCF will also be at risk of moderate disruption in the high-emissions scenario, with increases in the frequency, intensity, and duration of all the climate drivers, including flooding.

Subfunctions

The demand for nearly all the subfunctions is expected to increase over time as the frequency of extreme climate events increases. This will cover the spectrum for Prepare for Emergencies, Manage Emergencies, Protect Against Threats and Hazards, Mitigate Impacts of Threats and Hazards, Respond to Incidents, and Recover from Incidents (FEMA, 2020; Silverman et al., 2010). The one subfunction for which there is not enough evidence to project an increase as a result of climate change is Prevent Attacks.

As the frequency and severity of climate emergencies increase, so will the need to prepare and plan for emergencies. Preparation typically involves the engagement of communities, organizations, corporations, and government entities. In the context of natural hazards, protection can also take the form of physically hardening facilities to make them less vulnerable to damage or to having their functions degraded or disrupted. As the frequency and severity of emergencies increase, so will the need for such preparation and planning, as well as execution of hardening strategies.

An increase in the frequency and intensity of climate events is expected to lead to a corresponding increase in the need for emergency management to coordinate and manage response and recovery. This need is expected to be especially strong for climate drivers with the capacity to cause widespread damage, such as flooding, storms, and wildfire. Even weather events that are not expected to cause high levels of physical damage, such as extreme cold or extreme heat, could increase demand for emergency management to coordinate agencies’ outreach and sheltering efforts.

Demand for this NCF is also expected to be high after a weather incident because managing recovery and rebuilding after a disaster requires engagement with the community, rebuilding in a way that mitigates future hazards, and careful management of reconstruction grants (Central Office for Recovery, Reconstruction and Resiliency, 2018).

Climate Drivers

Nearly every one of the climate drivers is expected to have an effect in increasing demand for emergency management. Chief among them will be the climate drivers with the potential to cause widespread damage and injury, such as flooding, storms, and wildfire. In contrast, neither drought nor extreme heat on its own typically causes damage of the sort requiring EMS, so these drivers are expected to have only moderate impact on this NCF. The one driver not expected to have much impact on emergency management is extreme cold. Although extreme cold does have effects on health, as well as on utilities, the frequency of extreme cold events is not expected to increase.
Cascading Risk
Prepare for and Manage Emergencies is critically dependent on the following NCFs:28

- Transport Cargo and Passengers by Road
- Distribute Electricity
- Operate Government
- Provide Wireless Access Network Services
- Provide Wireline Access Network Services
- Provide Satellite Access Network Services

Emergency management requires personnel who can get to their jobs and is therefore dependent on the ability to transport cargo and passengers by road. Emergency personnel must be able to work from functioning facilities in order to coordinate the response of multiple agencies. Therefore, this NCF is dependent on electrical power, as well as wireless, wire-line, and satellite communications and Global Positioning System services. Finally, emergency management is a government function involving coordination of private- and public-sector entities. It therefore requires an operating government.

Other Factors Driving Risk
Preparing for and managing emergencies requires cooperation and coordination among multiple agencies and the private sector. Therefore, strong institutions are required for the effective functioning of this NCF. In addition, because emergency management requires communication to, and the cooperation of, the public, maintaining the public’s trust in institutions is crucial. Any degradation in public trust in institutions would pose a significant risk to this NCF.

Strength of Evidence
Evidence of climate change’s effect on natural disasters is well established and has been recognized by government agencies (Anderson et al., 2017; Reidmiller et al., 2018). However, the magnitude of climate change’s effect on the increased workload of emergency management is not as well documented. Far less clear is whether climate is expected to have an effect on the subfunction of Prevent Attacks. Some have theorized a relationship between climate, crime, and terrorist attacks due to increased instability and migration, but more evidence is needed (Abbott, 2008).29

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28 Critically dependent NCF was defined as an NCF that, if disrupted or in failure, would severely disrupt a given NCF and for which a given NCF could not recover until the upstream NCF was sufficiently operational. Upstream was defined as providing a key input to a downstream NCF.

29 See also the discussion of the Enforce Law NCF for more information about the potential link between climate, crime, and instability.
Assessing Risk to the National Critical Functions as a Result of Climate Change

Provide Medical Care

Scorecard

National Risk Assessment

SUMMARY: The provision of medical care is at risk of moderate disruption from climate change by 2050 because of the threat of physical damage to health care facilities posed by flooding, sea-level rise, severe storms, and wildfire.

1 = no disruption or normal operations.
2 = minimal disruption. 3 = moderate disruption. The table includes only drivers and subfunctions with risk ratings of 2 or higher.

Provide Medical Care: “Ensure the provision of healthcare services” (CISA, 2020, p. 5).

<table>
<thead>
<tr>
<th>Current Emissions</th>
<th>High Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>2030</td>
<td>2050</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

Highest-Risk Climate Drivers

<table>
<thead>
<tr>
<th>MECHANISMS OF IMPACT</th>
<th>Drought</th>
<th>Extreme cold</th>
<th>Extreme heat</th>
<th>Flooding</th>
<th>Sea-level rise</th>
<th>Severe storm systems</th>
<th>Tropical cyclones and hurricanes</th>
<th>Wildfire</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical damage or disruption</td>
<td>2 2 2</td>
<td>2 2 2</td>
<td>2 2 2</td>
<td>2 3 3</td>
<td>2 3 3</td>
<td>2 3 3</td>
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<td>Input or resource constraint</td>
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<tr>
<td>Workforce shortage</td>
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<td>Demand change</td>
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</tbody>
</table>

The shade of gray indicates the strength of evidence for that NCF: dark gray = strong evidence.

Highest-Vulnerability Subfunctions

<table>
<thead>
<tr>
<th>CASCADING RISKS</th>
<th>Provide Operational Facilities</th>
<th>Provide Patient Care</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upstream linkages: 7</td>
<td>2 3 3</td>
<td>2 3 3</td>
</tr>
<tr>
<td>Downstream linkages: 1</td>
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</tbody>
</table>

Upstream and downstream linkages are detailed in Chapter Six.

Synopsis

Climate change poses a risk to the provision of medical care in two ways. The first involves the threat of physical damage to health care facilities posed by tropical cyclones and hurricanes, severe storm systems, and flooding and exacerbated by sea-level rise (Guenther and Balbus, 2014). Wildfire also poses a threat of physical damage and, in certain parts of the country, is the greatest climate threat to health care facilities (Adelaine et al., 2017). In addition to actual damage, the threat of harm posed by a storm, flooding, or wildfire could be enough to warrant evacuation of facilities, thus causing disruption in the provision of medical care (Office of Inspector General, 2014). Extreme weather events can also cut off utilities and prevent people from getting to work (Calma, 2021; Centers for Disease Control and Prevention and American Water Works Association, 2019; Montgomery and Romero, 2021).

A second way in which climate change poses a risk to the provision of medical care involves the potential for an increase in disease, which, in turn, causes an increase in the demand for health care. An increase in the number and severity of storms and floods can lead to injury and disease. Cold weather can also cause injuries and deaths due to traffic accidents and hypothermia. Heat can increase chronic illnesses, including heart, lung, and kidney problems, as well as issues with fetal health. Heat can also increase the number of mosquitoes and ticks and thus vector-borne illnesses, as well as water-related illnesses, such as those caused by toxic algal bloom. Extreme heat is also expected to increase ozone levels and airborne allergens. Wildfire
adversely affects air quality through smoke and increases in levels of particulate matter. Drought increases the frequency and severity of dust storms, which, in turn, can lead to an increase in the occurrence respiratory diseases. Drought is also expected to affect the availability, safety, and nutrient content of food, which, in turn, will have an impact on health. Disasters can also take a toll on people’s mental health.

For all these reasons, climate change is expected to increase demand for medical care, causing a strain on health care providers and institutions (Anderson et al., 2017; Carlton et al., 2016; Levy et al., 2016; Reidmiller et al., 2018).

The potential for increased physical damage is anticipated to pose a greater risk than the potential for an increase in demand for care. Increased demand due to increase in disease would be gradual, although increased demand due to injuries during disasters could put a strain on resources at a health care facility. However, physical damage could render an entire facility inoperable, resulting in a large loss of treatment capacity in a region.

By 2030, the Provide Medical Care function is anticipated to experience some minimal disruption from climate change but otherwise should be able to meet routine operational needs. In the current-emissions scenario, by 2050, increases in the frequency, intensity, and duration are expected for nearly all the climate drivers (all except flooding), leading to an increase in the demand for this NCF, which could result in a moderate disruption to this NCF and the inability to meet routine operational needs in some parts of the country.

In the high-emissions scenario, the frequency, intensity, and duration of flooding and extreme heat increase. This increase results in the risk of moderate disruption caused by flooding. Although the high-emissions scenario suggests a risk of moderate disruption that might be beyond that of the current-emissions scenario, we do not assess that it would rise to the level of a risk of major disruption, in which the NCF would be unable to meet needs in most of the country. Therefore, the provision of medical care in both the current- and high-emissions scenarios is assessed as having a risk of moderate disruption by 2050.

Subfunctions

Among the subfunctions, Provide Operational Facilities is most at risk of disruption because of the risk of property damage, as well as the loss of utilities necessary for facilities to function. This subfunction could face disruption in areas affected by specific climate events, rendering it unable to meet needs and therefore presenting a risk of moderate disruption. Assuming that facilities are operating, the next subfunction at risk is Provide Patient Care, which would experience an increase in demand due to an increase in disease related to the climate drivers, but, because this increase is expected to be gradual, the subfunction should be able to meet operational needs. Injuries caused by disasters created by climate drivers could strain patient care resources, however. The remaining subfunctions, which include teaching, R&D, and various business and regulatory functions, should not be affected by climate drivers, assuming that facilities are functioning and that staff can get to work.

Climate Drivers

All of the climate drivers will affect the ability to provide medical care. Chief among the concerns will be drivers with the potential to threaten or cause physical damage to facilities, including flooding, sea-level rise, severe storm systems, tropical cyclones and hurricanes, and wildfire. When such events occur, they can disrupt the NCF in the affected parts of the country. These climate drivers, along with drought, extreme cold, and extreme heat, will also increase the demand for medical care, producing a strain on the system.
Cascading Risk

Provide Medical Care is critically dependent on the following NCFs:...

- Distribute Electricity
- Supply Water
- Manage Wastewater
- Transport Cargo and Passengers by Road
- Maintain Supply Chains
- Maintain Access to Medical Records
- Support Community Health.

Health care facilities require utilities to function. Electricity is needed to operate medical equipment and to maintain access to medical records, as well as to operate the buildings themselves. Although hospitals have backup generators, those generators cannot function indefinitely and at minimum require resupply of fuel. Health care facilities also require clean water for sanitation, cooking, and medical procedures; wastewater must be managed as well.

In addition to functioning facilities, the provision of medical care requires trained personnel who can get to their jobs because most medical care requires an in-person component. This requires the ability to transport cargo and passengers by road. The transportation function, along with the maintenance of supply chains, is also needed so that health care facilities can be resupplied with medications, medical supplies, personal protective equipment, and other items. Maintaining access to medical records is a dependency because tracking a patient’s medical history and treatments given is so important for ensuring patient safety. Hospitals can find short-term work-arounds when their systems are down, and they regularly treat patients without having a full medical history. Finally, the support of community health, as conducted by public health departments, is crucial to the provision of medical care, through disease surveillance, laboratory testing, coordination across health care agencies, and facilitation of medical supply chains.

Other Factors Driving Risk

A health care facility, such as a hospital, cannot operate without an operational facility, including electricity, water, sewage, and heat. Buildings that are not hardened against storms and flooding and utility infrastructure that is not robust will add to the risk of facilities being unable to function. In addition, the provision of medical care requires that trained workers be able to get to their jobs. Therefore, infrastructure is a significant factor driving risk. Indeed, the poor state of hospital infrastructure has been cited as contributing to the challenges faced in providing medical care during hurricanes (Office of Inspector General, 2014).

Strength of Evidence

Experience from recent events has shown the vulnerability of health care facilities to extreme weather (Guenther and Balbus, 2014). Further, ample research shows climate change’s effect on people’s health (Anderson et al., 2017; Reidermiller et al., 2018). The research is less clear on the magnitude of the health effects, the number of people affected, and the size of the burden imposed on the health care system. Also unclear is...
how much of an effect climate change would have on some of the other subfunctions of medical care, such as teaching, R&D, and business and regulatory functions.
Enforce Law

Scorecard

National Risk Assessment

SUMMARY: Enforce Law is at risk of moderate disruption by 2050 because expected increases in demand for law enforcement and public safety services because of flooding, sea-level rise, severe storm systems, heat, and wildfire.

1 = no disruption or normal operations.
2 = minimal disruption. 3 = moderate disruption. The table includes only drivers and subfunctions with risk ratings of 2 or higher.

Enforce Law: “Operate Federal, State, local, tribal, territorial, and private sector assets, networks, and systems that contribute to enforcing laws, conducting criminal investigations, collecting evidence, apprehending suspects, operating the judicial system, and ensuring custody and rehabilitation of offenders” (CISA, 2020, p. 4).

Current Emissions  | High Emissions
---|---|---|---|---|---|---
2030 | 2050 | 2100 | 2030 | 2050 | 2100
---|---|---|---|---|---
2 | 3 | 3 | 2 | 3 | 3

Highest-Risk Climate Drivers

<table>
<thead>
<tr>
<th>MECHANISMS OF IMPACT</th>
<th>Extreme heat</th>
<th>Flooding</th>
<th>Sea-level rise</th>
<th>Severe storm systems</th>
<th>Tropical cyclones and hurricanes</th>
<th>Wildfire</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical damage or disruption</td>
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<td>Demand change</td>
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<td>3</td>
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</tbody>
</table>

The shade of gray indicates the strength of evidence for that NCF: dark gray = strong evidence and medium gray = moderate evidence. We also found moderate evidence for drought and weak evidence for extreme cold.

Highest-Vulnerability Subfunctions

CASCADING RISKS

Upstream linkages: 4
Downstream linkages: 0
Upstream and downstream linkages are detailed in Chapter Six.

Contribute to Public Safety
Conduct Investigations
Charge Alleged Suspects
Prosecute Crimes
Operate Judicial System
Operate Corrections System
Operate Detention Systems

Synopsis

Enforce Law is vulnerable to climate change in that increases in natural hazards will increase the need for law enforcement and, more broadly, for law enforcement support to other public safety agencies. Increases in demand come at a time when the law enforcement workforce is already under considerable strain. There is very limited research on the relationship between crime and climate change. However, the available research projects significant increases in demand for law enforcement due to projected increases in violent crime (e.g., murder, rape, assault) and property crime (e.g., burglary, larceny) attributed to climate change and its social and environmental impacts (Ranson, 2014). Conflict and social instability are also projected to increase (Burke, Hsiang, and Miguel, 2015), as are strains affecting people who are theorized to cause crime (Agnew, 1992) and opportunities for crime (Agnew, 2012). There is also some evidence of temperature having a curvilinear effect on violence and crime (Rotton and Cohn, 2000), in which incidents increase to a certain point before declining, and of weather’s effects on crime that further support these assumptions (Brunsdon et al., 2009). Past incidents involving natural disasters have demonstrated vulnerabilities for this NCF, including those following Hurricane Katrina and other climate events (Linning and Silver, 2021; Prelog, 2016). For
example, New Orleans Police Department and other agencies faced several issues during Hurricane Katrina, such as the loss of material (including weapons), lack of supplies, and failures in command and control. Wildfire has also increased the need for law enforcement agencies to assist with search and rescue and evacuation, causing threats to personnel safety and the need to divert staff to fulfill these duties (Estill, 2018).

Many law enforcement actions flow through the criminal justice system, so strain in one part of the system is reflected in other parts of the system. For example, an increase in violent crime associated with climate change would likely increase demand for investigative time; increased numbers of arrests are likely to increase the demand for prosecutions; and increased numbers of prosecutions are likely to lead to additional demand for correctional services.31

Subfunctions
The justice system is interconnected, creating some risk of disruption across all subfunctions. However, the Contribute to Public Safety subfunction is expected to experience the most stress as a result of climate change. Operate Detention Systems and Operate Corrections System are also at risk because of demand, location of facilities, and infrastructure concerns. Infrastructure concerns include lack of ventilation and air-conditioning, which affects the populations housed and facility employees (A. Jones, 2019).

Climate Drivers
Each of the eight climate drivers affects Enforce Law. Flooding and hurricanes are likely to place the most-significant strain on this NCF, according to historical precedent. This includes the need to evacuate cities, resulting risks for looting and crime, and closures of courts and correctional facilities. Extreme heat also poses a health risk to the workforce for this NCF and to the incarcerated. Climate drivers that cause mass migration of people into and within the United States also affect risk to this NCF.

Cascading Risk
Enforce Law is critically dependent on the following NCFs:32

- Provide Public Safety
- Operate Government
- Prepare for and Manage Emergencies
- Preserve Constitutional Rights.

Enforce Law has a significant overlap in workforce and mission with Provide Public Safety; a failure in one would cause the failure of the other. For this NCF to operate effectively, it must also be supported by a capable and fully functioning government that can support efforts prior to and during emergencies.

Other Factors Driving Risk
Enforce Law is dependent on personnel throughout the criminal justice process: in policing or other law enforcement roles, in the court systems, and in corrections. Historically, strains on the availability of an ade-

31 An example of the criminal justice system flow is at Bureau of Justice Statistics, 1997.

32 Critically dependent NCF was defined as an NCF that, if disrupted or in failure, would severely disrupt a given NCF and for which a given NCF could not recover until the upstream NCF was sufficiently operational. Upstream was defined as providing a key input to a downstream NCF.
quate law enforcement workforce contribute to risk, including increasing difficulties attracting and retaining workers. Funding for this NCF is highly dependent on taxes at the local, state, and federal levels; downward shifts in funding drive risk upward. The credibility and legitimacy of law enforcement also depend on public trust in the institutions. Degradation in the functioning of institutions, real or perceived, would be a significant factor driving risk. Additionally, the location of law enforcement facilities and growth in communities in “high-risk” areas for specific climate threats present an additional layer of risk, especially when no mitigating strategies are employed.

**Strength of Evidence**

There is moderate evidence of climate change’s impact on this NCF. Although there is a lack of direct research examining climate change’s effects and crime and disorder, research has examined the relationship between weather and crime (which has cascading effects through the criminal justice system), the seasonality of crime (with the summer typically witnessing more violent crime) (Lauritsen and White, 2014), and law enforcement’s relationships and demands as they relate to extreme weather events (Birkland and Schneider, 2007; Goin, Rudolph, and Ahern, 2017).
Provide Housing

Scorecard

National Risk Assessment

SUMMARY: Provide Housing is at risk of moderate disruption from climate change by 2100 primarily because of the effects that flooding, sea-level rise, and extreme heat are anticipated to have on the Provide Permanent Housing and Provide Long-Term Housing subfunctions.

Provide Housing: “Construct and/or provide safe and secure permanent or temporary shelter for people (includes physical construction and emergency sheltering)” (CISA, 2020, p. 6).

1 = no disruption or normal operations.
2 = minimal disruption. 3 = moderate disruption. The table includes only drivers and subfunctions with risk ratings of 2 or higher.

Highest-Risk Climate Drivers

<table>
<thead>
<tr>
<th>MECHANISMS OF IMPACT</th>
<th>Current Emissions</th>
<th>High Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2030</td>
<td>2050</td>
</tr>
<tr>
<td>Drought</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Extreme cold</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Extreme heat</td>
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<td>2</td>
</tr>
<tr>
<td>Flooding</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Sea-level rise</td>
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<td>2</td>
</tr>
<tr>
<td>Severe storm systems</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Tropical cyclones and hurricanes</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Wildfire</td>
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</table>

Highest-Vulnerability Subfunctions

<table>
<thead>
<tr>
<th>CASCADING RISKS</th>
<th>Current Emissions</th>
<th>High Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<tr>
<td>Provide Permanent Housing</td>
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</tr>
<tr>
<td>Provide Long-Term Housing</td>
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</table>

Synopsis

Provide Housing is at risk of minimal to moderate disruption due to climate change, with flooding, sea-level rise, and extreme heat leading to the greatest points of vulnerability within the function. Risks, other than extreme cold, increase steadily over time, with the high-emissions scenario reaching levels of moderate disruption by 2050. Housing is a substantial area of private investment, as well as direct and indirect government subsidy (for example, Section 8 vouchers and the mortgage-interest deduction), that affects everyone in the United States, often in unique ways depending on geographic and socioeconomic circumstance. For homeowners, housing is often the largest asset and source of net worth; for both homeowners and renters, it is often one of the largest costs and components of monthly budgets. Assets in areas at risk from sea-level rise have already begun collectively to alter the mortgage, leasing, financing, and insurance markets—with growing potential for systemic impact across other critical functions (Keenan and Bradt, 2020). Sea-level rise and other climate change drivers could cause direct damage to housing stock, as well as indirect consequences to financial mechanisms necessary for its production and maintenance. For example, increasing flooding or a more regulated wildland–urban interface could decrease the availability of greenfield and existing land resources. As populations move in response to economic opportunities, policy decisions, and climate change, demand for housing might be unevenly distributed across geographies, with a large number of vacant or uninhabitable units in one location at the same time as regional shortages for developable land accessible to 

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necessities, opportunities, and amenities; available skilled and unskilled labor; and appropriate materials for relevant building codes resulting in unaffordable prices in another location.

The most direct consequence of climate change will be a reduction in NCF performance—diminished standards of living, displacement, or homelessness. The disruption of housing and potentially associated displacement or wealth erosion have direct economic, health, safety, and well-being effects at the individual, household, and community levels. In aggregate, this could result in substantial personal, municipal, and regional economic losses despite mitigation strategies, such as insurance. For example, by 2100, a predicted 2.4 million residential properties, valued at more than $1 trillion, will be at risk of chronic flooding (Dahl et al., 2018).

Subfunctions

The Provide Permanent Housing subfunction is at risk of moderate disruption by 2100 and is already showing consequences from flooding, especially in coastal areas. For example, the Federal Home Loan Mortgage Corporation (Freddie Mac) and other researchers have estimated that, between 2005 and 2017, $16 billion in home value was lost along the East and Gulf Coasts. As a result, in some places, banks have required an increasing share of homeowner equity or have been derisking their loan portfolios by disproportionately shifting debts in floodplains to government-backed mortgage enterprises (Cash et al., 2020; Climate Central, 2019; Colman, 2020; Environmental and Energy Study Institute, 2021; Keenan and Bradt, 2020).

Similarly, the Provide Long-Term Housing subfunction is at risk of moderate disruption by 2100 and is already showing consequences from two climate drivers: hurricanes and wildfire. For these two drivers, traditional approaches—mobile and manufactured homes and rented hotel rooms and apartments—have recently shown to be increasingly inadequate in quality and quantity, especially given the risk of becoming semipermanent housing for the displaced. In addition, some of these temporary housing options are inaccessible for the relative level of public assistance. For example, despite three-quarters of damaged properties being available for rent after Hurricane Michael (which were typically used either seasonally or for income), one in ten residents were still experiencing homelessness because the units were unaffordable or duration of the lease terms untenable for many people. With Hurricanes Harvey, Irma, and Maria causing multiple disasters along the Gulf Coast and in the southeast, long-term recovery times increased, in part causing the homeless population in greater Houston to grow 15 percent (FEMA, 2019; Fung, 2019; Ortiz et al., 2019).

Climate Drivers

Flooding is assessed to create a risk of moderate disruption of this function. Despite over five decades of federal intervention in and guidelines for floodplain development, prior investments in housing, subsequent rapid urban growth, and growing hazard exposure result in there still being substantial risk. For example, 400,000 federally subsidized homes (over 20 percent of all such homes) are in a designated Special Flood Hazard Area, or floodplain. Some of these homes are clustered in regions that could yield substantial damage depending on the event (e.g., affordable and public housing developments in New York City after Hurricane Sandy) (Buchanan et al., 2020). The estimated number of market-rate homes (typically, those unsubsidized beyond the mortgage interest deduction or other local policies) at risk varies depending on the source of analysis, with recent work suggesting up to 15 million homes threatened, 70-percent higher than official FEMA estimates (Ivanova and Layne, 2020).

For sea-level rise as a climate driver, approximately 150,000 affordable and market-rate homes (1 percent of 140 million total residences—affordable and market—in 2020) will be subject to disruptive tidal flooding every two months by 2030, the percentage of which is expected to double by 2050. In addition, by 2050, an additional half a million homes, valued at $241 billion, are expected to be newly vulnerable to tidal nuisance
flooding at least once per year because of sea-level rise (equivalent to 7 percent of the value of affordable and market homes worth $33.6 trillion) (Aurand et al., 2021; Buchanan et al., 2020; Dahl et al., 2018; Flavelle, 2021; Gerrity, 2020; U.S. Census Bureau, 2021).

Extreme heat is also associated with moderate disruption of this function, especially because public and subsidized housing that is required by law to provide heat has neither federal nor, usually, state requirements for air-conditioning (and, in fact, property owners may explicitly prohibit window air conditioners because of concerns about heightened energy usage or fall hazards). In addition, although homeowners in need can access assistance for heat through programs, such as Low Income Home Energy Assistance Program, similar national-scale cost-share programs do not exist for cooling (Khimm and Eaton, 2021). Without mechanical ventilation, many housing units would be uninhabitable, and this climate driver can increase exacerbate indoor air quality issues and increase utility costs that disproportionately affect disadvantaged communities because of their built environments. As a result, local communities, such as Phoenix, Arizona, and Dallas, Texas, have passed ordinances requiring landlords to provide air-conditioning equipment, while some states, such as Oregon and Connecticut, have implemented work-arounds using Medicaid to purchase equipment for vulnerable residents (Green and Healthy Homes Initiative, 2020). Access to amenities, such as air-conditioning, in heat waves is unevenly distributed, exposing community-based vulnerabilities (e.g., in Chicago in 1995 and California's Central Valley in 2006) or regional-based power grid brownouts, rolling blackouts, and catastrophic failure (Cash et al., 2020; Vardoulakis et al., 2015). For example, 71 percent of subsidized housing stock in Fresno County, California, is in census tracts that are in the top quartiles for heat sensitivity, have the most days per year with temperatures in the 98th percentile of historical heat averages in the 2040s, and contain 20 percent of all of California's housing (Gabbe and Pierce, 2020).

Consequences from hurricanes and severe storms are largely confined to certain regions, resulting in minimal national-scale disruption. Damage pathways for hurricanes are similar to those for flooding and sea-level rise. More generally, extreme weather events and secondary effects, such as stormwater flooding, erosion, and mudslides, can destroy housing stock, sap personal savings, and diminish both homeowner and renter ability to pay, destabilizing financial mechanisms and further delaying recovery processes (Aurand et al., 2021; Cash et al., 2020; Flavelle, 2019b; Flavelle, 2021; Ouazad and Kahn, 2021; U.S. Department of Housing and Urban Development [HUD], 2014).

Housing in some regions is increasingly built in drought- and wildfire-prone areas, sometimes introducing a positive feedback mechanism that increases water demands, introduces urban heat-island concerns alongside ignition sources, and disrupts natural ecosystem patterns, thereby increasing the intensity of the climate driver (Aurand et al., 2021; Cash et al., 2020). Wildfire risks are unevenly distributed—for example, more than a quarter of Montana's and Idaho's housing stock is in high-risk fire zones, whereas these risks are considered minimal or manageable, even in such states as New Jersey or in the southeast that are occasionally prone to marsh or forest conflagrations. Wildfire is already a growing, variable threat, with an immense $71 billion to $341 billion in annual damage. Shift in land-use trends that increase exposure, more-valuable homes that increase losses, and land degradation increasing the probability of a catastrophic event all point toward growing impacts (Aurand et al., 2021; Cash et al., 2020; Flavelle, 2019a). For example, climate change has been cited as part of the reason for the December 30, 2021, wildfires in Boulder County, Colorado, where a firestorm destroyed nearly 1,000 homes because of record rains feeding grass growth and warm temperatures keeping fuel drier longer—expanding what many consider to be typical conditions of the wildland–urban interface (Brasch, 2022). On the other hand, updated building codes in the Paradise, California, Camp Fire showed themselves to greatly limit damage at the wildland–urban interface, where 51 percent of 350 homes built after 2008 survived, whereas only 18 percent of 12,100 homes built prior to 2008 were undamaged. Behaviors could continue to shift as insurers in high-risk states, such as California,
Washington, Montana, and Colorado, continue to increasingly not renew policies (Aurand et al., 2021; Cash et al., 2020; Flavelle, 2019a).

In contrast with these climate drivers, extreme cold will generally trend in the opposite direction, likely producing less serious consequences for this function in the future. At present, having inadequate heating capacity or dependence on one form of delivery, especially electricity, can render housing vulnerable to hypothermic conditions, freezing pipes, or secondary forms of hazards, such as carbon monoxide poisoning from inadequate generator ventilation or improper use of heating appliances, such as stoves. One exception is region 10, where the thawing of permafrost could jeopardize house foundations or entire communities through erosion. In this regard, HUD’s Indian Housing Block Grant Program and other tribal programs are particularly vulnerable (GAO, 2020b; HUD, 2014).

**Cascading Risk**

Provide Housing is critically dependent on the following NCFs:\(^{33}\)

- Distribute Electricity
- Prepare for and Manage Emergencies
- Provide Capital Markets and Investment Activities
- Provide Identity Management and Associated Trust Support Services
- Provide Insurance Services
- Provide Payment, Clearing, and Settlement Services.

Providing permanent and affordable housing requires reliable access to capital markets for its construction, as well as payment processing for rent and mortgage checks. The transfer of assets or enrollment in short- or long-term shelter programs requires a chain of title or identity verification. The short- and long-term shelter system requires emergency preparedness plans, and returning people to their permanent housing often requires insurance adjustment. Without electricity, extreme heat and cold cannot be mitigated and can lead to potentially catastrophic health consequences (Aurand et al., 2021; Cash et al., 2020; Flavelle, 2019b; Flavelle, 2021).

**Other Factors Driving Risk**

The Provide Permanent Housing subfunction is tightly connected with population and economic growth (or decline). The affordability of permanent housing is a function not only of supply and demand but also of administrative and legislative institutional priorities. In turn, affordability of permanent housing and the availability of short- and long-term housing are key equity concerns (Aurand et al., 2021; Cash et al., 2020; Flavelle, 2019b; Flavelle, 2021).

**Strength of Evidence**

The Provide Permanent Housing subfunction has a strong body of evidence linked to the consequences of climate change, especially for flooding, sea-level rise, hurricanes, and extreme heat. The literature consists of many organization-sponsored and peer-reviewed reports—some after disasters but also many as proactive surveys—as well as pieces in the popular media. Private capital markets have also begun to take a keen

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\(^{33}\) Critically dependent NCF was defined as an NCF that, if disrupted or in failure, would severely disrupt a given NCF and for which a given NCF could not recover until the upstream NCF was sufficiently operational. Upstream was defined as providing a key input to a downstream NCF.
interest in the housing sector’s exposure to climate change, and the resulting research will generate new data sets and analyses. There is a moderate and growing body of evidence on the performance of the Provide Long-Term Housing subfunction, which largely demonstrates the inadequacy of traditional approaches, such as mobile and manufactured homes and rented hotel rooms and apartments. At this point, short- and long-term housing studies are largely linked to disasters, but this is an active area of policy, planning, and design research.
Assessing Risk to the National Critical Functions as a Result of Climate Change

Produce and Provide Agricultural Products and Services

Scorecard

National Risk Assessment

SUMMARY: Produce and Provide Agricultural Products and Services is at risk of moderate disruption from climate change by 2100 because of the effects that climate drivers are anticipated to have on vegetation and agricultural commodities. 1 = no disruption or normal operations. 2 = minimal disruption. 3 = moderate disruption. The table includes only drivers and subfunctions with risk ratings of 2 or higher.

Current Emissions  High Emissions

<table>
<thead>
<tr>
<th>Year</th>
<th>2030</th>
<th>2050</th>
<th>2100</th>
<th>2030</th>
<th>2050</th>
<th>2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drought</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Extreme cold</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Extreme heat</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Flooding</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Sea-level rise</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Severe storm systems</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Tropical cyclones and hurricanes</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Wildfire</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

Highest-Risk Climate Drivers

<table>
<thead>
<tr>
<th>Mechanisms of Impact</th>
<th>2030</th>
<th>2050</th>
<th>2100</th>
<th>2030</th>
<th>2050</th>
<th>2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical damage or disruption</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Input or resource constraint</td>
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<tr>
<td>Workforce shortage</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Demand change</td>
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</tr>
</tbody>
</table>

The shade of gray indicates the strength of evidence for that NCF: dark gray = strong evidence and medium gray = moderate evidence.

Highest-Vulnerability Subfunctions

<table>
<thead>
<tr>
<th>CASCADING RISKS</th>
<th>2030</th>
<th>2050</th>
<th>2100</th>
<th>2030</th>
<th>2050</th>
<th>2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purchase Materials</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Store Agricultural Materials</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Maintain Infrastructure</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Regulate Plant and Animal Management</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Manage Animals</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Manage Vegetation</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Practice Sustainability</td>
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<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Produce Raw Agricultural Commodities</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

Synopsis

The Produce and Provide Agricultural Products and Services NCF is at risk of minimal disruption by 2050 and moderate disruption by 2100 because of climate change. Disruptions to historical weather patterns, temperature, and climate, in addition to the effects of extreme events, make food production and agricultural management more difficult for producers and can lead to variable and often unpredictable crop yields (S. L. Wang et al., 2018). As a result, production of agricultural commodities have already been disrupted by drought (Woloszyn et al., 2021), extreme temperatures (Newburger, 2019), flooding (Daniels, 2019), and severe storm systems (Polansek, 2020; Wilde, 2021), which will only continue to increase in frequency and intensity. Currently, commodity markets have been able to manage disruptions and low crop harvests, buttressed by stockpiles and the relative infrequency with which these drivers affect growing seasons. Average yields of many commodity crops (for example, corn, soybean, wheat, rice, sorghum, cotton, oats, and silage) decline once the
growing environment exceeds certain maximum temperature thresholds (in conjunction with rising atmospheric carbon dioxide levels), so long-term temperature increases, which can result in increased incidence of extreme heat events, are expected to reduce future yields under both irrigated and dryland production conditions (Marshall et al., 2015). However, even with efforts to reduce GHG emissions and introduce more-sustainable farming practices designed to reduce risk, by 2100, instability to agriculture will increase, as will the ability to reliably produce sufficient yields. Physical damage and disruptions to the supply of water for irrigation, as well as increases in soil erosion from wind or runoff, will just exacerbate those effects (Marshall et al., 2015). Moreover, extreme temperatures (both heat and cold) and severe storm systems in particular increase the risk to the agricultural workforce (De Lima et al., 2021; Pal, Patel, and Banik, 2021), leading to unhealthy and dangerous working conditions. The risk of wildfire will continue to increase in frequency and intensity by 2100 (M. Jones et al., 2020), affecting agricultural infrastructure, especially land, and the labor force (Assembly Committee on Agriculture, 2020).

Subfunctions
Almost all of the subfunctions will experience minimal disruption by 2050, with Manage Vegetation and Produce Raw Agricultural Commodities at the highest risk of disruption (Walthall et al., 2013). The variability and unpredictability of climate and temperature fluctuation place these subfunctions at the highest risk, as has been shown historically and continues to manifest (Parker et al., 2020). By 2050, Manage Animals will become increasingly risky because of flooding, severe storms, and extreme temperatures, especially in regions 3, 4, and 7 (Food and Agriculture Organization of the United Nations, 2016; Rojas-Downing et al., 2017). Climate change will also affect Maintain Infrastructure and Store Agricultural Materials because these infrastructural elements were designed for stabler and less extreme climates and fluctuations (Olson et al., 2018).

Climate Drivers
Because agriculture is a primarily outdoor activity, all of the climate drivers will eventually affect the sector by 2100, albeit at varying rates. Tropical cyclones and hurricanes and other severe storm systems exacerbate drought and flooding cycles (Kunkel et al., 2013), and this trend will only continue to worsen. Extreme temperatures contribute to the shifting of growing seasons (U.S. Department of Agriculture [USDA], undated), and the changes to favorable growing climates will further reduce crop productivity and resilience (Eck et al., 2020; Parker et al., 2020). By 2100, these climate changes will probably also degrade the physical infrastructure used to store and move products, despite efforts to implement more-sustainable farming practices (Olson et al., 2018).

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34 However, there is limited evidence of more hurricanes making landfall on the U.S. East Coast over time. Nonetheless, additional research highlights that tropical cyclones and hurricanes affect wider areas when they do make landfall. So, although the landfall frequency on the U.S. Eastern Seaboard might not change, the damage caused when these storms do make landfall might be more expansive or occur in regions where they historically did not land. See Knutson, 2021; Studholme et al., 2022; and Emanuel, 2021.
Cascading Risk

Produce and Provide Agricultural Products and Services is critically dependent on the following NCFs:\textsuperscript{35}

- Distribute Electricity
- Transport Cargo and Passengers by Road
- Produce and Provide Human and Animal Food Products and Services
- Maintain Supply Chains.

Agricultural producers rely on electricity to operate efficiently, in particular to manage animals, store agricultural materials, and maintain infrastructure. Transportation and supply chain infrastructure remain necessary to ensure the movement of food products off farms to processing facilities and markets for the food system to operate efficiently and properly.

Other Factors Driving Risk

In August 2021, USDA published its *Action Plan for Climate Adaptation and Resilience* (USDA, 2021), as required by EO 14008, “Tackling the Climate Crisis at Home and Abroad.” USDA recognizes the vulnerability to the agricultural sector from “shocks due to extreme climate events,” specifically naming drought, flooding, severe storm systems, tropical cyclones and hurricanes, and wildfire (USDA, 2021, pp. 10–11). It further identified activities to build community resilience and reduce the risk from these events, which include soil, forest, and land management and planning (USDA, 2021, pp. 7, 11–12, 15); investing in water management and irrigation systems (USDA, 2021, p. 8); and improving access to climate data and tools to plan for and manage the effects of the extreme climate drivers (USDA, 2021, pp. 5, 20–22). Securing water sources—in particular, those that support irrigation from surface water and groundwater—will become crucial to ensure the survival of the agriculture sector (Marshall et al., 2015; Rehkamp, Canning, and Birney, 2021). Processes and policies to enforce water rights and manage the use or limit the depletion of these water sources are necessary for the survival of the agricultural sector. EPA’s climate adaptation plan additionally notes the sector’s vulnerability to increased competition for water supplies as a result of drought, extreme heat, and changes in precipitation (EPA, 2021g, p. 5).

Strength of Evidence

There is an extensive literature on climate change effects on agricultural and livestock systems, including assessment reports written by USDA and USGCRP and decades of peer-reviewed research. In addition, climate variability’s consequences for different types of agricultural and livestock systems have been well documented, including multiyear drought events and extremes of heat, flooding, and hurricanes that destroy crops and kill livestock. However, there appears to be a gap in the literature on the effect that extreme cold temperatures have on agricultural production.

\textsuperscript{35} Critically dependent NCF was defined as an NCF that, if disrupted or in failure, would severely disrupt a given NCF and for which a given NCF could not recover until the upstream NCF was sufficiently operational. Upstream was defined as providing a key input to a downstream NCF.
Generate Electricity

Scorecard

National Risk Assessment

**SUMMARY:** Generate Electricity is at risk of moderate disruption from climate change by 2100 primarily because of the effects that drought, extreme heat, and sea-level rise are anticipated to have on power plants.

1 = no disruption or normal operations.
2 = minimal disruption. 3 = moderate disruption. The table includes only drivers and subfunctions with risk ratings of 2 or higher.

<table>
<thead>
<tr>
<th>Highest-Risk Climate Drivers</th>
<th>Current Emissions</th>
<th>High Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2030</td>
<td>2050</td>
</tr>
<tr>
<td>Drought</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Extreme cold</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Extreme heat</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Flooding</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Sea-level rise</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Severe storm systems</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Tropical cyclones and hurricanes</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Wildfire</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Highest-Vulnerability Subfunctions

<table>
<thead>
<tr>
<th>CASCADING RISKS</th>
<th>Obtain Resources</th>
<th>Enable Infrastructure</th>
<th>Operate Infrastructure</th>
<th>Secure Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upstream linkages: 6</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Downstream linkages: 3</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Upstream and downstream linkages are detailed in Chapter Six.</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Synopsis

Electricity generation is vulnerable to all assessed climate drivers because of its geographic breadth of critical infrastructure across the United States in many climate-vulnerable areas, reliance on water supply, and legacy design and maintenance standards that are unequipped for more-frequent and -intense climate disasters. For example, flooding events from heavy precipitation events on the East and West Coasts and regions with dense riverine systems, sea-level rise on the East Coast, and hurricane events along the Gulf Coast are already having unprecedented and outsized impacts on electricity generation infrastructure (Dullo et al., 2021; Gangrade et al., 2019; Qiang, 2019). Sustained drought conditions threaten reliable sources of water that are used for cooling equipment and generating power in fossil fuel–burning plants. Although these climate change–driven disruptions will have cascading impacts on NCFs and sectors that rely on power on a regional basis, the interconnected redundancies that exist throughout the U.S. power grid generally increase the national system’s resilience to national cascading failures of the Generate Electricity NCF (Abi-Samra, 2017). However, Texas, Hawaii, and Puerto Rico are notable exceptions because of their isolation or interconnection constraints with the national power grid. In addition, the increased intensity and frequency of these events are likely to stress the maintenance and response operations put in place to mitigate vulnerabilities and longer, sustained power outages, causing moderate disruption to the NCF nationally. The interconnected
nature of assets this NCF encompasses and the upstream and downstream NCFs together pose significant cascading risk across the system.

Subfunctions
All but one Generate Electricity subfunction, Comply with Regulations, face some risk of disruption due to climate change. Extreme weather that degrades or destroys power plants and supporting infrastructure can lead to significant regional interruptions to the operation of power generation, resulting in the inability to provide power access to all customers (Nateghi, 2018) and disruption of power generation security (DOE, 2015). In the health and security sectors, power outages can have cascading implications (Van Eeten et al., 2011). Power outages often lead to regional economic loss, although prolonged outages can also propagate economic losses nationally or globally (Shuai et al., 2018; Y. Zhang and Lam, 2016). For the Generate Electricity subfunctions Obtain Resources, Enable Infrastructure, Operate Infrastructure, and Secure Operations, climate change hazards could frequently disrupt the ability to provide uninterrupted and reliable power, causing moderate disruption to the NCF nationally.

Climate Drivers
All climate drivers pose risks to electricity generation at regional scales (Wuebbles et al., 2017). Electricity generation infrastructure is susceptible to climate drivers that increase the frequency of drought (Zohrabian and Sanders, 2018) and flooding (Boggess, Becker, and Mitchell, 2014) and increase extreme temperature volatility (Hassan Daher et al., 2018; Loew et al., 2020). According to historical impacts and projected exposure of critical power generation assets, hurricanes, sea-level rise, and extreme heat are projected to pose the largest risk to power distribution by 2100. Hurricanes and flooding cause major disruptions regionally on an acute temporal basis (Doherty and Dewey, 1925; Nateghi, 2018), but these effects rarely, if ever, affect the NCF on a national scale. Extreme heat and sea-level rise pose more chronic risk to power generation infrastructure (Burillo et al., 2019; Griggs and Patsch, 2019; Wuebbles et al., 2017), but the effects are largely limited to the infrastructure within each region. Most U.S. power plants, regardless of fuel source (for example, coal, natural gas, nuclear, concentrated solar, and geothermal), rely on a steady supply of water for cooling (because most thermal power plants use once-through or recirculating water cooling), and operations are projected to be threatened when water availability decreases or water temperatures increase. This is difficult to mitigate. Preemptively decreasing a plant’s output is a protection method, but drought effects exacerbate the magnitude and frequency of these deratings. Electricity generation infrastructure could cause cascades to other NCFs within a region, but cascading risk between regions caused by climate drivers is much rarer because of the footprint of climate disasters and the redundancies present in distribution infrastructure systems across regions.

36 We added a subfunction to the table only if it received a risk rating greater than minimal disruption between 2030 and 2100. Operate in Market received a risk rating of minimal disruption for the entirety of the time frame considered.
Cascading Risk

Generate Electricity is critically dependent on the following NCFs:\footnote{Critically dependent NCF was defined as an NCF that, if disrupted or in failure, would severely disrupt a given NCF and for which a given NCF could not recover until the upstream NCF was sufficiently operational. Upstream was defined as providing a key input to a downstream NCF.}

- Distribute Electricity
- Transmit Electricity
- Exploration and Extraction of Fuels
- Store Fuel and Maintain Reserves
- Fuel Refining and Processing Fuels
- Supply Water.

In the NCF framework, electricity generation is one part of three interconnected NCFs that compose bulk power delivery. If Transmit Electricity, Generate Electricity, or Distribute Electricity should fail, all three fail (Vartanian et al., 2018). Additionally, some NCFs—Exploration and Extraction of Fuels, Store Fuel and Maintain Reserves, Supply Water, and Fuel Refining and Processing Fuels—maintain the development of fuel resources that are critical inputs to the generation of electricity. Should any of the fuel NCFs fail, it would likely be exceptionally difficult to maintain continuous power delivery through electricity generation (Murphy et al., 2020). The U.S. power plants with the greatest capacity rely on a continuous supply of fossil fuels to produce power. In addition, supply chain issues can also affect the on-time delivery of fuels and components meant to support and expand power production across the country.

Other Factors Driving Risk

Generate Electricity infrastructure that has not received adequate maintenance or is being used beyond its designed life poses significant risk to the continued operation of the uninterrupted-power system (Chen, Wang, and Ton, 2017). Furthermore, electricity utilities’ responses to generation system restoration procedures are typically based on predefined priorities, and the absence of situational awareness following a hazard severely slows the restoration process (Afsharinejad, Ji, and Wilcox, 2020; Zamuda, Wall, et al., 2019). Maintenance and disaster response delays can increase the time to recover power distribution systems and threaten the short- and long-term viability of uninterrupted power delivery. Dated codes and standards also pose a chronic threat to legacy systems, as well as to the future design and construction of power generation systems (Pudyastuti and Nugraha, 2018). Design standards that do not consider the increased frequency and intensity of climate disasters increase the risk of perpetuated power outages in critical electricity generation infrastructure.

Strength of Evidence

The body of existing literature and studies of climate risk to electricity generation infrastructure is expansive and well studied. However, because of the variance in power plant types, some gaps are not as well studied for certain generation technologies and climate change vulnerabilities. Some studies have detailed risks to the NCF-related infrastructure by U.S. region (Glick and Christiansen, 2019; Wakiyama and Zusman, 2021), and complementary studies have analyzed climate risk to supporting infrastructure and components from other countries that can be used to assess and substantiate risk ratings (Rübbelke and Vögele, 2010; Tobin et al., 2018; Turner et al., 2017; Zamuda, Mignone, et al., 2013). Because most modern systems rely on unin-
terrupted power supply (FEMA, 2007), there is a general interest in studying how to maintain continuous power through all types and scales of climate disasters (Boggess, Becker, and Mitchell, 2014; Huang, Swain, and Hall, 2020; Saint, 2009).
Maintain Supply Chains

Scorecard

National Risk Assessment

SUMMARY: Maintain Supply Chains is at risk of moderate disruption from climate change by 2100 under current emissions and by 2050 under high emissions primarily because of the effects that flooding, sea-level rise, and hurricanes are anticipated to have on supply chain operations, management, and logistics and because of anticipated damage to key transportation infrastructure.

1 = no disruption or normal operations. 2 = minimal disruption. 3 = moderate disruption. The table includes only drivers and subfunctions with risk ratings of 2 or higher.

Maintain Supply Chains: “Manage and sustain the networks of assets, systems, and relationships that enable the movement of goods and services from producers to consumers” (CISA, 2020, p. 3).

<table>
<thead>
<tr>
<th>Current Emissions</th>
<th>High Emissions</th>
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<tbody>
<tr>
<td>2030</td>
<td>2050</td>
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Highest-Risk Climate Drivers

<table>
<thead>
<tr>
<th>MECHANISMS OF IMPACT</th>
<th>Drought</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>□ Physical damage or disruption</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3</td>
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<tr>
<td>□ Input or resource constraint</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>□ Workforce shortage</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>□ Demand change</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

The shade of gray indicates the strength of evidence for that NCF: dark gray = strong evidence and light gray = little evidence. We also found weak evidence for extreme cold and wildfire.

Drought 1 2 2 1 2 3  
Flooding 2 2 3 2 3 3  
Sea-level rise 1 2 3 1 2 3  
Severe storm systems 1 2 2 1 2 2  
Tropical cyclones and hurricanes 2 2 3 2 3 3  
Extreme heat 1 1 2 1 2 3

Highest-Vulnerability Subfunctions

<table>
<thead>
<tr>
<th>CASCADING RISKS</th>
<th>Maintain Supply Chain Operations</th>
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<tbody>
<tr>
<td>Upstream linkages: 4</td>
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<td>2</td>
<td>3</td>
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<tr>
<td>Downstream linkages:13</td>
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<tr>
<td>Upstream and downstream linkages are detailed in Chapter Six.</td>
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<tr>
<th>Manage Product Development and Manufacturing</th>
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<tbody>
<tr>
<td>Manage Product Distribution</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
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<tr>
<td>Manage Retailers</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
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<tr>
<td>Manage Purchasing</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
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</tbody>
</table>

Synopsis

Supply chains are vulnerable to several climate drivers because of their complicated logistic structure and reliance on coastal transportation infrastructure (Scholz et al., 2021). For instance, flooding of transport systems in the Midwest, tropical cyclone and hurricane damage to coastal ports on the Gulf Coast, and drought and extreme heat causing shipping delays along the Mississippi River waterway have caused disruptions to the flow of goods between producers and consumers (Austin, 2019; English et al., 2021; Friedt, 2021; Friedt and Crispin, 2021; National Integrated Drought Information System, undated; Sytsma, 2020; Trans-Border Global Freight Systems, undated). Generally, these disruptions have been regional and temporary and have had only modest impacts on supply chains at a national level (Friedt, 2021). However, as such climate drivers as floods and tropical cyclones and hurricanes become more intense in the next century, disruptions could grow to the point at which supply chains fail to meet routine operational needs in vulnerable regions and industries (Woetzel et al., 2020). In cases in which climate drivers force shippers to substitute alternative ports (Friedt, 2021), demand surges could cause additional delays if demand for port services outpaces port capacity. Additionally, crucial coastal seaports are vulnerable to extreme tides and sea-level rise, which are predicted to cause disruptions to international trade flows in the United States and globally (Becker, Acciaro,
et al., 2013; Becker, Ng, et al., 2018; Christodoulou, Christidis, and Demirel, 2019; Izaguirre et al., 2021). In some regions, such as the Gulf Coast, sea-level rise of 4 ft. could affect up to three-quarters of coastal port facilities (Kafalenos et al., 2012). This could lead to significant local disruptions to supply chain operations.

In some sectors, supply chain disruptions can have health and safety implications (Mirchandani, 2020). For instance, the supply chain disruptions in the health care sector have contributed to medical equipment shortages during the COVID-19 pandemic (Mendoza and Linderman, 2020). Supply chain disruptions often lead to regional economic loss, although losses can also propagate nationally or globally, depending on which sector is most affected (Y. Zhang and Lam, 2016). Given the importance of supply chain operations to other NCFs, supply chain disruptions could have cascading effects for other critical functions.

Subfunctions

Maintain Supply Chains has six subfunctions, and five of these face some risk of disruption due to climate change. Climate drivers that strain regional transportation systems can lead to interruptions to the flow of goods between producers and consumers, limited access to critical inputs and resources, and limited mobility of the supply chain workforce (Scholz et al., 2021). These disruptions are expected to be larger for Maintain Supply Chain Operations, Manage Product Development and Manufacturing (which involves product conceptualization and creating a minimum viable product), Manage Product Distribution, Manage Retail, and Manage Purchasing. For subfunctions dedicated to the movement of goods, such as Maintain Supply Chain Operations, climate change effects could reach a point at which regional operations fail to meet routine needs. Subfunctions that involve management-related processes are likely to be less affected, although climate change could cause minor issues by the end of the century because of increased logistic costs imposed on managers.

Climate Drivers

Except for extreme cold and wildfire, all climate drivers pose risks to supply chains. Given the reliance on coastal transportation infrastructure, coastal climate drivers pose the greatest threat to supply chain operations. According to historical impacts and projected exposure of critical assets (Christodoulou, Christidis, and Demirel, 2019), tropical cyclones and hurricanes and sea-level rise are projected to pose the largest risk to supply chains by the end of the century. These disruptions will likely be highly regional, although they could have repercussions nationally through prices of supply chain–reliant goods and services (Chopra and Sodhi, 2014). Tropical cyclones and hurricanes and flooding currently cause relatively minimal disruption to national supply chains (Friedt, 2021), but their impact is projected to grow as storms become more intense and flooding becomes more frequent (Woetzel et al., 2020). Sea-level rise is expected to have a moderate impact on supply chain operations by the end of the century because of the projected loss of port infrastructure and damage to coastal transport networks (Kafalenos et al., 2012).
Cascading Risk
Maintain Supply Chains is critically dependent on the following NCFs:38

- Distribute Electricity
- Transport Cargo and Passengers by Vessel
- Transport Cargo and Passengers by Road
- Transport Cargo and Passengers by Rail.

Maintaining supply chains requires access to electricity to manage retail and purchasing and to power warehousing and distribution centers. Additionally, supply chain operations require maintaining distribution networks and functioning transportation networks to carry products to consumers (Scholz et al., 2021). A failure of these NCFs would lead to a near-immediate failure of supply chains.

Other Factors Driving Risk
The degradation of infrastructure is likely to be the most significant climate risk–enhancing factor for supply chain operations. Supply chains rely intensively on physical infrastructure, and poorly maintained infrastructure is more exposed than its well-maintained counterparts to climate-related disruptions that cause supply chain issues (Wuebbles et al., 2017). Infrastructure in the United States received an overall grade of C– from ASCE. ASCE reported that critical supply chain infrastructure, such as roads (with a grade of D) and inland waterways (with a grade of D+), are at risk of failure, while others, such as ports (with a grade of B–), might be adequate for now but are showing some signs of deterioration (ASCE, 2021a).

Strength of Evidence
There is a relatively large literature on extreme weather’s effects on specific aspects of supply chain operations. For instance, studies have analyzed the effects that hurricanes, floods, and extreme heat have on the process of moving goods from producers to consumers (see, e.g., English et al., 2021; Friedt, 2021; and B. Jones and Olken, 2010). This research encompasses the relationships between extreme weather and supply chain maintenance, product distribution, retail performance, and access to intermediate goods and materials. There is less research on the effects that climate change and extreme weather have on product marketing. Additionally, there is little research on the effect that extremely cold temperatures or wildfire can have on supply chain operations.

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38 Critically dependent NCF was defined as an NCF that, if disrupted or in failure, would severely disrupt a given NCF and for which a given NCF could not recover until the upstream NCF was sufficiently operational. Upstream was defined as providing a key input to a downstream NCF.
Manufacture Equipment

Scorecard

National Risk Assessment

SUMMARY: Manufacture Equipment is at risk of moderate disruption from climate change by 2100 under current emissions and by 2050 under high emissions primarily because of the effects that flooding and hurricanes are anticipated to have on the processing of raw materials for manufacturing, producing components, and assembling components for equipment.

1 = no disruption or normal operations.
2 = minimal disruption. 3 = moderate disruption. The table includes only drivers and subfunctions with risk ratings of 2 or higher.

<table>
<thead>
<tr>
<th>Highest-Risk Climate Drivers</th>
<th>Current Emissions</th>
<th>High Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2030</td>
<td>2050</td>
</tr>
<tr>
<td>Drought</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Extreme heat</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Flooding</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Sea-level rise</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Severe storm systems</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Tropical cyclones and hurricanes</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Highest-Vulnerability Subfunctions

| Processing Raw Materials for Manufacturing | 2 | 2 | 3 | 2 | 3 | 3 |
| Produce Components | 2 | 2 | 3 | 2 | 3 | 3 |
| Assemble Components to Equipment | 2 | 2 | 3 | 2 | 3 | 3 |
| Maintain Equipment Quality | 1 | 2 | 2 | 1 | 2 | 3 |
| Maintain Compliance with Manufacturing Regulations | 1 | 2 | 2 | 1 | 2 | 3 |
| Operate Automation for Manufacturing | 1 | 2 | 2 | 2 | 2 | 3 |

Synopsis

Manufacture Equipment is assessed to be at risk of minimal disruption by 2050 and of moderate disruption by 2100 because of climate change under current emissions. The assessment of the projected risk is based on current disruptions to manufacturing due to climate drivers and projections that climate drivers will intensify in the next century. For instance, there is evidence that hurricanes and floods have caused disruptions to manufacturing historically (Leitold et al., 2021; Scholz et al., 2021; Seetharam, 2018). Additionally, extreme heat has been found to reduce labor and capital productivity in manufacturing sectors (Hsiang, Kopp, et al., 2017; P. Zhang et al., 2018; Scholz et al., 2021), and there is some evidence that droughts have hurt manufacturing in some water-intensive sectors (Business Forward Foundation, 2017). Currently, climate drivers’ disruptions to manufacturing are mostly temporary (Cachon, Gallino, and Olivares, 2012) and relatively minor, from a national perspective. However, some studies point to the compounding effects that climate drivers have on production, suggesting that frequent temporary effects could lead to more-permanent declines in
productivity and output (Hsiang and Jina, 2014; Letta and Tol, 2019). Thus, in some instances, the NCF might fail to meet routine operational needs in some regions by the end of the century.

Subfunctions

Subfunctions dedicated to the physical process of manufacturing (Processing Raw Materials for Manufacturing, Produce Components, and Assemble Components to Equipment) are likely at the highest risk of disruption because these subfunctions are the most likely to be directly affected by facility damage from floods, tropical cyclones and hurricanes, and, later in the century, sea-level rise and extreme tides (Scholz et al., 2021). Climate change is also predicted to have significant consequences for raw material sourcing (Scholz et al., 2021), which could adversely influence production processes. Component production and assembly require operational facilities as well. Although single climate events generally have temporary effects on manufacturing (Cachon, Gallino, and Olivares, 2012), long-term exposure to more-intense hurricanes and floods could have compounding impacts through the continued degradation of facilities or physical capital required to carry out some production processes (Letta and Tol, 2019). In regions that are highly exposed to climate drivers, some of these subfunctions might fail to meet operational needs. Climate change is less likely to affect the subfunctions Maintain Equipment Quality and Maintain Compliance with Manufacturing Regulations because they might be less reliant on physical structures that climate drivers can damage. However, some evidence suggests that the quality of some manufacturing equipment is highly sensitive to extremely high temperatures (Scholz et al., 2021), which could make maintaining equipment quality and more difficult by 2100. Finally, climate drivers that degrade manufacturing facilities could make it more difficult to operate automated equipment, although there is little research on this topic.

Climate Drivers

Some climate drivers have already had an effect on manufacturing. For instance, there is evidence that flooding and hurricanes can temporarily disrupt manufacturing processes in affected regions through facility degradation and disruptions to critical inputs (Leitold et al., 2021; Seetharam, 2018). As these climate drivers intensify in the next century (Wuebbles et al., 2017), the disruptions to manufacturing could grow to the point at which the NCF fails to meet routine needs in some highly exposed regions. Coastal facilities could face disruptions by 2050 and by 2100 from flooding and sea-level rise (Scholz et al., 2021). Similarly, drought and extreme heat could cause disruptions to manufacturing in some high-risk regions or in sectors that require extensive outdoor work or rely intensively on water as an intermediate input (Scholz et al., 2021).

Cascading Risk

Manufacture Equipment is critically dependent on the following NCFs: 39

- Distribute Electricity
- Maintain Supply Chains
- Store Fuel and Maintain Reserves
- Provide and Maintain Infrastructure
- Supply Water.

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39 Critically dependent NCF was defined as an NCF that, if disrupted or in failure, would severely disrupt a given NCF and for which a given NCF could not recover until the upstream NCF was sufficiently operational. Upstream was defined as providing a key input to a downstream NCF.
Manufacture Equipment requires timely access to intermediate inputs and raw materials (Goldberg et al., 2010), access to infrastructure (Cohen and Paul, 2004), and electric power (Acar and Berk, 2022). Although these upstream NCFs have some resilience to temporary disruptions, any sustained period of failure would cause significant disruption to the Manufacture Equipment NCF. For instance, power infrastructure is critical to manufacturing performance (Acar and Berk, 2022). Similarly, if the Maintain Supply Chains or Provide and Maintain Infrastructure NCFs failed, most manufacturing processes would struggle to source important imported inputs, causing significant production delays (Wuebbles et al., 2017). Finally, some manufacturing processes rely intensely on water as an intermediate input (Scholz et al., 2021), and disruptions to the Supply Water NCF could cause production delays for some products.

Other Factors Driving Risk

Manufacturing relies intensively on technology (Milgrom and Roberts, 1990), human capital (workforce knowledge and skills) (Black and Lynch, 1996), and infrastructure (Cohen and Paul, 2004). Thus, degradation in these factors would likely make Manufacture Equipment more susceptible to climate-related disruptions (Wuebbles et al., 2017). These factors, particularly technology and human capital, play a role in overall manufacturing productivity, which is likely crucial in determining sectors' long-run economic resilience to climate change (Hsiang and Jina, 2014; Letta and Tol, 2019). Stagnant technology and human capital might make recovering from climate-related disruptions more difficult in the future.

Strength of Evidence

A relatively large body of research focuses on climate change’s effects on manufacturing. The literature focuses on hurricanes (Business Forward Foundation, 2017; Seetharam, 2018) and flooding (Leitold et al., 2021), although there is some research on drought (Scholz et al., 2021) and extreme heat (Wuebbles et al., 2017; P. Zhang et al., 2018). There is little research on the effect of other climate drivers, such as extreme cold and wildfire. Additionally, a research gap surrounds climate change’s implications for the ability to operate automated manufacturing equipment. Therefore, it is unclear whether manufacturing processes that substitute automated or robotic capital for human labor will be more or less resilient to climate drivers.
Produce Chemicals

Scorecard

National Risk Assessment

SUMMARY: Produce Chemicals is at risk of moderate disruption from climate change by 2100 and by 2050 under high emissions primarily because of the effects that flooding, sea-level rise, and hurricanes are anticipated to have on the production of basic and applied chemicals and the distribution of chemical products.

1 = no disruption or normal operations. 2 = minimal disruption. 3 = moderate disruption. The table includes only drivers and subfunctions with risk ratings of 2 or higher.

Produce Chemicals: “Manufacture basic chemicals from raw organic and inorganic materials and manufacture intermediate and final products from basic chemicals” (CISA, 2020, p. 6).

<table>
<thead>
<tr>
<th>Current Emissions</th>
<th>High Emissions</th>
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<tbody>
<tr>
<td>2030</td>
<td>2050</td>
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Highest-Risk Climate Drivers

MECHANISMS OF IMPACT

- Physical damage or disruption
- Input or resource constraint
- Workforce shortage
- Demand change

The shade of gray indicates the strength of evidence for that NCF: medium gray = moderate evidence and light gray = little evidence. We also found weak evidence for extreme cold and wildfire.

Drought 1 2 2 1 2 2
Extreme heat 1 2 2 1 2 2
Flood 2 2 3 2 3 3
Sea-level rise 1 2 3 1 2 3
Severe storm systems 1 2 3 1 2 3
Tropical cyclones and hurricanes 2 2 3 2 3 3

Highest-Vulnerability Subfunctions

CASCADING RISKS

Upstream linkages: 7
Downstream linkages: 3
Upstream and downstream linkages are detailed in Chapter Six.

Produce Basic Chemicals 2 2 3 2 3 3
Produce Applied Chemicals 2 2 3 2 3 3
Distribute Chemicals 2 2 2 2 3 3

Synopsis

Chemical production is assessed to face a risk of moderate disruption due to climate change by 2100. Currently, chemical production facilities are vulnerable to flooding because many U.S. chemical plants are close to bodies of water (Tabuchi et al., 2018). There is also evidence that hurricanes have disrupted chemical production historically through facility damage and disruptions to operational procedures (DiChristopher, 2017). Extreme heat can damage facilities when chemicals combust (World Health Organization [WHO], 2018), and drought conditions can limit access to water needed in production (Glaser, 2014), resulting in minimal disruptions to chemical production facilities. As these climate drivers intensify, the disruptive impacts they have on chemical production are likely to grow. Additionally, as sea levels rise over the century, new disruptions, such as the corrosion of exposed equipment because of saltwater inundation, are likely to arise, particularly at chemical production facilities along the Gulf Coast (WHO, 2018).

Subfunctions

Produce Basic Chemicals and Produce Applied Chemicals are assessed to be at risk of moderate disruption due to climate change by 2100. These two subfunctions are particularly vulnerable to flooding because many U.S. chemical plants are on or near waterways and in flood-prone regions (Tabuchi et al., 2018). Also, news reports have provided some evidence that coastal production facilities are vulnerable to tropical cyclones and hurricanes. For instance, Hurricane Harvey resulted in facility damage and caused significant produc-
tion delays because it takes time for facilities to come back online after they are shut down (DiChristopher, 2017). Along with its disruptions to production, climate change is likely to adversely affect the distribution of chemical products. Specifically, drought, flooding, sea-level rise, and tropical cyclones and hurricanes are expected to make supply chain operations more difficult to sustain in some regions (Austin, 2019; Banker, 2017; Christodoulou, Christidis, and Demirel, 2019; DiChristopher, 2017; English et al., 2021; Izaguirre et al., 2021; National Integrated Drought Information System, undated; Trans-Border Global Freight Systems, undated). In some cases, these disruptions could result in these subfunctions failing to meet routine operational needs in vulnerable areas.

Climate Drivers
Given their proximity to bodies of water, which have historically provided advantages for transportation and supply of cooling water, many chemical production facilities are vulnerable to flooding (Tabuchi et al., 2018). As flooding becomes more intense and frequent, chemical production might fail to meet routine operational needs in some regions by the end of the century. Additionally, more-intense tropical cyclones and hurricanes could lead to moderate disruptions to chemical production nationally and significant disruptions locally (DiChristopher, 2017). By the end of the century, sea-level rise could disrupt some regions’ ability to trade and transport chemical products locally and internationally (Christodoulou, Christidis, and Demirel, 2019). Finally, extreme heat could reduce labor and capital productivity (P. Zhang et al., 2018), and drought can reduce carrying capacities in critical water transport arteries (National Integrated Drought Information System, undated), either of which could cause minimal disruption to chemical production.

Cascading Risk
Produce Chemicals is critically dependent on the following NCFs:

- Distribute Electricity
- Maintain Supply Chains
- Manage Hazardous Materials
- Manage Wastewater
- Provide and Maintain Infrastructure
- Provide Capital Markets and Investment Activities
- Supply Water.

The physical process of chemical production requires access to electricity and complex supply chain operations (DiChristopher, 2017). Additionally, producing chemicals involves the disposal of hazardous materials and wastewater used in some production processes (Tabuchi et al., 2018). The Supply Water NCF also plays a critical role in supplying chemical production facilities with water as an intermediate input or cooling agent (Centers for Disease Control and Prevention, 2016; Moody’s, 2021). Finally, access to infrastructure (e.g., roads, ports) and capital markets are required to transport products and finance production activities (American Chemistry Council [ACC], 2021; DiChristopher, 2017). Failures of these upstream NCFs would likely cause significant disruptions to chemical production. However, depending on the upstream NCF, some of the disruptions to chemical production could occur over longer time scales. For instance, an inability to

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40 Critically dependent NCF was defined as an NCF that, if disrupted or in failure, would severely disrupt a given NCF and for which a given NCF could not recover until the upstream NCF was sufficiently operational. Upstream was defined as providing a key input to a downstream NCF.
provide access to capital markets could affect future chemical production more than current production. On the other hand, the inability to dispose of hazardous materials could force chemical production facilities to shut down immediately.

Other Factors Driving Risk
Chemical production relies on functioning infrastructure and supply chains to move products to domestic and international markets (Scholz et al., 2021; Woetzel et al., 2020) and on governance and management to regulate the disposal of hazardous materials (GAO, 2019). The degradation of these factors could increase exposure of the Produce Chemicals NCF to climate-related disruptions. Infrastructure tends to degrade over time, and, without necessary maintenance and upgrades, U.S. infrastructure might not perform sufficiently in the future (ASCE, 2021b). Degraded infrastructure, coupled with declining supply chain functionality, would make transporting chemical products more difficult in a future with more-intense and -frequent climate drivers. Additionally, chemical production is a highly regulated field. For instance, some special regulations govern shutting down and restarting chemical plants, a practice shown to limit hurricane effects (Misuri et al., 2019). The degradation of the governance and management of these regulations would make chemical plants more exposed to damage and chemical spills following hurricanes.

Strength of Evidence
Overall, there is relatively little research on extreme weather’s effects on chemical production. Most of the analysis comes from reporting after extreme weather events (see, e.g., DiChristopher, 2017, on the effects of Hurricane Harvey), reports that are tangentially related to climate change (see, e.g., WHO, 2018), or reports by industry stakeholder groups (see, e.g., ACC, 2021). With anecdotal reports, assessing the effects that climate change or extreme events have on chemical production because these reports might not be systematic in their data analysis and might not accurately capture uncertainty in their estimates. However, some academic analysis exists, particularly around hurricanes’ effects, on the chemical sector (Misuri et al., 2019).
Transport Cargo and Passengers by Vessel

Scorecard

SUMMARY: Transport Cargo and Passengers by Vessel is at risk of minimal disruption from climate change by 2030 primarily because of the anticipated impacts of tropical cyclones and hurricanes, which already disrupt port operations.

1 = no disruption or normal operations.
2 = minimal disruption. 3 = moderate disruption. The table includes only drivers and subfunctions with risk ratings of 2 or higher.

Transport Cargo and Passengers by Vessel: “Provide and operate maritime systems, assets, and facilities to enable a system of securely and safely conveying goods and people from place to place by the Maritime Transportation System” (CISA, 2020, p. 4).

Current Emissions: 2030, 2050, 2100
High Emissions: 2030, 2050, 2100

<table>
<thead>
<tr>
<th>Climate Driver</th>
<th>Current Emissions</th>
<th>High Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2030</td>
<td>2050</td>
</tr>
<tr>
<td>Drought</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Extreme heat</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Flooding</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Sea-level rise</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Severe storm systems</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Tropical cyclones and hurricanes</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Highest-Vulnerability Subfunctions

Build Marine Transportation System
Maintain Workforce

Synopsis

Transport Cargo and Passengers by Vessel is vulnerable to multiple climate drivers primarily because of infrastructure damage and, to a lesser extent, because of disruptions that lower water levels cause for inland shipping. Coastal ports are vulnerable to sea-level rise because rising water levels could render some landside port infrastructure unusable. Gulf Coast and East Coast ports are already vulnerable to hurricanes (in the past 50 years, all East Coast and Gulf Coast ports have been exposed to tropical storms that have come within 30 miles) (Becker, Ng, et al., 2018), which can both damage landside infrastructure and blow debris into shipping channels. Inland shipping could be vulnerable to drought if water levels are too low for normal shipping operations. However, drought is expected to be a large climate driver in the western part of the country, and most inland (river and Great Lake) shipping is concentrated in the east. Overall, this suggests a risk of minimal disruption in 2030 and a moderate disruption by 2100, with risk increasing as tropical storm intensity grows.

Disruptions due to climate change can have cascading impacts throughout the maritime system. Two trends in cargo shipping—increasing specialization in ports (e.g., container goods, bulk cargo, petroleum) and ports with shipping lanes deep enough to accommodate increasing vessel size—mean that vessels cannot easily load or offload at other ports if operations are disrupted (Verschuur, Koks, and Hall, 2020). For this reason, disruptions at ports moving the highest volume of goods (Los Angeles, Long Beach, and New York/New Jersey for containers, South Louisiana for bulk cargo, and Houston for petroleum) (Bureau of Transportation Statistics, 2021) could have a disproportionate economic impact. Ocean shipping is an inherently
international function, so climate-driven disruptions at major ports in other countries that serve as important origins or destinations for U.S. goods could also have an effect on this NCF.

**Subfunctions**

The primary subfunction affected is Build Marine Transportation System because the main mechanism by which climate change affects this NCF is through damage to port physical infrastructure. This includes both temporary disruption due to storms and longer-term damage that could result from sea-level rise and render some landside infrastructure unusable. This could reach a risk of minimal disruption by 2030 and a moderate disruption by 2100 as sea levels and tropical storm intensity both rise.

Although climate change might not directly affect the ability to attract and retain the skilled workers required to operate the maritime transportation system, it could affect workers’ ability to function outdoors if temperatures are too hot to work safely (NIOSH, 2016). Port operations require some degree of outdoor labor for normal functioning. This could reach a risk of minimal disruption by 2100 as the annual number of days above 90 degrees increases.

**Climate Drivers**

Transport Cargo and Passengers by Vessel is vulnerable to six of the eight climate drivers: drought, extreme heat, flooding, sea-level rise, severe storm systems, and tropical cyclones and hurricanes. Coastal ports are most vulnerable to sea-level rise and hurricanes because they are, by necessity, located on bodies of water. Sea-level rise can cause inundation, nuisance flooding, or high-tide flooding, rendering coastal port landside infrastructure unusable either permanently or temporarily, depending on the depth of the water. Researchers studying Gulf Coast ports found that a 4-ft. rise in sea level would affect three-quarters of port facilities (Kafalenos et al., 2008). Hurricanes can damage both vessels and landside infrastructure or create debris in shipping channels, leading to temporary closures (Verschuur, Koks, and Hall, 2020); severe storms and flooding can also damage port infrastructure at both coastal and inland ports. Researchers in one study found a median disruption length of six days, a relationship between the intensity of the storm and the length of the disruption, and a lack of substitution between ports (Verschuur, Koks, and Hall, 2020). Analysts performing a multihazard climate analysis (including high winds, extreme heat, heavy precipitation, storm surge, flooding, and sea-level rise) of coastal ports around the world found that, by 2100, 21 ports in the United States would be considered “very high risk” (the second-highest category) and another 127 considered “medium risk” (the fourth category). Overall, risk from hurricanes reaches minimal disruption in 2030 and moderate disruption by 2100 because storm intensity is projected to increase over time, which will cause lengthier disruptions and longer times to repair damage.

Drought could have an effect on barge shipments that travel by river or vessels that travel on the Great Lakes because vessels require a minimum water level to operate. However, climate change’s effects on Great Lakes water levels are difficult to predict because water levels generally fluctuate on an annual basis, and climate change might be increasing these fluctuations (Gronewold et al., 2013; Posey, 2012). This risk is rated minimal disruption by 2100 because, if such fluctuations continue to become more extreme, inland shipping

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41 Nuisance flooding is low levels of inundation that do not pose significant threats to public safety or cause major property damage, but can disrupt routine day-to-day activities, put added strain on infrastructure systems such as roadways and sewers, and cause minor property damage. (Moftakhar, et al., 2018, abstract)

42 This analysis was conducted using the RCP8.5 scenario, which corresponds to the high-emissions scenario in this report (Izaguirre et al., 2021).
would be disrupted because of both unusually high and unusually low water levels. There is also risk in planning for long-term operations in the face of uncertainty.

Cascading Risk
Transport Cargo and Passengers by Vessel is critically dependent on the following NCFs:43

• Transport Cargo and Passengers by Road
• Transport Cargo and Passengers by Rail
• Provide Positioning, Navigation, and Timing Services
• Provide Satellite Access Network Services
• Fuel Refining and Processing Fuels.

Transportation via both road and rail are considered crucial because these are the modes via which goods move to and from ports’ landsides. Port operations would be severely disrupted if there were no modes to move goods via land, because warehouse space is finite and would quickly become overwhelmed (Goodman, 2021). PNT and satellite services are critical to shipping operations for vessel positioning, as wire-line services are for landside operations (DOT, undated; MarineTraffic, undated; Wallischeck, 2016). Finally, fuel-related NCFs are important because almost all shipping vessels require diesel fuel to operate (U.S. Energy Information Administration, 2015).

Other Factors Driving Risk
Underlying the risk ratings for Transport Cargo and Passengers by Vessel are key factors that contribute to the risk ratings. Although this NCF is heavily dependent on physical infrastructure, ports are overall in reasonable condition.44 If port infrastructure were to be degraded in the future, this NCF would be at an elevated risk because most metropolitan regions have only one major port. Ports are not readily substitutable, inexpensive, or easy to build; ports have generally been constructed in their current locations because of desirable geographic features that are not easily replicated. In addition, regional economic development drives demand for ocean and inland shipping. Because ports generally depend financially on user fees (rather than tax revenues), a lack of demand can lead to a loss of revenue, which would diminish a port’s ability to fund its operations (Verschuur, Koks, and Hall, 2020). Finally, if there are warmer winters (that is, fewer extremely cold days), the shipping season could be extended for northern ports, and, if new shipping routes through the Arctic are available, global shipping patterns could change. Either of these could affect the risk profile of Transport Cargo and Passengers by Vessel because carriers could shift cargo away from ports that are currently at risk and toward ports that are at less risk (Transportation Research Board and National Research Council, 2008).

Strength of Evidence
There is a fairly robust literature about the effects that sea-level rise and hurricanes have on ports, with some rigorous analysis of the different risk levels by port (Becker, Ng, et al., 2018; Izaguirre et al., 2021; Verschuur,

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43 Critically dependent NCF was defined as an NCF that, if disrupted or in failure, would severely disrupt a given NCF and for which a given NCF could not recover until the upstream NCF was sufficiently operational. Upstream was defined as providing a key input to a downstream NCF.

44 ASCE gave U.S. port infrastructure a grade of B– in its most recent infrastructure report card. See ASCE, 2021e.
Koks, and Hall, 2020; Wright and Hogan, 2008). There is less literature on the specific impact of flooding and other types of storms and very little on extreme temperatures and wildfire. There is mixed evidence on whether and how drought will affect inland cargo shipping (Gronewold et al., 2013; Posey, 2012).
## Educate and Train

### Scorecard

**National Risk Assessment**

**SUMMARY:** Educate and Train is at risk of minimal disruption from climate change by 2050 primarily because of the effects that flooding, hurricanes, severe storm systems, and wildfire are anticipated to have on the provision of formal education and of workforce training.

1 = no disruption or normal operations.
2 = minimal disruption. 3 = moderate disruption. The table includes only drivers and subfunctions with risk ratings of 2 or higher.

Educate and Train: “Provide education and workforce training including PreK [prekindergarten]–12, community college, university, and graduate education, technical schools, apprenticeships, non-formal education, and on-the-job training” (CISA, 2020, p. 4).

<table>
<thead>
<tr>
<th>Mechanism of Impact</th>
<th>Current Emissions</th>
<th>High Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>2030</td>
<td>2050</td>
<td>2100</td>
</tr>
<tr>
<td><strong>Extreme heat</strong></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>Flooding</strong></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td><strong>Sea-level rise</strong></td>
<td>1</td>
<td>1</td>
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<tr>
<td><strong>Severe storm systems</strong></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td><strong>Tropical cyclones and hurricanes</strong></td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td><strong>Wildfire</strong></td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

### Highest-Risk Climate Drivers

- Physical damage or disruption
- Input or resource constraint
- Workforce shortage
- Demand change

The shade of gray indicates the strength of evidence for that NCF: dark gray = strong evidence and medium gray = moderate evidence. We also found weak evidence for drought and extreme cold.

### Highest-Vulnerability Subfunctions

- **Provide Formal Education**: 2 2 3 2 2 3
- **Provide Workforce Training**: 2 2 3 2 2 3

### Synopsis

Climate change affects education and training primarily through the effects that extreme weather events have on education infrastructure—specifically, schools and training facilities. There are also plausible pathways by which disruptions of other infrastructure functions, such as power and water, could impede the ability to operate education facilities. Schools vary in their resilience, with some being commonly used as public shelters in the event of emergency but others built in low-lying flood-prone areas that leave them vulnerable. Major climate-related disasters, such as hurricanes, can also displace significant numbers of both students and teachers—sometimes for months and sometimes permanently, producing lasting disruption to the education system (Sacerdote, 2012). All of these effects are largely temporary in nature or would occur at the local to regional level (e.g., flood events that force school closures). However, large events can affect large regions (e.g., all of Puerto Rico, or a mainland metropolitan area, such as New York or New Orleans), and these disruptions can bring education to a halt for months and lead to suboptimal conditions for years (Pane et al., 2006; Sentell, 2021).

### Subfunctions

The two subfunctions of the Educate and Train NCF have similar requirements and are therefore subject to similar vulnerabilities in the face of changing climate. Both formal education (Provide Formal Education, including prekindergarten through 12, university and college education, and vocational to maintain cutting-
edge skills and capabilities) and workforce training (Provide Workforce Training to maintain cutting-edge skills and capabilities) rely heavily on working buildings and facilities that have electricity and internet access. Infrastructure disruptions can also disrupt remote education and training, whether they are conducted in the home or in the workplace (Sheffield et al., 2017).

**Climate Drivers**

Because education and training facilities are highly distributed geographically and are dependent on a wide variety of infrastructure, they are vulnerable to impacts from most of the identified climate drivers, with the exceptions of drought and extreme cold. Flooding, sea-level rise, hurricanes, and severe storms collectively present hazards across most of the country and can cause major disruption to schools (Heberger et al., 2011). Working facilities and stable home environments are both crucial to successful education outcomes. Large-scale floods have proven highly disruptive to education (Machtinger, 2007). Because schools are distributed in a way that is very similar to population distribution in general, flooding’s effect on schools can be expected to grow in step with general flooding trends. Increases in these disruptions are expected by 2050, and they could put this NCF at risk of moderate disruption by 2100 under both the current- and high-emissions scenarios (Wuebbles et al., 2017). Extreme heat events can stress education infrastructure and distract from learning in schools with insufficient cooling capacity. Schools in areas not accustomed to high temperatures might have limited cooling capacity, and all regions are expected to see heat events that significantly exceed the climatic conditions for which their school facilities were designed (Muurlink and Matas, 2010). Although U.S. school districts generally possess the resources to adapt to higher temperatures, these adaptations could be both expensive and disruptive. Wildfire can threaten education buildings directly, disrupt home environments, and produce smoke that causes school closures. This happened on a previously unprecedented scale in 2020 and 2021 in several western states (Canon and Kamal, 2021). Although fires can cause losses of facilities and even whole communities, it is not expected that this will happen at such a scale that it would cause national-level disruptions. Fire damage can be extreme, but it is generally fairly localized and concentrated in areas with relatively small populations.

**Cascading Risk**

Educate and Train is critically dependent on the following NCFs:45

- Distribute Electricity
- Provide Internet Routing, Access, and Connection Services
- Supply Water
- Transport Cargo and Passengers by Road
- Provide Housing.

Most education and training functions involve either a working facility (e.g., a school) or remote internet resources. Each of these depends heavily on electricity in order to function. Although a school might be able to function in a limited capacity without internet services, modern learning environments are generally highly dependent on them—while remote learning environments depend on internet services directly. Functional education facilities require water in order to operate and must be reachable—usually by road—in order

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45 *Critically dependent NCF* was defined as an NCF that, if disrupted or in failure, would severely disrupt a given NCF and for which a given NCF could not recover until the upstream NCF was sufficiently operational. *Upstream* was defined as providing a key input to a downstream NCF.
for people to make use of them. A functional learning environment also requires that learners be housed in functional housing (Broton, 2020).

Other Factors Driving Risk
Education and training require functional infrastructure, spanning a wide variety of infrastructure types, including suitable buildings, electrical service, and adequate roads to transport people to the facility in question. Most modern education and training relies on information technology (IT) and internet services to provide access to teaching and training material and to manage student and instructor workflows. Because education and training are crucial to everyone in the United States—particularly to school-age children—equity in access is essential to successfully delivering this function. Successful education requires qualified teachers in adequate numbers and with a geographic distribution that aligns with student needs, allowing students access to teachers with suitable skills. The previous factors affect education directly, while governance and management influence education largely by enabling these other factors to be healthy and strong. Rapid changes in population size (growth or contraction) can present challenges to successful education and training by either straining capacity (growth) or limiting funding and creating excess capacity (contraction). Such rapid changes can be produced by climate-driven shocks or large changes in the desirability of vulnerable (particularly coastal) areas. Finally, economic development drives the tax base that pays for most education, with lean economic times creating funding challenges for education and training.

Strength of Evidence
The topic of climate change effects on education has received little direct attention in the literature. A few papers in the peer-reviewed literature from around the world address the topic directly (Randell and Gray, 2019), which is a very small number relative to that addressing other infrastructure service areas. That said, recent events, such as Hurricanes Ida and Katrina, have demonstrated that severe weather can damage education facilities, making them unusable and necessitating time and money to repair while causing a wide variety of disruptions to education (Culbertson et al., 2020; Fothergill and Peek, 2015; Nelson et al., 2020).
Provide and Maintain Infrastructure

Scorecard

National Risk Assessment

SUMMARY: Provide and Maintain Infrastructure is at risk of moderate disruption by 2100 primarily because of the effects that flooding, sea-level rise, hurricanes, and extreme heat are anticipated to have on infrastructure maintenance.

1 = no disruption or normal operations.
2 = minimal disruption. 3 = moderate disruption. The table includes only drivers and subfunctions with risk ratings of 2 or higher.


<table>
<thead>
<tr>
<th>Current Emissions</th>
<th>High Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>2030</td>
<td>2050</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
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</tbody>
</table>

Highest-Risk Climate Drivers

MECHANISMS OF IMPACT

- Physical damage or disruption
- Input or resource constraint
- Workforce shortage
- Demand change

The shade of gray indicates the strength of evidence for that NCF: light gray = little evidence.

Drought

- 1
- 1
- 2
- 1
- 1
- 2

Extreme cold

- 1
- 1
- 2
- 1
- 1
- 2

Extreme heat

- 1
- 2
- 3
- 1
- 2
- 2

Flooding

- 1
- 2
- 3
- 1
- 2
- 3

Sea-level rise

- 1
- 2
- 3
- 1
- 2
- 3

Severe storm systems

- 1
- 2
- 2
- 1
- 2
- 2

Tropical cyclones and hurricanes

- 1
- 2
- 3
- 1
- 2
- 3

Wildfire

- 1
- 1
- 2
- 1
- 1
- 2

Highest-Vulnerability Subfunctions

CASCADING RISKS

Upstream linkages: 7
Downstream linkages: 3
Upstream and downstream linkages are detailed in Chapter Six.

Build Infrastructure

- 1
- 2
- 2
- 1
- 2
- 2

Perform Maintenance

- 1
- 2
- 3
- 1
- 2
- 3

Purchase Materials

- 1
- 1
- 2
- 1
- 1
- 2

Store Materials

- 1
- 1
- 2
- 1
- 1
- 2

Dispose of Materials

- 1
- 1
- 2
- 1
- 1
- 2

Synopsis

Infrastructure (both physical and nonphysical) is crucial for socioeconomic development and growth within a community. The ability to effectively provide and maintain infrastructure is complex and is driven by many physical factors, such as availability of materials and equipment, as well nonphysical factors, such as financial resources and stable governance structures (Beckers and Stegemann, 2013). Although the nonphysical factors are less likely than physical ones to be at risk of disruption from climate drivers, physical factors are at risk of minimal disruption and, in some instances, of moderate disruption by 2100. Flooding, hurricanes, and wildfire can hinder the availability of and access to basic equipment and other resources needed to build infrastructure, such as roads, electricity, and communication systems, because of physical damage and deterioration, workforce shortage, and input constraints. For instance, Hurricane Sandy in 2012 damaged electrical infrastructure in many states along the East Coast and led to more than 15,000 outages for 500,000 customers; after the storm, many communities in New York and New Jersey were without electrical power for many months (Manuel, 2013). Maintenance of infrastructure is also susceptible to disruptions from climate drivers. Sea-level rise, for instance, can increase saltwater exposure and corrosion of coastal infrastructure, which increases maintenance needs (Nasr et al., 2021). The cost for coastal protection in the United States is...
estimated at approximately $2 billion to $3 billion per year through 2100 (Sussman et al., 2014). With aging infrastructure in the United States and growing deferred-maintenance costs, local and state governments could be overwhelmed and unable to meet additional maintenance demands in the future.

**Subfunctions**

Three of the nine subfunctions for this NCF (specifically, Perform Maintenance, Build Infrastructure, and Store Materials) are expected to have minimal to moderate risk for disruption from climate drivers by the end of the century. Because the need for infrastructure maintenance is expected to grow from more-frequent and -intense flooding, hurricanes, and wildfire, additional resources (e.g., capital, materials, labor) will be needed to avoid disruption. As of 2019, the national total for deferred-maintenance costs for public infrastructure was estimated at approximately $1 trillion (Zhao, Fonseca-Sarmiento, and Tan, 2019). Approximately 80 percent of funding for public infrastructure is provided by state and local governments; as climate drivers require additional maintenance in the future, state and local governments could become overwhelmed and might not have sufficient resources to properly maintain existing infrastructure and invest in new infrastructure projects. The ability to build and store materials for infrastructure projects is also vulnerable to certain climate drivers. Temporary storage facilities, for instance, face some of the same risks and vulnerabilities from climate drivers as other structures in the built environment face. For example, damage from extreme wind and precipitation during hurricanes can lead to failures in the building envelope and roof, thereby allowing water intrusion and potential growth of mold in the interior (FEMA, 2009). Although some remaining subfunctions of this NCF, such as Obtain Finances, Develop Plans, and Comply with Regulations, are critical in providing and maintaining infrastructure, these subfunctions are expected to continue operations without disruption from climate drivers through 2100.

**Climate Drivers**

Flooding, sea-level rise, hurricanes, and extreme heat conditions are the climate drivers that are expected to pose the most risk of disruption for this NCF. Researchers in one study, for instance, estimated the change in risk from flooding for critical infrastructure in the United States as an approximately 6-percent increase from 2021 to 2051 (First Street Foundation, 2021). Those in another study estimated that projected temperature increases by 2060 will result in a 2- to 20-percent loss in electric power capacity for Los Angeles County (Burillo et al., 2019). The need for increased infrastructure maintenance because of climate drivers will vary regionally. Infrastructure in coastal communities, for example, will be more susceptible to erosion and degradation from rising sea levels, whereas infrastructure in the southwest is likely to require additional maintenance because of extreme heat conditions (Narayanan et al., 2016).

**Cascading Risk**

Provide and Maintain Infrastructure is critically dependent on the following NCFs:46

- Distribute Electricity
- Maintain Supply Chains
- Educate and Train

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46 Critically dependent NCF was defined as an NCF that, if disrupted or in failure, would severely disrupt a given NCF and for which a given NCF could not recover until the upstream NCF was sufficiently operational. Upstream was defined as providing a key input to a downstream NCF.
• Operate Government
• Provide Information Technology Products and Services
• Provide Capital Markets and Investment Activities
• Supply Water.

The development and maintenance of infrastructure involve numerous stakeholders, including both public entities (e.g., local, state, and federal governments) and private ones (e.g., banks; developers; architecture, engineering, and construction firms). Failures in financial markets and governance structures pose challenges in the procurement of materials and equipment needed for infrastructure projects (Ben Ammar and Eling, 2015), while failures in education systems can potentially disrupt workforce development and have consequences for infrastructure maintenance, which typically requires highly skilled labor (Parlikad and Jafari, 2016). Additionally, infrastructure development and maintenance depend on basic services, including access to reliable energy and water supplies.

Other Factors Driving Risk
Local and state governments’ ability to invest in climate resilience is a significant factor in reducing this NCF’s risk of disruption by climate drivers. As infrastructure in the United States continues to degrade, some communities might have the means to invest earlier in mechanisms to mitigate risk from climate drivers; these communities are less likely to be overwhelmed by future maintenance needs and might experience fewer disruptions.

Strength of Evidence
There is sufficient literature that examines climate drivers’ effect on infrastructure from an adaptation and risk management perspective. ASCE, for instance, publishes a report every four years that examines the condition and need for improvements in U.S. infrastructure systems. There is less well-documented literature, however, on how climate drivers affect other components of development and maintenance of infrastructure, such as obtaining finances, complying with regulations, and developing plans and specifications.
Assessing Risk to the National Critical Functions as a Result of Climate Change

Transport Passengers by Mass Transit

Scorecard

National Risk Assessment

**SUMMARY:** Transport Passengers by Mass Transit is at risk of minimal disruption from climate change by 2030 primarily because of the anticipated impacts of tropical cyclones and hurricanes, which can cause damage to physical infrastructure.

1 = no disruption or normal operations. 2 = minimal disruption. 3 = moderate disruption. The table includes only drivers and subfunctions with risk ratings of 2 or higher.

### Current Emissions

<table>
<thead>
<tr>
<th>2030</th>
<th>2050</th>
<th>2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2</td>
<td>2</td>
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</tbody>
</table>

### High Emissions

<table>
<thead>
<tr>
<th>2030</th>
<th>2050</th>
<th>2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2</td>
<td>3</td>
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</table>

### Highest-Risk Climate Drivers

<table>
<thead>
<tr>
<th>MECHANISM OF IMPACT</th>
<th>2030</th>
<th>2050</th>
<th>2100</th>
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</thead>
<tbody>
<tr>
<td>Physical damage or disruption</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Input or resource constraint</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Workforce shortage</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Demand change</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

The shade of gray indicates the strength of evidence for that NCF: medium gray = moderate evidence and light gray = little evidence. We also found weak evidence for extreme cold.

### Highest-Vulnerability Subfunctions

<table>
<thead>
<tr>
<th>CASCADING RISKS</th>
<th>2030</th>
<th>2050</th>
<th>2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Management of Mass Transit System</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Conduct Transport Operations</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Provide Diverse Energy Sources</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

Synopsis

Transport Passengers by Mass Transit is vulnerable mostly to climate drivers that affect the physical infrastructure: flooding, sea-level rise, tropical cyclones and hurricanes, severe storm systems, extreme heat, and wildfire. These climate drivers can cause damage to roads, bridges, rail, stations, and vehicles, resulting in higher maintenance costs and suspensions of service.

Most cities have some transit service, and transit overall is highly localized—a transit disruption in one city would be unlikely to affect transit service in other cities. In addition, transit modes vary from city to city—although bus service is the most common mode, most larger cities also operate at least one type of rail (light, heavy, or commuter). Cities also vary in ridership levels. These factors make it difficult to assess transit as a national function. The transit systems likely to experience disruptions from climate change are older ones because their infrastructure might not have been built to modern engineering specifications (the country’s oldest transit tunnel was built in 1897 and remains operational) (Massachusetts Bay Transportation Authority, undated) and because they might not be in a state of good repair because of deferred maintenance. Overall, we judge transit to be at risk of minimal disruption by 2030 because of this decentralized nature but that individual systems could be at risk from climate drivers that affect their geographic areas.

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47 DOT found that 23 percent of rail assets were in marginal or poor condition. See Federal Transit Administration, 2020.
Subfunctions
Management of Mass Transit System would be affected by the effects that extreme heat, flooding, sea-level rise, tropical cyclones and hurricanes, and wildfire could have on physical infrastructure. This would reach a level of minimal disruption by 2030 because such effects are already occurring on a sporadic basis (for example, Hurricane Ida caused transit malfunctions and shutdowns in New York City) (McKinley, Rubinstein, and Mays, 2021).

Provide Diverse Energy Sources would be affected by lack of both diesel fuel (to operate buses) and electricity (to operate rail service). This suggests a risk of minimal disruption by 2030 and a moderate disruption by 2100. This increases with the risk of energy provision becoming more vulnerable, as well as the fact that limited energy availability would have wider impacts on transit overall than events that damage transit infrastructure in individual cities.

Some research has shown that transit ridership on modes with outdoor waiting areas is affected by temperature, with ridership highest in cities with temperate climates. This suggests that extreme temperatures, either hot or cold, discourage ridership (Kuby, Barranda, and Upchurch, 2004), as do other weather-related variables. Ridership is affected by these daily fluctuations, but there has been no nationwide study of whether climate change effects would increase or decrease overall ridership. This would affect the Conduct Transport Operations subfunction, reaching a level of minimal disruption by 2100. Fare revenues are an important part of transit operating budgets, so a reduction in the number of riders can lead to service reductions.

Climate Drivers
Individual transit systems are vulnerable to flooding, tropical cyclones and hurricanes, and severe storm systems because of the potential for damage to rolling stock, track and stations, and maintenance facilities. Flooding can damage tunnels and low-lying facilities, bus lots, vehicles, and rights of way. Flooding necessitates power shutoff to third-rail systems and can erode material or soils directly adjacent to paved track areas, disrupting normal operations. Sea-level rise can endanger the continued use of assets in low-lying areas, which are vulnerable to permanent or temporary inundation, thereby interrupting normal operations. Heavy rain can cause landslides that damage tracks and facilities. High winds can topple trees and blow other debris onto tracks and roads and disrupt communication. Storms can produce bridge scour (the cumulative weakening effect of waterborne particles), and strong-enough storms can cause severe bridge damage. Critical physical infrastructure for train control, monitoring, and communication for rail systems can overheat and malfunction. Overhead catenary wires can fail in extreme heat, leading to loss of power (Hodges, 2011). Heat can cause tracks to buckle, which can lead to derailments, and agencies generally issue “slow orders” as a precaution to allow railcars to stop more easily if they encounter this (Chinowsky et al., 2019). If air-conditioning does not work, staff and riders could be exposed to dangerous heat. Finally, wildfire can damage vehicles, buildings, tracks, and roads and lead to service suspensions.

Drought could affect transit through making energy sources less available and more expensive. This is true for both electricity and liquid fuels. Drought can limit hydropower supplies (a key electricity source in region 10) (Hodges, 2011) and increase the cost of extraction of liquid fuels (Pagoulatos, Pagoulatos, and Debertin, 1977; Skjærseth and Skodvin, 2001; Verbruggen and Al Marchohi, 2010; Wuebbles et al., 2017). Without ready access to energy sources, transit provision could be limited by energy shortages, blackouts, or high prices. This is rated at risk of moderate disruption by 2100.

For example, researchers on one study estimated ridership changes caused by air mass. See Kalkstein et al., 2009.
Cascading Risk
Transport Passengers by Mass Transit is critically dependent on the following NCFs:49

- Transport Cargo and Passengers by Road
- Distribute Electricity
- Fuel Refining and Processing Fuels

Transportation by mass transit requires road-based transportation both for passengers to stations and because buses, the transit mode with the highest ridership, operate on roads (Office of Budget and Policy, 2020). Most transit modes operate on some kind of fossil fuel or electricity (Davis and Boundy, 2021). PNT systems are used for vehicle location (DOT, undated; Wallischeck, 2016).

Other Factors Driving Risk
Underlying the risk ratings for Transport Passengers by Mass Transit are key factors that contribute to the risk ratings. This NCF is heavily dependent on physical infrastructure, but more than 40 percent of bus assets and 25 percent of rail assets have been assessed in marginal or poor condition, often because of deferred maintenance (Rose et al., undated). When infrastructure is not in a state of good repair, it is more vulnerable to damage from extreme weather events than infrastructure that has been adequately maintained (Giglio, Friar, and Crittenden, 2018). In addition, transit demand is strongly tied to economic development and employment (because commute trips are the primary reason customers use transit), so lack of economic growth or high unemployment can reduce the revenues needed to maintain transit infrastructure. This can, in turn, reduce ridership, leading to an outcome commonly called a “transit death spiral” (Learner, 2020).

Strength of Evidence
There is relatively little research on climate drivers’ effects nationally on public transit systems specifically. This is likely due to a combination of the fact that transit is local, so studies from one transit agency are not easily generalizable to other agencies, and that climate drivers’ effects will vary depending on the mode of transit. For example, one Federal Transit Administration report provides case studies of transit and potential climate change effects from a variety of cities and transit systems, including heavy rail in the San Francisco Bay area, heavy rail and buses in Chicago, light rail in Houston, and bus-only systems in Tampa and Galveston. Risks vary with location, as well as with the type of transit system (Office of Budget and Policy, 2014).

49 Critically dependent NCF was defined as an NCF that, if disrupted or in failure, would severely disrupt a given NCF and for which a given NCF could not recover until the upstream NCF was sufficiently operational. Upstream was defined as providing a key input to a downstream NCF.
Transport Cargo and Passengers by Road

Scorecard

SUMMARY: Transport Cargo and Passengers by Road is at risk of minimal disruption from climate change by 2030 primarily because of the effects that flooding, sea-level rise, tropical cyclones and hurricanes, severe storm systems, and heat are anticipated to have on physical road infrastructure, including bridges and tunnels, and, to a lesser extent, on vehicles. The table includes only drivers and subfunctions with risk ratings of 2 or higher.

1 = no disruption or normal operations.
2 = minimal disruption. 3 = moderate disruption.

Transport Cargo and Passengers by Road: “Provide and operate roadway systems, assets, and facilities—including commercial motor carriers and associated facilities, motor coaches, buses, and associated systems, assets, and facilities—to enable a system of securely and safely conveying goods and people from place to place by highway” (CISA, 2020, p. 3).

Highest-Risk Climate Drivers

<table>
<thead>
<tr>
<th>MECHANISMS OF IMPACT</th>
<th>Current Emissions</th>
<th>High Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2030</td>
<td>2050</td>
</tr>
<tr>
<td>Physical damage or disruption</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Input or resource constraint</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Workforce shortage</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Demand change</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

The shade of gray indicates the strength of evidence for that NCF: dark gray = strong evidence and medium gray = moderate evidence. We also found weak evidence for drought and moderate evidence for extreme cold.

Highest-Vulnerability Subfunctions

<table>
<thead>
<tr>
<th>CASCA DING RISK</th>
<th>Current Emissions</th>
<th>High Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Provide Road System</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Transport Passengers by Road</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Maintain Road Transit Workforce</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Synopsis

Transport Cargo and Passengers by Road is vulnerable to multiple climate drivers, largely through potential effects on the roadway network itself but also through potential damage to vehicles and harm to the road construction workforce. The roadway network includes various types of roads, along with bridges and tunnels. Potential damage to surface roads due to changes in climate drivers tends to occur more gradually over time. For example, additional maintenance might be needed to keep roads in a state of good repair. A small proportion of roads could be vulnerable to landslides or slope failure brought on by storms. Damage to roads can be caused by multiple climate drivers: extreme heat, flooding, sea-level rise, and wildfire. Bridges can suffer more-catastrophic effects, such as bridge collapse, because of high winds and bridge scour (the cumulative weakening effect of waterborne particles). Tunnels can flood with sea-level rise and storms with heavy precipitation (both tropical cyclones and hurricanes and severe storm systems).

Although the climate drivers can affect the roadway network through any of a variety of mechanisms, collectively, these effects suggest risk of minimal disruption due to climate change. This is because the country’s extensive roadway network means that there are generally multiple routes available between origins and destinations, because roadway damage is generally confined to specific areas, and because only a small fraction of the country’s roads (about 1.5 percent) are in coastal zones that could be permanently inundated (Douglass and Krolak, 2008).
Subfunctions

The largest effects are anticipated on the subfunction Provide Road System because the main mechanism by which climate change affects this NCF is through damage or disruption of its physical infrastructure: roads, bridges, and tunnels. All three types of roadway infrastructure can be damaged by flooding and sea-level rise, with underground tunnels being particularly vulnerable. Bridges can also be damaged by high wind during severe storms or hurricanes. This subfunction is rated at risk of minimal disruption by 2030 because the effects that these climate drivers have on physical infrastructure are generally localized and affect only a very small fraction of the national road network at any given time.

Transport Passengers by Road is affected because of the effects on the vehicles themselves, which can be physically damaged by some of the climate drivers (e.g., flooded, blown off the road by high winds from storms, destroyed in wildfire). This suggests a risk of minimal disruption by 2100 because these impacts worsen over time. Maintain Road Transit Workforce is affected because, although climate change might not directly affect the ability to attract and retain workers, it could affect workers’ ability to function outdoors if temperatures are too hot to work safely. This could limit the ability to carry out road construction and maintenance work (NIOSH, 2016) or prompt changes in construction policies, such as carrying out more work at night when temperatures are lower (Arizona Department of Transportation, 2011). This could reach a risk of minimal disruption by 2100 as extreme heat continues to worsen and road construction and maintenance are delayed.

Climate Drivers

Transport Cargo and Passengers by Road can be affected by extreme heat, flooding, sea-level rise, severe storm systems, tropical cyclones and hurricanes, and wildfire. Flooding can wash out roads and severely damage bridges, requiring rehabilitation or reconstruction of damaged areas. Depending on the road segment or bridge, detours can impose additional costs on drivers. Flooding also produces bridge scour, which can weaken structural support and lead to bridge collapse; according to one analysis, by 2100, between 40 and 80 percent of bridges will be vulnerable, depending on location (EPA, 2017). Flooding can also damage and destroy vehicles.

Sea-level rise can cause inundation, nuisance flooding, or high-tide flooding, rendering the roadway unusable either permanently or temporarily, depending on the depth of the water (Douglass and Krolak, 2008). Even if roadways are not themselves inundated, higher groundwater tables can weaken roadway base materials, thus requiring more-frequent maintenance (Knott et al., 2017). Tunnels are also likelier to flood with higher water tables. Bridges can be severely damaged by high winds from hurricanes and other storms. Low-clearance bridges are vulnerable to increased wave loads from storm surges that can dislodge a bridge deck. Roads can be temporarily blocked by wind-blown debris (T. Wang et al., 2020).

Extreme heat, combined with increased salinity and humidity, accelerates deterioration in concrete roads and bridges. Higher temperatures and extreme heat events can negatively affect pavement performance through pavement blowups, gradual or sudden bumps in pavement ranging from a few inches to 1 ft. (Nebraska Department of Transportation, 2016). Also, expansion joints in steel girder bridges can fail in extreme temperatures, especially if they were installed during cooler temperatures, and that can lead to possible bridge collapse (Palu and Mahmoud, 2019).

Wildfire, if sufficiently hot, can cause roadways to crack and asphalt to burn, requiring resurfacing or other maintenance. Other dangers are postwildfire, when hazard trees alongside roads might have burned in

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50 This effect is noted in NCA4. Humidity is also projected to rise, although with significant regional variation; see Coffel, Horton, and de Sherbinin, 2017. Soil salinity is expected to increase with drought (Corwin, 2021).
place and need to be cut down for safety reasons so they do not topple onto roads or vehicles (Oregon Department of Transportation, undated). A wildfire followed by precipitation can create debris flows (landslides of trees, soil, and other objects) “that can escalate the vulnerability of transportation infrastructure to severe precipitation events” (Jacobs et al., 2018, p. 489).

With one exception, all of these drivers are rated at risk of minimal disruption across all time periods because the roadway network is extensive and any specific incident is expected to affect only a small proportion of roads. Wildfire is anticipated to reach minimal risk only in 2100, as the frequency increases, but it does not generally reach major urban areas, where most roadway travel occurs. Sea-level rise is considered at risk of moderate disruption in 2100, based on analysis of the percentage of roads that would be permanently inundated (on the East Coast, 5 percent or less at 1.9 ft. [Wright and Hogan, 2008], and, on the Gulf Coast, 27 percent at 4 ft. [Kafalenos et al., 2008]). Given that the high end of sea-level rise in the high-emissions scenarios is almost 6 ft., these estimates might be conservative.

Cascading Risk
Transport Cargo and Passengers by Road is critically dependent on the following NCFs: Fuel Refining and Processing Fuels, Provide Positioning, Navigation, and Timing Services.

Transportation by road requires gasoline for most passenger vehicles and diesel fuel for most trucks (Davis and Boundy, 2021). PNT services are widely used in the trucking industry for vehicle location and routing (DOT, undated; Wallischeck, 2016).

Other Factors Driving Risk
Underlying the risk ratings for Transport Cargo and Passengers by Road are key factors that contribute to the risk ratings. Although this NCF is heavily dependent on physical infrastructure, roads, bridges, and tunnels are overall in reasonable condition. If roadway infrastructure were to be degraded in the future, this NCF would be at an elevated risk. However, the U.S. roadway network is extensive and highly redundant, so degradation would have to be very widespread before the entire NCF experienced a loss of function. In addition, regional economic development drives demand for both passenger travel and cargo. The roadway network is largely funded by user fees collected at various levels of government, so a decrease in demand could reduce these funding streams and lead to a lack of investment in maintenance. But given the roadway network’s critical importance to the U.S. economy, even when federal user fee revenues have fallen short, revenue has been transferred from other sources to ensure continued funding (Kirk and Mallett, 2020).

51 Roughly 70 percent of vehicle-miles traveled are in areas defined as urban. See Office of Highway Policy Information, 2020.
52 Critically dependent NCF was defined as an NCF that, if disrupted or in failure, would severely disrupt a given NCF and for which a given NCF could not recover until the upstream NCF was sufficiently operational. Upstream was defined as providing a key input to a downstream NCF.
53 For example, according to the Federal Highway Administration, 92 percent of U.S. bridges are in good or fair condition. See Office of Bridges and Structures, 2021.
Strength of Evidence
There is strong evidence of the ability of flooding and sea-level rise to damage the physical infrastructure of the roadway network (roads, bridges, and tunnels), as well as vehicles (Douglass and Krolak, 2008; EPA, 2017; Knott et al., 2017). There is also literature on the effects that various types of storms, as well as extreme cold and heat and wildfire, have on roadways and vehicles (T. Wang et al., 2020). Less work has been done on the effects of drought.
Exploration and Extraction of Fuels

Scorecard

National Risk Assessment

SUMMARY: Exploration and Extraction of Fuels is at risk of minimal disruption from climate change by 2050 primarily because of the effects that drought, sea-level rise, and hurricanes are anticipated to have on mining and other fuel extraction facilities. 1 = no disruption or normal operations. 2 = minimal disruption. 3 = moderate disruption. The table includes only drivers and subfunctions with risk ratings of 2 or higher.

<table>
<thead>
<tr>
<th>Exploration and Extraction of Fuels: “Identify resources and collect energetic materials (including fossil fuels, nuclear materials, and others)” (CISA, 2020, p. 6).</th>
<th>Current Emissions</th>
<th>High Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2030</td>
<td>2050</td>
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<td></td>
<td>2</td>
<td>2</td>
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</tbody>
</table>

Highest-Risk Climate Drivers

<table>
<thead>
<tr>
<th>MECHANISMS OF IMPACT</th>
<th>Drought</th>
<th>Extreme heat</th>
<th>Flooding</th>
<th>Sea-level rise</th>
<th>Severe storm systems</th>
<th>Tropical cyclones and hurricanes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical damage or disruption</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Input or resource constraint</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Workforce shortage</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Demand change</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>The shade of gray indicates the strength of evidence for that NCF: dark gray = strong evidence and medium gray = moderate evidence. We also found moderate evidence for extreme cold and wildfire.</td>
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</tbody>
</table>

Highest-Vulnerability Subfunctions

<table>
<thead>
<tr>
<th>CASCA\ begin{adjustwidth}{-2.5em}{0em}DING RISKS</th>
<th>Extract Coal</th>
<th>Extract Natural Gas</th>
<th>Explore for Natural Gas</th>
<th>Extract Petroleum</th>
<th>Explore for Petroleum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upstream linkages: 6</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Downstream linkages: 3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Upstream and downstream linkages are detailed in Chapter Six.</td>
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</tbody>
</table>

Synopsis

Fuel extraction and exploration are vulnerable to most assessed climate drivers because of the geographic distribution of critical infrastructure related to the NCF across the United States in many climate-vulnerable areas, reliance on water supply, and the sector’s lack of preparation to harden fuel extraction infrastructure to climate change. For example, sea-level rise on the East Coast and hurricane events along the Gulf Coast could cause significant damage to exploration and extraction wellheads. Sustained drought conditions threaten reliable sources of water that are used for mining equipment. The increased intensity and frequency of climate events are likely to stress the maintenance and response operations put in place to mitigate infrastructure vulnerabilities.

However, although these climate change–driven disruptions will have cascading effects on a regional basis on NCFs and sectors that rely on fuels, the interconnected redundancies that exist throughout national and international fuel markets increase resilience to national cascading failures of this NCF. Overall, this assessment found that Exploration and Extraction of Fuels is at risk of minimal disruption from climate change by 2050.
Subfunctions
Half of the Exploration and Extraction of Fuels subfunctions face minimal disruption due to climate change by 2100. The subfunctions facing this risk are those that depend more for downstream fuel consumption or are more prevalent in the United States. For example, the Extract Nuclear Fuel subfunction does not experience as much climate risk simply because the United States relies primarily on numerous redundant and diverse foreign supply chains for its nuclear fuel. However, extreme weather that degrades or destroys fuel extraction and exploration sites and supporting infrastructure can lead to significant regional interruptions resulting in the inability to provide continuous fuel to downstream NCFs (Skjærseth and Skodvin, 2001). The primary fuels for which exploration and extraction operations are most affected by climate change are coal, natural gas, and petroleum. Disruptions to these sectors can cause fuel shortages and regional economic loss, with prolonged outages propagating economic losses nationally or globally (Judson, 2013; Painter, 2012).

For Exploration and Extraction of Fuels subfunctions Explore for Natural Gas, Extract Natural Gas, Extract Coal, Explore for Petroleum, and Extract Petroleum, hazards exacerbated by climate change could minimally disrupt the ability to provide continuous fuel nationally by 2100.

Climate Drivers
Most climate drivers pose risks to fuel extraction and exploration; however, climate risk varies regionally because of regional differences in climatology (Wuebbles et al., 2017). Fuel exploration and extraction infrastructure is vulnerable primarily to climate drivers that cause volatility in water supply, such as droughts. Drilling exploratory wells is highly dependent on available water resources (Zabbey and Olsson, 2017). According to historical impacts and projected exposure of critical fuel exploration and extraction assets, drought, sea-level rise, and hurricanes are projected to pose the largest risk to fuel extraction by 2100. Projected changes in global mean tropical cyclone and hurricane wind speeds and precipitation rates will likely increase, and the frequency of tropical cyclones and hurricanes might remain the same as seen in the historical record. Estimates of increases suggest that these changes are likely by the end of the 21st century, with more-moderate increases occurring by midcentury. These climate effects have already affected the offshore wellheads in the Gulf of Mexico, and this trend is likely to continue into the future. Fuel exploration and extraction disruption from climate hazards could cause cascades to other NCFs within a region, but cascading risk between regions due to climate drivers is much rarer because of the regional confinement of climate disasters and the supply redundancies present in international fuel markets.

Cascading Risk
Exploration and Extraction of Fuels is critically dependent on the following NCFs:54

- Distribute Electricity
- Transmit Electricity
- Generate Electricity
- Store Fuel and Maintain Reserves
- Fuel Refining and Processing Fuels
- Supply Water.

54 Critically dependent NCF was defined as an NCF that, if disrupted or in failure, would severely disrupt a given NCF and for which a given NCF could not recover until the upstream NCF was sufficiently operational. Upstream was defined as providing a key input to a downstream NCF.
Fuel extraction and exploration are part of four interconnected NCFs within the NCF framework—Exploration and Extraction of Fuels, Store Fuel and Maintain Reserves, Supply Water, and Fuel Refining and Processing Fuels—that represent the production and commercialization of refined fuel products. If any of these four NCFs should fail, the others could experience significant disruption nationally. Additionally, the generation and transmission of electricity are critical to continued operation of fuel extraction and exploration sites. Should any of the electricity NCFs fail, maintaining continuous fuel extraction operations would likely be exceptionally difficult.

Other Factors Driving Risk
Fuel extraction and exploration are sensitive to international fuel markets that determine the financial viability of continuous operation. Climate threats to these supply chains can cause significant uncertainty to fuel extraction operations. Market uncertainty and fuel price volatility can reduce the profitability of these fuel operations, causing them to shut down temporarily. However, when a fuel extraction site shuts down, a ramp-up period is often required to reestablish the site’s production. This can occur on a regional basis and have cascading effects across other regions and NCFs.

Strength of Evidence
There are gaps in the body of existing literature and studies of climate's risk to fuel extraction and exploration. The sector's professionals have been identified as having a “knowledge gap” in the quantification of potential losses from climate risks (Verbruggen and Al Marchohi, 2010). There has not been enough preparation or measurement of how extreme weather events can affect the geomorphology of critical fuel extraction and exploration infrastructure. This has limited sector professionals’ understanding of how climate could affect their infrastructure climate by 2100. Studies have detailed risks to the NCF-related infrastructure by U.S. region (Glick and Christiansen, 2019; Wakiyama and Zusman, 2021), and complementary studies have analyzed climate risk to supporting infrastructure and components from other countries (Turner et al., 2017) and can be used to assess and substantiate risk ratings. However, more work could be done to estimate climate’s risk to fuel exploration and extraction infrastructure.
Assessing Risk to the National Critical Functions as a Result of Climate Change

Provide Insurance Services

Scorecard

National Risk Assessment

SUMMARY: Provide Insurance Services is at risk of minimal disruption from climate change by 2050 primarily because of the effects that drought, flooding, hurricanes, and wildfire are anticipated to have on the pooling of multiple exposures to transfer insurable risk.

1 = no disruption or normal operations.
2 = minimal disruption. 3 = moderate disruption. The table includes only drivers and subfunctions with risk ratings of 2 or higher.

Provide Insurance Services: “Operate systems and markets to transfer financial risks among parties through contractual relationships, including products for individuals, corporations, and public-sector entities” (CISA, 2020, p. 5).

<table>
<thead>
<tr>
<th>Highest-Risk Climate Drivers</th>
<th>Current Emissions</th>
<th>High Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2030</td>
<td>2050</td>
</tr>
<tr>
<td>Drought</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Extreme heat</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Flooding</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Sea-level rise</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Severe storm systems</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Tropical cyclones and hurricanes</td>
<td>1 2 2</td>
<td>2 2 3</td>
</tr>
<tr>
<td>Wildfire</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Highest-Vulnerability Subfunction

CASCADING RISK
Upstream linkages: 3
Downstream linkages: 1
Upstream and downstream linkages are detailed in Chapter Six.

Pool Multiple Exposures to Transfer Insurable Risk

Synopsis

In the absence of behavior changes of insurers and the insured, insurers will be exposed to greater losses in response to changes in climate drivers and in response to ongoing development of housing and infrastructure in areas that are at risk (Bevere and Weigel, 2021; Wuebbles et al., 2017). For insurers, these losses could result in reduced profits, firm-level insolvencies, and greater reliance on the reinsurance market (Collier, Elliott, and Lehtonen, 2021). Proper pricing of risk will become increasingly difficult as climate conditions depart from the historical climate on which actuarial risk estimations are based (Kunreuther and Michel-Kerjan, 2007). Insurers will necessarily respond to changes in risk by adjusting premiums for insured assets, denying coverage, and shifting their business models to incentivize mitigation (Moody’s Investors Service, 2018). These changes in insurer behavior could increase the costs of insurance for consumers and reduce the availability of insurance in some markets, as it already has in wildfire-prone areas of some western states (Kaufman and Roston, 2020). These cost increases and reductions in availability could, in turn, drive (and, to some extent, are already driving) expansion of publicly backed insurance schemes, such as the National Flood Insurance Program and the California Fair Access to Insurance Requirements Plan for fire insurance.

There is also some risk that certain carbon-intensive industries and firms (mostly in the petrochemical and energy production sectors) would be held liable for climate-related damage to personal property and infrastructure in the same way that manufacturers of tobacco products and asbestos have been held liable for actions that took decades to manifest as harms in public health. Although this development appears unlikely...
at present, mounting damage from climate change could drive changes in the tort system (Kysar, 2011). This development has the potential to be extremely expensive, and much of the resulting burden could fall to insurers (Faure and Peeters, 2011; Faure and Peeters, 2019).

Ultimately, the provision of insurance is likely to have growing importance in response to climate change. But how it is provisioned, to whom, and under what conditions will be contingent more on how insurers respond to risk (Lucas and Booth, 2020). Changes in the accessibility of insurance are likely to have strong regional elements, with assets exposed to flooding, sea-level rise, and wildfire being particularly implicated (Lamond and Penning-Rowsell, 2014).

**Subfunctions**

Climate change does not appear to directly affect the subfunctions Provide Surety Services and Negotiate Over-the-Counter Derivatives to Transfer Risk. Risk to this NCF comes primarily through its third subfunction, Pool Multiple Exposures to Transfer Insurable Risk. Insurance markets depend on reasonably stable risk levels and low levels of correlation between the risks to various insured properties (S. S. Wang, 1998). Risk is generally estimated and priced based on historical experience, leading to real difficulties in pricing risk in a situation in which climate has changed enough to produce new (now unknown), expected levels of loss. Climate change also has the potential to create strongly correlated risk, in which losses to many assets happen at the same time and place—greatly complicating the calculation of expected losses and requiring extremely large payouts. Correlated risk has traditionally created market problems in the flood and wildfire insurance markets, in which government support has been required in high-risk areas. These issues are likely to get worse, and the other climate drivers also tend to produce highly correlated regional risk (Wuebbles et al., 2017).

Because insurance markets are generally functioning at present, this NCF is rated 1 across all drivers except for wildfire, for which some areas are already seeing failures of the market, but changes before 2050 are likely to cause potentially problematic losses in drought, flooding, and hurricanes. By 2100, all of the analyzed climate drivers have the potential to produce problematic correlated losses, with flooding, sea-level rise, and wildfire likely to produce major failures in regional settings.

**Climate Drivers**

The climate drivers included in this risk assessment all cause damage to insurable goods and real property, and the insurance industry is often liable for covering the resulting damage. Increased levels of risk do not necessarily pose problems to the industry as long as it can properly price this risk and cover any resulting losses. Flood- and fire-related climate drivers have the potential to create losses that are so extensive and regionally correlated that they could cause insurers to withdraw from at-risk markets, resulting in a failure of the insurance market. Flooding is traditionally a challenging risk to insure against because of regionally correlated losses (Lamond and Penning-Rowsell, 2014). More-frequent flooding will increase these problems and could require additional government support for flood insurance, without which affected regional insurance markets could collapse (Kousky, 2018).

Sea-level rise has the potential to increase losses drastically in low-lying coastal areas (Jevrejeva et al., 2018). Risks to buildings and infrastructure are primarily from storm surges when a higher mean water level interacts with high tides that coincide with storm winds. Increased coastal risk could lead to insurers’ withdrawal from these areas in the face of potentially unmanageable losses. Similarly, increased flooding risk could produce large losses for the federal flood insurance program (Lamond and Penning-Rowsell, 2014).

Hurricanes can be extremely expensive for insurers because they affect a large percentage of structures in a region, producing correlated losses, which have the potential to be destabilizing and lead to the with-
drawal of insurance services from areas at risk. Climate change is expected to increase hurricane frequency and severity.

Extreme heat can damage infrastructure directly and gives rise to crop failures, drought, and fire losses. Increases in extreme heat will result in both increased rates of loss and correlated losses (Hussain and Cohn, 2021). Insurance rates are based on expected losses that are, in turn, estimated from historical losses. For some drivers, climate change could produce losses that are greater than those that would be expected from historical precedent. This could result in unexpectedly large loss events that trigger major reevaluations of risk and sudden increases in insurance premiums for affected sectors as was seen in the western United States following the 2018 wildfire season (Hussain and Cohn, 2021). These loss events could cause some damage to the insurance industry but are unlikely to impose costs that are beyond the industry’s ability to adapt. Wildfire can cause complete losses over a limited region, creating locally correlated losses. These fires tend to take place in less populated areas, and the resulting losses are not likely to become large enough to destabilize the insurance industry. They might, however, cause the failure of insurance markets in some areas. Drought causes crop failures and other insured losses that are correlated over a very wide area (Hornstein, 2016). Crop losses are likely to be the largest concern with respect to drought.

**Cascading Risk**

Provide Insurance Services is critically dependent on the following NCFs:55

- Distribute Electricity
- Provide Internet Routing, Access, and Connection Services

The immediate operation of the insurance industry relies heavily on IT and digital communication. All of this requires electricity. Communication within the industry requires functional internet services, and communication with insured parties and field adjusters often depends heavily on mobile device communications, which require wireless access network services. These dependencies might not pose a major threat of disruption because the insurance industry works on a longer time scale than the duration of most electricity and communication outages. In many cases, insurers can continue to operate by shifting their computing operations to areas that are not affected by electrical outage, and delays in claim processing created by communication outages can be resolved when communication is restored, resulting in full delivery of insurance services—even if they are delayed by some days.

**Other Factors Driving Risk**

Insurance services require competent governance and management in order to function efficiently because of the information asymmetries that are inherent in the insurance business. States have insurance commissioners because regulation is essential to making these markets work. IT is the functional lifeblood of the insurance industry, with data storage, retrieval, and analysis underlying essentially all aspects of its functioning. Without access to centralized computers and workflows, the industry cannot assess and price risk, evaluate claims, or pay settlements. The industry also relies on infrastructure for communication and transportation services that are central to its work. These infrastructure elements (broadly defined) also make up

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55 *Critically dependent NCF* was defined as an NCF that, if disrupted or in failure, would severely disrupt a given NCF and for which a given NCF could not recover until the upstream NCF was sufficiently operational. *Upstream* was defined as providing a key input to a downstream NCF.
a large proportion of the things that are covered by insurance—meaning that large-scale damage to infrastructure creates potentially destabilizing losses for insurers.

**Strength of Evidence**

A growing body of work has explored climate change’s potential effects on insurance services (Collier, Elliott, and Lehtonen, 2021). Because the industry relies on accurate assessments of risk, it also generates substantial literature on the topic. Although the functioning of the insurance services industry is well understood, as are best practices for managing high-consequence events and correlated risks, the shifting nature of the risks themselves is less well understood (Moody’s Investors Service, 2018). For this reason, many of the unknowns in assessing the Provide Insurance Services NCF trace back to unknowns in the effects of climate change itself, with gaps in understanding related to expected storm frequency and severity, extreme cold weather events, and drought incidence being particularly evident (Wuebbles et al., 2017).
Transport Cargo and Passengers by Rail

Scorecard

SUMMARY: Transport Cargo and Passengers by Rail is at risk of minimal disruption from climate change by 2030 primarily because of the effects that flooding, sea-level rise, tropical cyclones and hurricanes, severe storm systems, and heat are anticipated to have on physical rail infrastructure, including track and stations.

1 = no disruption or normal operations. 2 = minimal disruption. 3 = moderate disruption. The table includes only drivers and subfunctions with risk ratings of 2 or higher.

Highest-Risk Climate Drivers

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Flooding</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sea-level rise</td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Hurricanes</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Severe storm systems</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Extreme heat</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Wildfire</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Highest-Vulnerability Subfunctions

CASCADING RISKS

Upstream linkages: 5
Downstream linkages: 0
Upstream and downstream linkages are detailed in Chapter Six.

Provide Rail Systems

Maintain Rail Workforce

Synopsis

Transport Cargo and Passengers by Rail is vulnerable to climate change because any of several climate drivers, including flooding, sea-level rise, and storms, can damage the physical infrastructure (primarily tracks and stations). These effects are anticipated to cause minimal disruption through 2100. These climate drivers can damage infrastructure directly, or they can affect the surrounding areas (e.g., via landslides or slope failure) (Palin et al., 2021). Extreme heat can cause rail track to buckle, leading to unsafe conditions, and the need to run trains more slowly can increase overall operating costs (Chinowsky et al., 2019). Some rail infrastructure is more than 150 years old and was built prior to development of modern engineering standards, making its resilience to climate effects uncertain (Palin et al., 2021). However, these effects tend to be very localized, and the rail network is spread throughout the country. Most rail infrastructure is privately owned and not redundant (i.e., there are not generally multiple sets of tracks between specific origins and destinations), so if one section of rail track is not available because of damage, rerouting trains could lead to substantial detours (see, e.g., “California Fires Disrupt BNSF,” 2021).

Subfunctions

The primary subfunction likely to be at risk of disruption by climate change is Provide Rail Systems because the primary mechanism by which climate change affects this NCF is through potential damage to the physical infrastructure of rail and stations. This subfunction is rated at risk of minimal disruption by 2030 because...
this infrastructure is spread widely throughout the country, and the main geographic choke point, the Chicago area, is not at heightened climate risk. The Maintain Rail Workforce subfunction is assessed to be less affected. Although climate change is not expected to directly affect the ability to attract and retain the skilled workers required to operate the rail transportation system, it could affect workers’ ability to function outdoors if temperatures are too hot to work safely (NIOSH, 2016). This could reach a risk of minimal disruption by 2100 because of temperatures halting outdoor work. This effect would vary by region, depending on the combination of future heat and humidity.

**Climate Drivers**

Extreme heat, flooding, sea-level rise, severe storm systems, hurricanes, and wildfire are the main climate drivers of concern for this NCF. They can lead to infrastructure slope failure; bridge scour; inundation of track, tunnels, and buildings; and water damage to electronic equipment. Any of these can disrupt rail operations by rendering track unusable until cleared or creating unsafe operating conditions, and scour can cause bridge collapse (Palin et al., 2021). Extreme heat can cause tracks to buckle, which can lead to derailments. In extreme heat conditions, train operators move train traffic more slowly through affected areas as a precaution, which leads to operating delays (Chinowsky et al., 2019). Wildfire can damage track and stations (Marsh, 2021). Although extreme cold can also cause damage to physical infrastructure, extreme cold events are anticipated to be fewer with climate change. Although drought could affect rail transportation through slope failure or through track or overhead pole misalignment, this risk has not been extensively studied (Palin et al., 2021).

These effects are general effects on rail infrastructure. There has been less study of specific effects based on the location of that infrastructure within the United States. Amtrak, the country’s passenger rail system, conducted a climate study in 2015 that assessed 10 miles of track along its busiest corridor, the Northeast Corridor (which is about 450 miles long). In 2050, four half-mile segments are at high vulnerability from sea-level rise; by 2100, the entire 10-mile segment will be.56 Freight rail is more heavily concentrated in the middle of the country, where flooding presents a greater risk.57 Flooding could reach a risk of moderate disruption by 2100.

**Cascading Risk**

Transport Cargo and Passengers by Rail is critically dependent on the following NCFs:58

- Transport Cargo and Passengers by Road
- Fuel Refining and Processing Fuels
- Distribute Electricity
- Transport Cargo and Passengers by Vessel

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56 Although the report states that it is creating a framework for analyzing the entire corridor, at the time of this writing, no corridor-long assessment is available (Amtrak and Stantec, 2015).

57 Two severe floods that affected rail in the Midwest took place in 1993 and 2019. See Meyer and Larson, 2021.

58 *Critically dependent NCF* was defined as an NCF that, if disrupted or in failure, would severely disrupt a given NCF and for which a given NCF could not recover until the upstream NCF was sufficiently operational. *Upstream* was defined as providing a key input to a downstream NCF.
Transportation by rail requires road-based transportation for both goods and people (staff and passengers) to reach rail stations; it is also heavily reliant on carrying shipments to and from seaports (Bureau of Transportation Statistics, 2020). Freight rail is largely powered by diesel fuel, while some passenger rail service requires electricity (Nunno, 2018). Rail operations rely on PNT services (DOT, undated; Wallischeck, 2016).

Other Factors Driving Risk
Underlying the risk ratings for Transport Cargo and Passengers by Rail are key factors that contribute to the risk ratings. Although this NCF is heavily dependent on physical infrastructure, rail track and stations are overall in reasonable condition.59 If rail infrastructure were to be degraded in the future, this NCF would be at an elevated risk. Although the rail network is extensive, most track and rolling stock are privately owned by freight rail carriers, so cargo cannot be easily shifted between carriers. In addition, regional economic development drives demand for both passenger travel and rail cargo; in a sluggish economy, demand for both long-distance travel and freight movement declines. The vast majority of rail track in the country is owned by private freight rail companies,60 so a decline in demand can lead to a loss of revenue, which would diminish those companies’ ability to make continued investments in rail infrastructure maintenance.

Strength of Evidence
There is strong evidence of extreme heat’s effect on railway tracks; this is a well-known vulnerability, and railroad operators already have speed precautions in place to prevent problems due to heat buckling (Baker et al., 2010). There is also literature on the effects of water-related damage (which could be caused by various types of storms) (Palin et al., 2021). Less work has been done on the effects of drought and wildfire. Although either of these drivers could affect rail operations through damage to physical infrastructure, we did not locate any systematic analysis on how widespread or damaging either driver might be.

59 In its most recent infrastructure report card, ASCE gave U.S. rail infrastructure a grade of B. See ASCE, 2021e.
60 Although Amtrak owns most of its most–heavily traveled tracks in the Northeast Corridor, overall, 72 percent of the miles that its trains travel are on rail owned by freight railroads (Amtrak, 2019).
Support Community Health

Scorecard

**SUMMARY:** Support Community Health is at risk of minimal disruption from climate change by 2050 because the increase in the frequency of injuries and diseases stemming from climate events will increase the demand for disease surveillance, lab testing, community outreach, and other public health efforts.

1 = no disruption or normal operations. 2 = minimal disruption. The table includes only drivers and subfunctions with risk ratings of 2 or higher.

Support Community Health: “Conduct epidemiologic surveillance, environmental health, migrant and shelter operations, food establishment inspections, and other community-based public health activities” (CISA, 2020, p. 6).

<table>
<thead>
<tr>
<th>Highest-Risk Climate Drivers</th>
<th>Current Emissions</th>
<th>High Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2030</td>
<td>2050</td>
</tr>
<tr>
<td>Drought</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Extreme heat</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Flooding</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Sea-level rise</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Severe storm systems</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Tropical cyclones and hurricanes</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Wildfire</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Highest-Vulnerability Subfunctions</th>
<th>Current Emissions</th>
<th>High Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>CASCADING RISK</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upstream linkages: 6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Downstream linkages: 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upstream and downstream linkages are detailed in Chapter Six.</td>
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</tr>
</tbody>
</table>

Track Community Health: 1 2 2 1 2 2
Communicate Health Information: 1 2 2 1 2 2
Support Emergency Response: 1 2 2 1 2 2

Synopsis

Support Community Health is anticipated to be at risk of minimal disruption from climate change as each of the climate drivers causes or exacerbates disease, affecting the health of the population and thus increasing demand for this NCF.

An increase in severe storms and flooding is expected to lead to a corresponding increase in injuries and disease in the affected populations. Extreme cold could lead to an increase in hypothermia, particularly among poor and elderly, who often cannot or do not sufficiently heat their homes. Extreme heat can lead to an increase in chronic illnesses, including heart, lung, and kidney problems, and can cause issues with fetal health. Heat can also increase the number of mosquitoes and ticks and thus vector-borne illnesses, as well as water-related illnesses, such as those caused by toxic algal bloom. Ozone levels and airborne allergens are expected to increase as well. Wildfire adversely affects air quality through smoke, and it increases levels of particulate matter. Drought can lead to an increase in dust storms, which, in turn, can cause or inflame respiratory diseases. Drought can also affect the availability, safety, and nutrient content of food, which, in turn, will have an effect on health. More generally, more-frequent disasters are expected to cause a disruption in the provision of health care and food supplies, which can adversely affect health. Mental health issues are also expected to increased because of climate-related disasters, leading to a greater need for disease surveillance, lab testing, and the development of countermeasures. An increase in community outreach efforts will also be necessary (Anderson et al., 2017; Carlton et al., 2016; Levy et al., 2016; Reidmiller et al., 2018).
By 2030, the Support Community Health function is expected be able to work normally, meeting routine operational needs. However, in the current-emissions scenario, by 2050, there will be increases in the frequency, intensity, and duration of nearly all of the climate drivers (except flooding), leading to an increase in demand for this NCF, which we assess will lead to a minimal disruption of the function, although the NCF is still expected to meet routine operational needs. In the high-emissions scenario, the frequency, intensity, and duration of flooding and extreme heat emergencies are expected to increase, potentially causing greater effect on the NCF, although the level of disruption is still assessed to be minimal.

Subfunctions
The subfunctions at greatest risk for this NCF are those for which demand would be expected to increase as the result of increased disease caused by climate change. Demand for Track Community Health is expected to increase as demand grows for disease and injury information needed for early detection of threats and the development of countermeasures. Demand for Communicate Health Information would increase as public health agencies educate members of the public on what actions to take to protect themselves. Finally, demand for Support Emergency Response would increase as the number of events causing emergencies and disasters increases.

Demand for Administer Public Health System and Promote Secure Operations would not be expected to increase per se because these are administrative and regulatory functions that would not be affected by changes in climate.

Climate change could also affect Enable Health Supply Chain because flooding, storms, and wildfire have the capacity to disrupt manufacturing facilities, as well as the transportation of goods, through the actual or threatened destruction of infrastructure. However, this subfunction focuses on the more general establishment of the industrial base and relations among different elements of the supply chain.

Climate Drivers
Nearly all climate drivers will have at least a minimal effect on the support of community health. This is because drought, extreme heat, severe storm systems, tropical cyclones and hurricanes, and wildfire all affect population health and are all expected to increase.

The one exception is extreme cold. Extreme cold does create community health problems, particularly in the elderly and in economically vulnerable populations, which would warrant public health action. However, the overall projection is that extreme cold events will not increase over current levels, so the effect on the operating of this NCF is not expected to change.

Cascading Risk
Support Community Health is critically dependent on the following NCFs: 61

- Distribute Electricity
- Transport Cargo and Passengers by Road
- Maintain Supply Chains
- Provide Medical Care

61 Critically dependent NCF was defined as an NCF that, if disrupted or in failure, would severely disrupt a given NCF and for which a given NCF could not recover until the upstream NCF was sufficiently operational. Upstream was defined as providing a key input to a downstream NCF.
• Maintain Access to Medical Records
• Operate Government.

The key functions of supporting community health include disease surveillance, lab testing, communicating to the public, coordinating among health care entities, and enabling the health supply chain. These functions require operational facilities with working utilities, especially electricity. They also require personnel who can arrive at their jobs and therefore need functioning transportation. Although the functions of public health departments are distinct from those of Provide Medical Care, they are nonetheless intertwined, with much of the data required by public health departments, such as incidence of disease and hospital bed capacity, collected by health care providers and institutions. Finally, because public health departments serve a governmental function, an operating government is required to support their work.

Other Factors Driving Risk
The key functions of supporting community health include disease surveillance, lab testing, communicating to the public, and coordinating among health care entities. Because this function requires coordination among public- and private-sector entities, strong institutions are required. In addition, because supporting community health requires communication with and cooperation of the public, maintaining the public’s trust in institutions is critical (Office of the Assistant Secretary for Preparedness and Response, 2016).

Strength of Evidence
Evidence on climate change’s effect on human health is well established and has been recognized by government agencies (Anderson et al., 2017; Reidmiller et al., 2018). A logical conclusion to draw is that an increase in health effects would cause a corresponding increase in the need to track health, communicate with the public, and support emergency response. However, the magnitude of that effect in terms of increased workload of public health departments is not well documented. Also unclear is whether any causal relationship exists between climate change and the other administrative and coordination subfunctions.
Produce and Provide Human and Animal Food Products and Services

Scorecard

National Risk Assessment

SUMMARY: Produce and Provide Human and Animal Food Products and Services is at risk of minimal disruption from climate change by 2050 primarily because of the effects that flooding, sea-level rise, tropical cyclones and hurricanes, and severe storm systems are anticipated to have on the Store Food, Process and Package Food Product, Distribute Food Products, and Maintain Infrastructure subfunctions.

1 = no disruption or normal operations. 2 = minimal disruption. The table includes only drivers and subfunctions with risk ratings of 2 or higher.

Highest-Risk Climate Drivers

<table>
<thead>
<tr>
<th>MECHANISMS OF IMPACT</th>
<th>Extreme heat</th>
<th>Flooding</th>
<th>Sea-level rise</th>
<th>Severe storm systems</th>
<th>Tropical cyclones and hurricanes</th>
</tr>
</thead>
<tbody>
<tr>
<td>☑ Physical damage or disruption</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>☑ Input or resource constraint</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>☑ Workforce shortage</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>☐ Demand change</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

We also found strong evidence for drought and wildfire and weak evidence for extreme cold.

Highest-Vulnerability Subfunctions

<table>
<thead>
<tr>
<th>CASCADING RISKS</th>
<th>Make Capital Investments</th>
<th>Store Food</th>
<th>Process and Package Food Product</th>
<th>Distribute Food Products</th>
<th>Maintain Infrastructure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upstream linkages: 3</td>
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</tr>
<tr>
<td>Upstream and downstream linkages are detailed in Chapter Six.</td>
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</table>

Synopsis

Food processing occurs downstream of food production and thus has less immediate and direct exposure but is still vulnerable to climate change. Increases in the frequency and severity of extreme events, such as drought, extreme heat, and flooding, all have the potential to affect the processing of harvested crops and livestock. Because extreme heat and severe storm systems physically damage and reduce crop yields (Newburger, 2019; Polansek, 2020; S. L. Wang et al., 2018; Wilde, 2021), food processing is assessed to be at risk of being able to manage variable processing levels. Flooding, tropical cyclones and hurricanes, and wildfire will significantly affect up to a third of food-processing manufacturers not later than 2050; extreme heat and flooding will affect around half of food-processing operations during the same period (Moody’s, 2021). Temperature increases, along with extreme heat instances, are very likely to affect processing, packaging, and storage, which could increase costs and spoilage, increasing food safety risks. Extreme weather events (flooding, severe storm systems, tropical cyclones and hurricanes, and wildfire), along with fluctuating extreme temperatures, can impede waterborne, railway, and road transportation in the short term (Olson et al., 2018). Temporary disruption of the supply and demand balance because of climate change and associated extreme weather events (or other factors, such as COVID-19) has already had systemic effects on the U.S. and global food systems and will only increase in the remainder of the century, which will also affect food and livestock.
as traded commodities. Labor supply is likely to be at risk as well because those working outside especially will have to manage changing severe climate conditions, including extreme temperatures and severe storm systems (Olson et al., 2018).

Subfunctions
Although processing and distribution centers (Process and Package Food Product) are increasingly located in areas where they are not immediately at risk to drivers, such as flooding and sea-level rise, these drivers will increasingly affect last-mile distribution and delivery to stores and institutions (Distribute Food Products). As long as pertinent capital investments are made, extreme cold and extreme heat should not significantly raise risk to storing and distributing food products by 2100 (Store Food and Maintain Infrastructure).

Climate Drivers
Flooding and severe storms threaten primarily those regions where commodity crops—wheat, corn, and soy—are processed and stored (such as regions 5 and 7) (Walthall et al., 2013). The rising frequency and severity of tropical cyclones and hurricanes and other severe storm systems predicted for the remainder of the century (Knutson, 2021; Kunkel et al., 2013), along with increasing temperatures, will increase risk and production costs to industries concentrated in regions 3, 4, and 6 (such as poultry [Berkhout, 2021] and pork processing [Paliwal, 2018]).

Cascading Risk
Produce and Provide Human and Animal Food Products and Services is critically dependent on the following NCFs:

- Distribute Electricity
- Transport Cargo and Passengers by Road
- Produce and Provide Agricultural Products and Services
- Maintain Supply Chains
- Transport Cargo and Passengers by Rail.

Without effective electricity distribution, livestock and plant crops cannot be processed efficiently. Once crops are harvested, each step of the processing process, including storage, processing, and transportation, requires a functioning electric grid to reduce spoilage. For the food system to operate efficiently and properly, transportation and supply chain infrastructure remain necessary to ensure the movement of food products from farms to processing facilities and markets. Of those, road and rail networks remain the most critical for transporting processed food items between regions.

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62 We did not assess that climate change would directly affect the general demand balance for food and animal products by 2030, by 2050, or by 2100. However, the U.S. food system will experience temporary effects on supply (such as the availability of raw agricultural products to process, the ability to process agricultural commodities in the face of labor shortages, or the ability to transport finished goods to market) and demand (i.e., consumers stockpiling for emergencies) as a result of severe climate events.

63 Critically dependent NCF was defined as an NCF that, if disrupted or in failure, would severely disrupt a given NCF and for which a given NCF could not recover until the upstream NCF was sufficiently operational. Upstream was defined as providing a key input to a downstream NCF.
Other Factors Driving Risk
As a result of the COVID-19 pandemic, processors and distributors are likely reconsidering just-in-time inventory and distribution schemes, which were shown to be less resilient than traditional schemes when multiple sectors were faced with supply and labor restrictions at the same time (Pisch, 2020; Shih, 2020). Cumulative extreme weather events will increase the risk and likelihood of drivers affecting multiple areas of food-processing and distribution networks concurrently. The effect on the labor market must be considered as well when assessing the resilience of the food system and its ability to return to normal business operations after a disruption. USDA’s *Action Plan for Climate Adaptation and Resilience* notes that vulnerable communities, of which agricultural workers and food-processing employees are often members, will be disproportionately affected by extreme events—such as drought, flooding, and wildfire—and the effects on the food system (USDA, 2021, p. 9). USDA plans to continue supporting these vulnerable communities.

Strength of Evidence
More research has focused on the effects that climate change and extreme weather events have on agricultural production (Produce and Provide Agricultural Products and Services) than on their effects on the production of food products and services. Literature focusing on the Produce and Provide Human and Animal Food Products and Services portion of the food system includes research by USDA (Antle and Capalbo, 2010; Rehkamp, Canning, and Birney, 2021; Canning et al., 2020), NCA4 (Olson et al., 2018), and a large body of peer-reviewed academic literature (Niles et al., 2018; Vermeulen, Campbell, and Ingram, 2012). Research on infrastructure and supply chains is often not food system–specific and considers the broader manufacturing and transportation communities, including sector-specific assessments (Moody’s, 2021). This has complicated our ability to provide a nuanced, specific assessment for this NCF.
Cascading Risks

Overview

NCFs do not operate in isolation from one another. Individual NCFs can depend on one or more other NCFs to ensure their own normal operations. For example, health care facilities require electricity and water to operate. Accordingly, Provide Medical Care is dependent on both Distribute Electricity and Supply Water. Relationships and dependencies of this type are common among the NCFs, and any given NCF might depend on other NCFs while also having one or more NCFs that depend on it.

As a result, an individual NCF’s risk from climate change can pose additional, cascading risks to other NCFs. This has several practical implications. An NCF might be assessed as not at risk of disruption from climate change but might depend on an NCF that is at risk of minimal or moderate disruption. The actual total risk associated with an individual NCF could be magnified by its dependence on an NCF that is at higher risk. Alternatively, an NCF might be assessed as being at risk of disruption but, because of other NCFs that depend on it, might represent significantly more risk to the country than is apparent by looking at the original NCF in isolation. Understanding NCF dependencies and incorporating analysis of cascading risks can help better identify which NCFs should be prioritized for mitigation.

For our study, we conducted a limited, one-way dependence analysis. For each of the 27 high-vulnerability NCFs included in this report, we identified critical upstream NCFs among the full set of 55 NCFs. We defined critical upstream NCF as an NCF that directly provides key inputs that are necessary for the continued operation of another NCF and that, if severely disrupted, would immediately cause a subsequent disruption to the other NCF. An example of this is the relationship between Produce Chemicals and Supply Water: Water treatment plants require chemicals, such as chlorine, to ensure safe operations and remain in compliance with regulations, so Supply Water is dependent on Produce Chemicals. In contrast, Operate Core Network was not considered to be a critical upstream NCF for Supply Water. Although disruption of Operate Core Network would create issues for water agencies, it would not constitute a severe disruption because operations and engineering staff could safely deliver water in its absence. We used our subject-matter expertise, knowledge of the NCFs, and available documentation on the NCFs to assess which were critical upstream NCFs.

This analysis produced two perspectives on NCF dependencies. The first identified downstream NCFs that depend on multiple upstream NCFs for their continued operation. These are NCFs that might be particularly vulnerable to climate change because of the risk of disruption of an upstream NCF, in addition to the risk posed directly to the given NCF. The second perspective identified NCFs that are critical upstream NCFs to many downstream NCFs. These are NCFs whose disruption would have a major effect on many other NCFs. Failure of an upstream NCF would therefore have particularly large consequences in excess of what might be assessed when looking at these NCFs in isolation.

As an input to our analysis, we also consulted preliminary CISA dependence analyses of all NCFs and incorporated CISA’s assessments into our own (CISA, 2020). Nevertheless, as described in the rest of this chapter, this should be considered a limited and preliminary analysis of the complex dependencies among the NCFs. We have characterized this as a one-stage dependence analysis because, for any given NCF, we con-
considered only those NCFs that are directly upstream of it. A more complete analysis could consist of multiple degrees of dependence, looking at each critical upstream NCF and identifying its critical upstream NCFs. This would require additional effort beyond what was possible for this study but might be ripe for future research.

In this chapter, we present our analysis of dependencies among the NCFs. We first examine downstream NCFs with multiple critical upstream dependencies, then examine upstream NCFs that are critical to multiple downstream NCFs. We conclude by briefly addressing dependencies within NCFs, such as risks that cascade geographically.

### Downstream National Critical Functions with Multiple Critical Upstream Dependencies

Table 6.1 shows the 14 NCFs among the 27 higher-vulnerability NCFs that have six or more critical upstream NCFs. NCFs vary in scope, a fact that has implications for this analysis. Although the provision of electricity is represented by three NCFs (Generate Electricity, Transmit Electricity, and Distribute Electricity), a single NCF represents the management of raw water supply, its treatment, and its distribution to end users (Supply Water). An NCF with a broader scope might inherently have more upstream dependencies and could therefore be at greater risk because of climate change.

Manage Hazardous Materials, which has the most identified upstream NCFs, is dependent on nine NCFs, including Distribute Electricity, Develop and Maintain Public Works and Services, Produce Chemicals, and Supply Water. Manage Hazardous Materials is itself assessed to be at risk of moderate disruption by 2050,

<table>
<thead>
<tr>
<th>NCF</th>
<th>Number of Critical Upstream NCFs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manage Hazardous Materials</td>
<td>9</td>
</tr>
<tr>
<td>Develop and Maintain Public Works and Services</td>
<td>8</td>
</tr>
<tr>
<td>Provide Public Safety</td>
<td>8</td>
</tr>
<tr>
<td>Provide and Maintain Infrastructure</td>
<td>7</td>
</tr>
<tr>
<td>Provide Medical Care</td>
<td>7</td>
</tr>
<tr>
<td>Produce Chemicals</td>
<td>7</td>
</tr>
<tr>
<td>Prepare for and Manage Emergencies</td>
<td>7</td>
</tr>
<tr>
<td>Exploration and Extraction of Fuels</td>
<td>6</td>
</tr>
<tr>
<td>Generate Electricity</td>
<td>6</td>
</tr>
<tr>
<td>Manage Wastewater</td>
<td>6</td>
</tr>
<tr>
<td>Produce and Provide Human and Animal Food Products and Services</td>
<td>6</td>
</tr>
<tr>
<td>Provide Housing</td>
<td>6</td>
</tr>
<tr>
<td>Supply Water</td>
<td>6</td>
</tr>
<tr>
<td>Manufacture Equipment</td>
<td>6</td>
</tr>
</tbody>
</table>

NOTE: We set the cutoff at six upstream NCFs because the resulting list at that cutoff had at least ten NCFs. Because multiple NCFs had six upstream NCFs, this list includes 14 rather than ten.
suggesting that this risk could be amplified. Develop and Maintain Public Works and Services is dependent on eight NCFs; Provide and Maintain Infrastructure, Provide Medical Care, and Provide Public Safety are dependent on seven NCFs; and each of the others in the table are dependent on six NCFs.

When analyzing the risk that climate change poses to the NCFs, policymakers should consider that these NCFs are vulnerable not only to climate drivers that will affect those individual NCFs directly but also to climate drivers that affect their upstream NCFs.

**Upstream National Critical Functions That Are Critical to Multiple Others Downstream**

Using the same analysis, we examined the critical upstream NCFs—those with multiple dependent downstream NCFs. Figure 6.1 shows the connections between NCFs using a similar format, with arrows pointing to the downstream NCFs.

Table 6.2 shows the 11 NCFs among the 27 higher-vulnerability NCFs with the largest number of critically dependent downstream NCFs. The NCFs in the table are those that, if disrupted, would result in the disruption of the largest number of other NCFs in our analysis. When analyzing the risk posed by climate change, policymakers should consider the added consequences of disruption of these NCFs.

As shown in the table, Distribute Electricity has the highest potential for cascading risk and serves as a critical upstream NCF to 22 of the 27 NCFs. We assessed Distribute Electricity as being at risk of moderate disruption due to climate change by 2050. Our dependence analysis suggests that, in addition, disruption or failure of this NCF has the potential for significant cascading and immediate effects on NCFs that include those supporting food production, medical care, and water supply. To further illustrate this risk cascade, Figure 6.2 shows the connections between Distribute Electricity and a subset of its downstream NCFs. In addition to these downstream connections, Distribute Electricity is itself dependent on Transmit Electricity and Generate Electricity. This suggests that risk mitigation strategies developed for the three electricity NCFs could have benefits for multiple other NCFs.

Similarly, we found that about half of the high-vulnerability NCFs could be affected by disruption or degradation of the Transport Cargo and Passengers by Road, Maintain Supply Chains, and Fuel Refining and Processing Fuels NCFs. Given the predominance of trucking for freight and personal vehicles for commuting, disruption of Transport Cargo and Passengers by Road could affect NCFs that require the movement of goods and an in-person workforce. Risk to Maintain Supply Chains has implications for NCFs that involve manufacturing or that depend on just-in-time delivery of crucial supplies. Maintain Supply Chains is at risk of moderate disruption by 2100, which suggests that investments in mitigation could reduce risk to this NCF and benefit those NCFs that depend on it. Although Fuel Refining and Processing Fuels was not considered a high-vulnerability NCF and not assigned a risk rating, it is considered a crucial input to transportation and energy NCFs, with implications for the performance of those NCFs.

The remainder of the NCFs had fewer relationships with other NCFs. This does not suggest they are less crucial to the United States but reflects that the results of their disruption are longer term in nature (such as disruption of Educate and Train) or that they were less prone to disruption in the event of an emergency (for example, Produce Chemicals).

**Cascading Risk Within National Critical Functions**

To this point, we have focused on risks that cascade across the NCFs. However, these are not the only types of cascading risks that can be relevant. Risks can also cascade within an NCF. NCFs themselves can be highly
NOTE: The nodes are sized to illustrate the number of NCFs that identify it as being a critical upstream NCF. A larger node is an NCF that is critical to a larger number of downstream NCFs. The color of the node corresponds to the NCF’s assessed risk to climate change in 2100 under the current-emissions scenario: Yellow indicates risk of minimal disruption, orange indicates risk of moderate disruption, and blue indicates that the given NCF was not included in the risk assessment but was identified as a critical upstream NCF.
TABLE 6.2
Number of Downstream National Critical Functions for Each Critical Upstream National Critical Function

<table>
<thead>
<tr>
<th>NCF</th>
<th>Number of Downstream NCFs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribute Electricity</td>
<td>22</td>
</tr>
<tr>
<td>Transport Cargo and Passengers by Road</td>
<td>14</td>
</tr>
<tr>
<td>Maintain Supply Chains</td>
<td>10</td>
</tr>
<tr>
<td>Fuel Refining and Processing Fuels</td>
<td>9</td>
</tr>
<tr>
<td>Supply Water</td>
<td>9</td>
</tr>
<tr>
<td>Operate Government</td>
<td>8</td>
</tr>
<tr>
<td>Provide Positioning, Navigation, and Timing Services</td>
<td>7</td>
</tr>
<tr>
<td>Store Fuel and Maintain Reserves</td>
<td>5</td>
</tr>
<tr>
<td>Provide Capital Markets and Investment Activities</td>
<td>4</td>
</tr>
<tr>
<td>Provide Satellite Access Network Services</td>
<td>4</td>
</tr>
<tr>
<td>Transport Cargo and Passengers by Rail</td>
<td>4</td>
</tr>
</tbody>
</table>

NOTE: We set the cutoff at four downstream NCFs because the resulting list at that cutoff had at least ten NCFs. Because multiple NCFs had four downstream NCFs, this list includes 11 rather than ten.

FIGURE 6.2
Cascading Risk of Bulk Power Delivery Failure
networked, so, for a single NCF, climate-induced effects in one geographic area or region could have cascading effects in other regions for that NCF, even if those regions are not directly affected. This type of cascading risk is also important for understanding how risk posed to NCFs might differ and what risk mitigation strategies might be most appropriate.

To understand these dynamics, we conducted a preliminary analysis of the potential for cascading risks within NCFs. We characterized NCFs according to one of the following definitions:

- **interconnected clusters or nodes**: The NCF has critical clusters or nodes that can cause cascading regional effects within this NCF.\(^1\)
- **independent clusters or nodes**: The NCF has critical clusters or nodes, but they operate relatively independently without significant regional or national implications.
- **distributed**: The NCF has little interdependence between regions, with each location operating autonomously.

As shown in Table 6.3, about half of the higher-vulnerability NCFs have high potential for cascading risks within the NCF, as indicated by having interconnected clusters or nodes. For example, in the case of Transport Cargo and Passengers by Rail, disruptions in the Chicago area, a key transshipment point for freight rail, would disrupt rail operations in other parts of the country. For Produce and Provide Human and Animal Food Products and Services, key clusters of operations, such as meatpacking plants, can have cascading effects across this NCF at the national scale if they are disrupted or fail. Neither of these NCFs is expected to be at a high risk because of climate change, however, compared with the other assessed NCFs.

Other NCFs are more distributed, with disruption in one area having little effect on operations in other regions. Supply Water is in this category because water systems serve residents and businesses in their immediate vicinity, and water transfers are typically moving water within regions. This means that, although Supply Water is at risk of moderate disruption due to climate change across all time periods and climate scenarios, climate change’s effects are unlikely to rise to a national-scale disruption unless multiple regions are affected by extreme events simultaneously.

Although Distribute Electricity was identified as having the highest cascading risk among NCFs, the probability of this NCF causing a risk cascade across regions because of any of the climate drivers is low. The U.S. power grid is highly interconnected, with many redundancies that increase its resilience nationally (Albert, Albert, and Nakarado, 2004). For example, the blackout in Texas caused by extreme cold in February 2021 did not cascade across the other regional power markets (Busby et al., 2021). Similarly, blackouts from wildfires in California did not affect electricity reliability on the East Coast (Rhodes, Ntaimo, and Roald, 2021). These examples also demonstrate the disparate regional effects that hazards have on NCFs. Although there were severe, acute effects on the NCF infrastructure locally, the effects did not cascade across regions.

A smaller subset of high-vulnerability NCFs is characterized by critical independent nodes, in which operations are more concentrated, but other regions would not be affected by disruptions at those nodes. For example, Produce and Provide Agricultural Products and Services is included in this category because some regions of the country produce more food than others, but a drought in one region would not affect growing conditions in another region. This also suggests that these NCFs are unlikely to be disrupted in most or all of the United States.

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\(^1\) We define *cluster* as a concentration of infrastructure in a specific location and *node* as a central point of connection of infrastructure.
### TABLE 6.3
**Characterization of Within–National Critical Function Cascading Risk**

<table>
<thead>
<tr>
<th>NCF</th>
<th>Clusters or Nodes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Interconnected</td>
</tr>
<tr>
<td>Distribute Electricity</td>
<td>x</td>
</tr>
<tr>
<td>Maintain Supply Chains</td>
<td>x</td>
</tr>
<tr>
<td>Transmit Electricity</td>
<td>x</td>
</tr>
<tr>
<td>Transport Cargo and Passengers by Air</td>
<td>x</td>
</tr>
<tr>
<td>Transport Cargo and Passengers by Rail</td>
<td>x</td>
</tr>
<tr>
<td>Transport Cargo and Passengers by Road</td>
<td></td>
</tr>
<tr>
<td>Transport Cargo and Passengers by Vessel</td>
<td>x</td>
</tr>
<tr>
<td>Transport Passengers by Mass Transit</td>
<td></td>
</tr>
<tr>
<td>Develop and Maintain Public Works and Services</td>
<td>x</td>
</tr>
<tr>
<td>Educate and Train</td>
<td></td>
</tr>
<tr>
<td>Manage Hazardous Materials</td>
<td></td>
</tr>
<tr>
<td>Manage Wastewater</td>
<td>x</td>
</tr>
<tr>
<td>Prepare for and Manage Emergencies</td>
<td></td>
</tr>
<tr>
<td>Provide and Maintain Infrastructure</td>
<td>x</td>
</tr>
<tr>
<td>Provide Insurance Services</td>
<td>x</td>
</tr>
<tr>
<td>Provide Medical Care</td>
<td></td>
</tr>
<tr>
<td>Provide Public Safety</td>
<td>x</td>
</tr>
<tr>
<td>Support Community Health</td>
<td></td>
</tr>
<tr>
<td>Exploration and Extraction of Fuels</td>
<td>x</td>
</tr>
<tr>
<td>Generate Electricity</td>
<td>x</td>
</tr>
<tr>
<td>Manufacture Equipment</td>
<td>x</td>
</tr>
<tr>
<td>Produce and Provide Agricultural Products and Services</td>
<td></td>
</tr>
<tr>
<td>Produce and Provide Human and Animal Food Products and Services</td>
<td>x</td>
</tr>
<tr>
<td>Produce Chemicals</td>
<td>x</td>
</tr>
<tr>
<td>Provide Housing</td>
<td>x</td>
</tr>
<tr>
<td>Supply Water</td>
<td></td>
</tr>
</tbody>
</table>
CHAPTER SEVEN

Conclusion

Summary of Findings

This report presents the findings of a climate risk assessment conducted by HSOAC researchers for CISA to identify NCFs that are at a heightened risk because of climate change.

Risk Management Framework

To conduct our assessment, we developed a risk management framework to assess and manage the risk that climate change poses to the NCFs. The framework is intended to be compatible with and integrate into existing CISA risk management efforts and, as a result, is built on other CISA risk assessment efforts, including incorporating the five-point risk rating scale used by CISA’s operational-level framework. Although we used the framework to support an initial assessment of climate-related risk to the NCFs, which is the focus of this project, the framework is also intended to provide CISA with an ongoing capability to assess climate-related risk moving forward. The risk management framework employed a five-step process:

1. Identify higher-vulnerability NCFs.
2. Identify and characterize climate drivers.
3. Identify impact pathways.
4. Assess risk to each NCF.
5. Identify mitigation strategies to reduce risk.

Steps 1 through 4 are described in detail in Chapter Two of this report.

Selection of Higher-Vulnerability National Critical Functions

We performed an initial assessment of all 55 NCFs to identify those that are more vulnerable to climate change, based on available evidence in scientific literature. As a result of this screening, we identified 27 higher-vulnerability NCFs for more in-depth assessment. However, the NCFs not included in our assessment might also themselves be vulnerable to climate change and have an increased risk of disruption as a result of climate change. Of the 27 NCFs analyzed for this report, we found that all are expected to experience at least minimal disruption from climate change by 2100 under a scenario based on current GHG emissions.

Risk Rating Scale

Drawing on CISA’s risk levels in the operational-level framework, we defined moderate disruption as meeting routine operational needs in most, but not all, of the country. Using these criteria, the disruption caused by a major historical weather event, such as Hurricane Katrina in 2005, would be characterized as moderate disruption. Although several NCFs, such as those related to the provision of power and water, failed at the local and regional levels as a result of effects from the storm, at a national level, these NCFs continued to function.
Accordingly, for purposes of our analysis, the risk of moderate disruption to an NCF at the national level should be regarded as highly significant and includes the potential for major disruption or failure of NCFs at a local or regional level and the potential for significant economic loss, health and safety impacts, and other consequences. Major disruption, indicating that an NCF is expected not to meet routine operational needs in most of the country, and critical disruption, indicating that an NCF is meeting none of its routine operational needs in most of the country, are expected to be less likely, given the nature of the NCFs and the geospatial variability in climate change.

Assessment of Climate Change’s Effects on Higher-Vulnerability National Critical Functions

Using this risk rating scale and projected changes in eight climate drivers identified by our analysis—drought, extreme cold, extreme heat, flooding, sea-level rise, severe storm systems, tropical cyclones and hurricanes, and wildfire—we examined how NCFs could be affected by and at risk from climate change over three future time periods (by 2030, by 2050, and by 2100) and two future climate scenarios. The climate scenarios represent two future trajectories of global GHG emissions that could shape the degree of climate change for each climate driver.

We assessed that, by 2030, at least two NCFs, Provide Public Safety and Supply Water, would be at risk of moderate disruption. In the case of Provide Public Safety, our assessment was based on the NCF’s role responding to threats, such as hurricanes and wildfire, which are already straining response capabilities. Similarly, our assessment of Supply Water is based on the disruptions the NCF is already facing in many parts of the western United States because of drought. These NCFs should be prioritized for further assessment and risk mitigation. We assessed that, in addition to these NCFs, 12 of the 27 NCFs will face risk of moderate disruption by 2050, meaning that these 12 NCFs might be unable to meet routine operational needs for at least some parts of the country for some period of time.

Our analysis suggests that flooding, sea-level rise, and tropical cyclones and hurricanes pose the greatest risk of disruption to the NCFs. Although there are important regional distinctions in how and where climate drivers are anticipated to change, these three climate drivers are anticipated to pose the greatest risk of disruption to the NCFs at the national level. By 2100, in the high-emissions scenario, nearly all of the 27 NCFs are anticipated to be at risk of moderate disruption or greater from sea-level rise; three-quarters of the 27 NCFs are anticipated to be at risk of moderate disruption from flooding; and more than two-thirds of the 27 NCFs are anticipated to be at risk of moderate disruption from tropical cyclones and hurricanes. These drivers should be prioritized for further assessment, and NCFs could benefit from investment in risk mitigation activities for these drivers. However, the other drivers we identified—drought, extreme cold, extreme heat, severe storm systems, and wildfire—also present risk to many of the NCFs and NCF subfunctions.

Cascading Risk

Because of the interconnected nature of U.S. infrastructure, risk to one NCF can cause cascading risk to others. We provided a preliminary analysis that identified dependencies among the NCFs to better understand which NCFs might present greater risk to the United States than their individual risk ratings might suggest because of their potential impact on other NCFs. We found that failure in the Distribute Electricity NCF has the highest potential for cascading risk in dependent NCFs, with 22 of the 27 assessed NCFs requiring electricity to ensure normal operations. Disruption or failure of this NCF has potential for significant cascading and immediate effects on NCFs that include those supporting food production and supplying medical care and water, which suggests that it should also be prioritized for further assessment and mitigation.
Limitations and Areas for Future Research

Because of the accelerated time period for analysis, availability of relevant research, and the assumptions made in this analysis, the application of the risk management framework presented in this report was subject to some limitations. Subsequent analyses and research could improve national situational awareness and add rigor to future climate risk assessments related to the future effects of climate change and the risk it poses to critical infrastructure systems.

Baseline Risk Assessment for All 55 National Critical Functions

Although all NCFs are likely to be at some risk due to climate change, we included only the 27 higher-vulnerability NCFs. The 28 NCFs not included in this risk assessment could still be at risk from climate change. This assessment focused on those NCFs with the most obvious, immediate vulnerability to climate change. Future work on climate change risk should incorporate all 55 NCFs and could provide a fuller picture of the risk profile that each climate driver poses to the country’s diverse range of critical infrastructure functions. Because of the complex nature of the NCFs and the impact pathways by which climate change could affect them, NCFs deemed at lower levels of vulnerability in this initial screening could still be at risk from climate change.

This line of research could also develop a baseline risk for all 55 NCFs. Although it is likely similar to the risk assessed by 2030 for many of the NCFs, a baseline risk assessment would examine the recent historical effects that the climate drivers have had on NCFs and establish a risk baseline for CISA. This analysis could either pick a point in time (e.g., 2022) as the baseline or utilize a longer time period, such as a period that reflects historical climatology (e.g., 1991 to 2020, using the National Oceanic and Atmospheric Administration’s Climate Normals [National Centers for Environmental Information, undated]). A baseline risk assessment would allow CISA to track and identify emerging risks related to climate change for infrastructure that might not currently be considered at risk.

Expanded Analysis of Cascading Disruptions

Because of the complex interdependencies among NCFs and their subfunctions, the risk of cascading disruptions among NCFs is not fully articulated in this report. Future iterations of this analysis could include an iterative approach to identifying the cascading risk that climate change poses for NCFs. Such an analysis could consider more degrees of risk cascade than considered in this report. For example, our analysis took a narrow definition of dependence and identified only those critically dependent NCFs directly upstream of a given NCF. Future work could characterize NCFs at varying degrees of separation and with varying types of dependencies.

Other Sources of Change to National Critical Functions

It is also important to note that the framework we used does not account for other sources of change to the NCFs, such as anticipated technological advances or population-based shifts. To generate risk assessments that were comparable across time periods and climate scenarios, one of the simplifying assumptions used was that NCFs in future time periods had the same capacities and infrastructure as they have today. The approximately 80-year period between 2021 and 2100 could see numerous changes that influence NCF operations, including changes in population and demographics, technologies, adaptations within the NCFs, governance structures, and laws and regulations. An understanding of how the changes within NCFs could influence future climate risk could support the development of risk mitigation strategies and climate-related
policies moving forward. This type of research could develop scenarios around population growth, economic development, climate migration, and other factors.

**A Broader Range of Future Scenarios**

Uncertainties in the magnitude and direction of future climate changes are greater by 2100. In addition to the uncertain nature of how NCFs will change and adapt in the future, future climate changes by 2100 have a high degree of uncertainty. Although, in this analysis, we considered two future climate scenarios to account for this uncertainty, best practices in climate science and decisionmaking under uncertainty are to look across a broader variety of future scenarios and update assessments as new science becomes available over time. Employing additional scenarios can help generate an understanding of how sensitive (or not) risk ratings are to future uncertainty in climate change.

**The Role of Subfunctions**

Risk ratings are dependent on how NCFs are characterized by their subfunctions. By employing the subfunctions as the basis for the risk assessment, we made risk ratings dependent on how subfunctions are defined and how they collectively represent an NCF. For example, the subfunctions for Support Community Health focus on the systems and functions that provide community health (operations, emergency response, and communications) but not on the health of the community itself. As such, risk to this NCF focuses on climate change’s effects on these types of functions. As subfunctions are refined, future iterations of this risk assessment might result in adjustments to risk ratings.

**Regional Disruptions**

We conducted a risk assessment at the national level, which is an important limitation with significant implications for interpreting our findings. Climate changes will not affect all areas of the United States equally. The geographic distribution of risk across the United States, which can occur because of the geographic orientation of NCFs or the geospatial nature of climate change, is therefore not fully captured by national-scale risk ratings. Future risk assessments at the regional scale could also rely on regional climate assessments or approaches that summarize and synthesize regional to local-scale literature to ensure that the most–locally appropriate future climate information is incorporated. These analyses could help highlight which regions and NCFs might need more-regular risk monitoring and additional support for climate risk mitigation.

**The Effect of Climate Drivers on Other Components of the Development and Maintenance of Infrastructure**

The strength of the evidence on climate change’s effects on NCFs varies widely across NCFs. For those with a legacy of climate effects, such as Supply Water and Distribute Electricity, a broad evidence base exists. For others, such as Educate and Train and Provide Public Safety, fewer analyses have been conducted. Future investments in research for NCFs with a weaker evidence base could support CISA in tracking climate change risk to all NCFs over time. Specifically, these NCFs include Produce Chemicals and Provide and Maintain Infrastructure. Overall, there is relatively little research on extreme weather’s effects on chemical production. Most of the analysis comes from reporting following extreme weather events (see, e.g., DiChristopher, 2017, on the effects of Hurricane Harvey), reports that are tangentially related to climate change (see, e.g., WHO, 2018), or reports by industry stakeholder groups (see, e.g., ACC, 2021). For Provide and Maintain Infrastructure, there is sufficient literature that examines climate drivers’ effect on infrastructure from an adaptation and risk management perspective. However, there is less well-documented literature on how climate driv-
ers affect other components of development and maintenance of infrastructure, such as obtaining finances, regulation compliance, and plan and specification development.

**Multilevel Consequences of National Critical Function Disruption**

The consequences of NCF disruption should be factored into future assessments. The consequences of disruption to an NCF as a result of climate change might be severe at the local or regional level. Although an NCF might not be disrupted at the national level, regional disruption of an NCF can create national-level consequences, including significant threats to health and safety, economic loss, and risks to national security. A more complete analysis of the consequences of the level of disruptions projected in this response should be conducted to inform the prioritization of future risk mitigation activities.

**Implications of the Findings**

**Prioritizing Specific National Critical Functions for Further Assessment**

Our analysis suggests that CISA should consider prioritizing specific NCFs for further assessment, communication, and risk mitigation. Specifically, we expect Provide Public Safety and Supply Water to be at risk of moderate disruption by 2030. CISA should consider prioritizing these NCFs for further assessment, including developing more-granular risk assessments at the local and regional levels and of the mechanisms by which climate drivers could disrupt these NCFs. These NCFs should also be prioritized for communication and outreach to stakeholders and the general public to ensure that the risk to these NCFs—and, as discussed below, the potential consequences—are well understood. Finally, these NCFs should be prioritized for developing risk mitigation strategies that address risks posed by the highest-risk drivers identified in this report. To support implementation, resources should be directed to mitigate risk.

We estimate that, by 2050, 11 of the 27 NCFs will face a risk of moderate disruption. Although these risks might be outside of typical planning horizons for many entities, this does not suggest that these NCFs will not suffer significant and costly disruptions in the interim. The adoption of successful risk mitigation strategies is often challenging and can take decades, particularly for strategies that involve complex physical infrastructure or individual behavior. The time to begin activities to mitigate risk to these NCFs from climate change has likely already arrived. The three drivers—flooding, sea-level rise, and tropical cyclones and hurricanes—that we identified as posing the greatest risk of disruption to the NCFs should be prioritized for further assessment and risk mitigation activities.

**Factoring the Consequences of National Critical Function Disruption into Future Assessments**

Our analysis also suggests that the consequences of NCF disruption should be factored into future assessments. The consequences of climate change disrupting an NCF could be severe at the local or regional level. Although an NCF might not be disrupted at the national level, regional disruption of an NCF can create national-level consequences, including significant threats to health and safety, economic loss, and risks to national security. A more complete analysis of the consequences of the level of disruptions examined in this report should be conducted to inform the prioritization of future risk mitigation activities. For example, it might be useful to assess—and communicate to stakeholders and the public—how disruptions at the scale projected in our report to Provide Public Safety and Supply Water would affect those NCFs and NCF stakeholders over time.
Communicating Risk from Climate Change and Climate Drivers
This study also illustrates the difficulty in conveying risk information about the NCFs, which, by nature, are difficult to disrupt given their national scale and inherent redundancies but which, given their criticality, can—and do—create severe life, safety, and economic effects when disrupted at the local or regional level. Effectively communicating risk that climate change and climate drivers pose to the NCFs is likely to be an ongoing challenge.

Updating Assessments of Climate Change’s Risk to National Critical Functions
Finally, our research suggests that CISA should continue to update assessments of the risk that climate change poses to NCFs over time. Projections for 2050 and 2100 are inherently subject to error and unpredictability and will be refined over time only as better information becomes available and projected risk from climate change manifests and demonstrates the NCFs' resilience, or lack thereof.
Appendix. National Critical Function Vulnerability Screening

Table A.1 details the results of the initial vulnerability screening we performed. These ratings were peer-reviewed and cross-checked to ensure consistency across results. We excluded from the risk assessment those NCFs rated as low. NCF functional groups are developed by CISA as a way to organize the NCFs (CISA, 2020). The shades of blue signify vulnerability: Dark blue indicates low vulnerability, medium indicates medium vulnerability, and light blue indicates high vulnerability.

**TABLE A.1**
National Critical Function Vulnerability Screening Results

<table>
<thead>
<tr>
<th>NCF</th>
<th>Vulnerability Rating Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connect</td>
<td>The core network carries data of many types between major communication nodes (e.g., internet service providers, telecom providers). It is composed largely of optical fiber and is generally robust. It is potentially subject to disruption by flooding and interruptions of power supply, although the large nodes it serves generally have sufficient generator backup to keep it operating in the face of significant electrical outages.</td>
</tr>
<tr>
<td>1. Operate Core Network</td>
<td>Cable access network services can be locally disrupted by severe storms that cause damage to overhead lines and flooding of underground equipment. Such disruption can be expected to be mostly local in scope and limited in duration—allowing for incremental hardening and adaptation.</td>
</tr>
<tr>
<td>2. Provide Cable Access Network Services</td>
<td>Coastal flooding could disrupt core network functions, and storms could disrupt access networks. Internet content servers require significant electricity, but critical infrastructure is generally well backed up with generator capacity, allowing it to continue through moderate disruptions. Much of the infrastructure needed for this NCF is located in large datacenters that are well positioned and designed to manage extreme weather situations.</td>
</tr>
<tr>
<td>3. Provide Internet Based Content, Information, and Communication Services</td>
<td>Internet routing and access depend on the network services covered by other NCFs. They are potentially subject to disruption by phenomena that disrupt those services, including flooding and interruptions of power supply.</td>
</tr>
<tr>
<td>4. Provide Internet Routing, Access, and Connection Services</td>
<td>Although foul weather might occasionally produce temporary disruptions in satellite communication, and power outages can affect the ability to make use of these services, PNT services can be expected to be largely free of vulnerability to climate-induced impacts.</td>
</tr>
<tr>
<td>5. Provide Positioning, Navigation, and Timing Services</td>
<td>Although power outages can temporarily disrupt radio transmission and the content being broadcast might be delivered by network services that are more subject to failure, radio transmission is quite robust to climate-induced disruption.</td>
</tr>
<tr>
<td>6. Provide Radio Broadcast Access Network Services</td>
<td>Satellite access network services can be temporarily disrupted by heavy precipitation, which can interfere with signal reception in small ground units, but both ground-based transmission equipment and space-based satellites are quite robust to precipitation, flooding, heat, and other climate-driven disruptions.</td>
</tr>
<tr>
<td>7. Provide Satellite Access Network Services</td>
<td>Wireless access network services can be locally disrupted by severe storms and wildfire that cause damage to the electrical and wired core network infrastructure on which they depend. Wireless service itself is generally quite robust to weather, flooding, heat, and other climate-related drivers.</td>
</tr>
<tr>
<td>8. Provide Wireless Access Network Services</td>
<td>Wire-line access network services can be locally disrupted by severe storms that cause damage to overhead lines and flooding of underground equipment. Such disruption can be expected to be mostly local in scope and limited in duration—allowing incremental hardening and adaptation.</td>
</tr>
</tbody>
</table>
Assessing Risk to the National Critical Functions as a Result of Climate Change

Table A.1—Continued

<table>
<thead>
<tr>
<th>NCF</th>
<th>Vulnerability Rating Justification</th>
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<tbody>
<tr>
<td><strong>Distribute</strong></td>
<td></td>
</tr>
<tr>
<td>10. Distribute Electricity</td>
<td>Distribution infrastructure is already highly vulnerable to today’s climate effects. Additionally, distribution infrastructure is physically connected with generation and transmission infrastructure and is subject to upstream, cascading risk of either infrastructure-type failure.</td>
</tr>
<tr>
<td>11. Maintain Supply Chains</td>
<td>Climate change, increasing climate variability, and extreme events affect global production and supply chains. Supply chains depend on functioning infrastructure and production globally. Thus, supply chains are vulnerable to climate change, variability, and extreme events within the United States and elsewhere.</td>
</tr>
<tr>
<td>12. Transmit Electricity</td>
<td>Transmission infrastructure is already highly vulnerable to today’s climate impacts. Additionally, transmission infrastructure is physically connected with generation and distribution infrastructure and is subject to upstream, cascading risk of either infrastructure-type failure.</td>
</tr>
<tr>
<td>13. Transport Cargo and Passengers by Air</td>
<td>Because of its nature and existing safety regulations, air travel is already vulnerable to weather disruptions. Climate effects that could affect airport infrastructure and air travel include extreme heat (which can damage runways and decrease the allowable weight at which aircraft can safely take off), more-frequent or more-extreme storms, and flooding, especially for airports in coastal areas.</td>
</tr>
<tr>
<td>14. Transport Cargo and Passengers by Rail</td>
<td>According to a recent study of climate impacts on rail, “[c]limate change is a threat to the rail network due principally to projected temperature increases, though indirect effects from changes in precipitation could also be important.”</td>
</tr>
<tr>
<td>15. Transport Cargo and Passengers by Road</td>
<td>Weather damage already contributes to road maintenance needs in well-understood ways. According to a recent review, “[c]limate change is projected to increase the costs of maintaining, repairing, and replacing infrastructure, with regional differences proportional to the magnitude and severity of impacts.”</td>
</tr>
<tr>
<td>16. Transport Cargo and Passengers by Vessel</td>
<td>There is a growing body of literature on climate change’s potential effects on ports, and the mechanisms are well-understood. A global review of anticipated risk to coastal ports by 2100 from climate change (under RCP8.5) found 15 U.S. ports at very high risk (the second-highest rating) and another 127 at medium risk.</td>
</tr>
<tr>
<td>17. Transport Materials by Pipeline</td>
<td>Reports about pipeline vulnerability tend to rely on anecdotes rather than comprehensive analysis. Reports shows that less than 5 percent of pipeline ruptures are related to natural disasters, which suggests that this has not historically been a major risk.</td>
</tr>
<tr>
<td>18. Transport Passengers by Mass Transit</td>
<td>Reports about transit vulnerability tend to rely on anecdotes rather than comprehensive analysis. Conducting comprehensive analysis for transit would be more difficult than for other modes because the mechanisms vary more widely, and risk would differ between metropolitan areas based not only on mode but also on system extent and type of climate exposure.</td>
</tr>
<tr>
<td><strong>Manage</strong></td>
<td></td>
</tr>
<tr>
<td>19. Conduct Elections</td>
<td>The main threat to holding elections would seem to come from a climate-related natural disaster that affects the ability to proceed with election administration. Because of congressionally set election deadlines, states are limited in the amount of time that an election can be postponed, but this provision has not been widely tested, and state laws governing emergency declarations vary. Our review did not find other analysis of climate’s effects on conducting elections.</td>
</tr>
<tr>
<td>20. Develop and Maintain Public Works and Services</td>
<td>The ability to design, build, and maintain infrastructure to supply government services, including the systems and assets used for transportation and traffic management, water supply, waste management, and other purposes, is highly vulnerable to climate change.</td>
</tr>
<tr>
<td>21. Educate and Train</td>
<td>Climate change’s effects on the ability to provide education and training are largely indirect, with the primary pathway being extreme weather’s effects on education infrastructure, specifically schools and training facilities. In addition, there is potential for higher temperatures to undermine indoor comfort that could disrupt or distract from education and training.</td>
</tr>
<tr>
<td>NCF</td>
<td>Vulnerability Rating Justification</td>
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<td>----------------------------</td>
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<tr>
<td>22. Enforce Law</td>
<td>There is a reasonably well-established correlation between high temperatures and increases in violent crime. This increase might be larger in areas of low income. Although this effect appears to be significant, the actual mechanism underlying it is not well understood, and it is not clear whether it can be extrapolated to future periods with differing climate.</td>
</tr>
<tr>
<td>23. Maintain Access to</td>
<td>Medical records are stored in multiple formats, including paper and digital forms, with the latter including cloud-based systems that can be distributed. Extreme weather events can cause physical damage to medical records.</td>
</tr>
<tr>
<td>Medical Records</td>
<td></td>
</tr>
<tr>
<td>24. Manage Hazardous</td>
<td>Climate change will bring more-extreme weather, including increased flooding and wind damage. These effects of climate change will cause consequences for communities living near sites with a legacy of toxic waste.</td>
</tr>
<tr>
<td>Materials</td>
<td></td>
</tr>
<tr>
<td>25. Manage Wastewater</td>
<td>The ability to collect and treat industrial and residential wastewater to meet applicable public health and environmental standards prior to discharge into a receiving body is vulnerable to climate change. The infrastructure that supports wastewater systems is vulnerable to climate shocks, such as hurricanes, extreme weather events, and even drought.</td>
</tr>
<tr>
<td>26. Operate Government</td>
<td>Increases in the frequency, intensity, or duration of climate hazards would increase pressure on this function but would be unlikely to disrupt it. A public perception of failure to manage response to or recovery from a major disaster could negatively affect public confidence and increase vulnerability of the function.</td>
</tr>
<tr>
<td>27. Perform Cyber Incident</td>
<td>Although the cyber environment in general relies on electrical and communication services, the ability to identify and manage cyber incidents appears to be largely independent of the effects of climate change.</td>
</tr>
<tr>
<td>Management Capabilities</td>
<td></td>
</tr>
<tr>
<td>28. Prepare for and Manage</td>
<td>Increases in the frequency, intensity, or duration of climate hazards have the potential to put increased stress on emergency management agencies and resources. Mechanisms for increased vulnerability directly related to climate change include the potential for larger and more-intense individual events, increased frequency of events, and increased likelihood of events occurring simultaneously, at the local, regional, or national level.</td>
</tr>
<tr>
<td>Emergencies</td>
<td></td>
</tr>
<tr>
<td>29. Preserve Constitutional</td>
<td>Many policy responses to climate change will be mediated by the political process, and this process is governed, in turn, by the Constitution and the rights it grants. Constitutionally based arguments can be made for both stronger and weaker government intervention—either to preserve citizens’ right to a livable environment or to protect citizens’ right to economic and other freedoms.</td>
</tr>
<tr>
<td>Rights</td>
<td></td>
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<tr>
<td>30. Protect Sensitive</td>
<td>Climate-driven issues appear to be unlikely to create vulnerabilities in the country’s ability to protect sensitive information.</td>
</tr>
<tr>
<td>Information</td>
<td></td>
</tr>
<tr>
<td>31. Provide and Maintain</td>
<td>The ability to design, construct, operate, repair, survey, and improve public and private infrastructure has been shown—through recent events; peer-reviewed research and international, national, and regional climate assessments; and industry reports—to be vulnerable to climate change.</td>
</tr>
<tr>
<td>Infrastructure</td>
<td></td>
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<tr>
<td>32. Provide Capital</td>
<td>Shifts in technology and possible reductions in economic growth have the potential to change the way in which capital markets allocate resources across industries. This is what capital and investment models are designed to do.</td>
</tr>
<tr>
<td>Markets and Investment</td>
<td></td>
</tr>
<tr>
<td>Activities</td>
<td></td>
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<tr>
<td>33. Provide Consumer</td>
<td>A literature is emerging that begins to tie vulnerabilities and shocks related to climate change to risk for the banking industry. The mechanisms of risk exposure include correlated variation in changes in the value of large asset classes, such as real estate that is threatened by flooding and by resulting disruptions in the insurance industry.</td>
</tr>
<tr>
<td>and Commercial Banking</td>
<td></td>
</tr>
<tr>
<td>Services</td>
<td></td>
</tr>
<tr>
<td>34. Provide Funding and</td>
<td>A literature is emerging that begins to tie vulnerabilities and shocks related to climate change to risk for the banking industry. The mechanisms of risk exposure include correlated variation in changes in the value of large asset classes, such as real estate that is threatened by flooding and by resulting disruptions in the insurance industry.</td>
</tr>
<tr>
<td>Liquidity Services</td>
<td></td>
</tr>
<tr>
<td>35. Provide Identity</td>
<td>Climate-driven issues appear to be unlikely to create vulnerabilities in the country’s ability to manage identities and associated trust services.</td>
</tr>
<tr>
<td>Management and Associated</td>
<td></td>
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<tr>
<td>Trust Support Services</td>
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</table>
### Table A.1—Continued

<table>
<thead>
<tr>
<th>NCF</th>
<th>Vulnerability Rating Justification</th>
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</thead>
<tbody>
<tr>
<td>36. Provide Insurance Services</td>
<td>In the absence of changes in behavior by insurers and the insured, insurers will be exposed to greater losses in response to increases in frequency, intensity, and duration of extreme weather events, as well as ongoing development of housing and infrastructure.(^{29})</td>
</tr>
<tr>
<td>37. Provide Medical Care</td>
<td>Increases in the frequency, intensity, or duration of climate hazards have the potential to affect community health through various mechanisms.(^{23}) This includes direct effects on health from people's exposure to hazards or indirectly through changes in the epidemiology of diseases, including water- and vector-borne disease or by disrupting or displacing livelihoods and well-being (including mental health).(^{23,35})</td>
</tr>
<tr>
<td>38. Provide Payment, Clearing, and Settlement Services</td>
<td>Although the payment, clearing, and settlement environment in general relies on electrical and communication services, the ability to identify and manage these systems appears to be largely independent of the effects of climate change.</td>
</tr>
<tr>
<td>39. Provide Public Safety</td>
<td>Increases in the frequency, intensity, and duration of climate hazards have the potential to increase the vulnerability of this NCF. Firefighters and EMS might be required to respond to more-frequent natural hazard–related emergencies and larger events and could be strained by responding to simultaneous events.(^{23})</td>
</tr>
<tr>
<td>40. Provide Wholesale Funding</td>
<td>The provision of wholesale funding does not appear to be directly vulnerable to the effects of climate change, although it might see indirect effects via effects on banking and communication services.</td>
</tr>
<tr>
<td>41. Store Fuel and Maintain Reserves</td>
<td>The infrastructure of Store Fuel and Maintain Reserves is sited in climate change–prone areas that will face increased exposure to extreme weather events and relative sea-level rise.(^{32}) However, as demonstrated during the COVID-19 pandemic supply shock, the fuel storage sector is highly adaptive and flexible to volatile changes in acute fuel price economics and chronic, geographically disparate operational outages caused by extreme weather.(^{23,35})</td>
</tr>
<tr>
<td>42. Support Community Health</td>
<td>Increases in the frequency, intensity, or duration of climate hazards have the potential to affect community health through various mechanisms.(^{23}) This includes direct effects on health through people's exposure to hazards or indirectly through changes in the epidemiology of diseases including water- and vector-borne disease or by disrupting or displacing livelihoods and well-being (including mental health).(^{23})</td>
</tr>
<tr>
<td>Supply</td>
<td></td>
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<tr>
<td>43. Exploration and Extraction of Fuels</td>
<td>Exploration and Extraction of Fuels infrastructure is likely to contend with two competing forces that affect its vulnerability to climate change: (1) shrinking demand for fossil fuels as the U.S. and international communities implement decarbonization policies and (2) increased extreme weather(^{29})</td>
</tr>
<tr>
<td>44. Fuel Refining and Processing Fuels</td>
<td>Fuel Refining and Processing Fuels is likely to be susceptible to some climate change effects—particularly, more-extreme weather.(^{32,33}) However, as demonstrated during the COVID-19 pandemic and through successive extreme weather events (such as hurricanes), fuel refineries and processing infrastructure are resilient to volatile market conditions because of the interconnected nature of international fuel markets and largely experiences only temporary outages thanks to significant investments in infrastructure hardening and operational adaptations derived from lessons learned.(^{23})</td>
</tr>
<tr>
<td>45. Generate Electricity</td>
<td>Generation infrastructure is already highly vulnerable to today's climate impacts.(^{23}) Additionally, generation infrastructure is physically connected with transmission and distribution infrastructure and is subject to the vulnerabilities and subsequent cascading risk of other infrastructure-type failure.(^{32,33})</td>
</tr>
<tr>
<td>46. Manufacture Equipment</td>
<td>Similar to the link between climate change and supply chains, manufacturing equipment requires stable transport markets, international exchange markets, and access to reliable factors of production. Climate change has affected and will continue to affect these requirements in numerous ways.</td>
</tr>
</tbody>
</table>
47. Produce and Provide Agricultural Products and Services
Changes in climate, including temperature and rainfall, as well as extremes, such as drought, extreme heat, and flooding, all have the potential to affect the productivity of agricultural crops.\(^{23}\) Average yields of many commodity crops (for example, corn, soybean, wheat, rice, sorghum, cotton, oats, and silage) decline beyond certain maximum temperature thresholds (in conjunction with rising atmospheric carbon dioxide levels), so long-term temperature increases might reduce future yields under both irrigated and dryland production.\(^{27}\)

48. Produce and Provide Human and Animal Food Products and Services
Although food processing lies downstream of food production and thus has less-immediate and -direct exposure to climate and climate change, there are various pathways by which food processing is vulnerable.\(^{26}\) Changes in climate, including temperature and rainfall, as well as extremes, such as drought, extreme heat, and flooding, all have the potential to affect the processing of crops and livestock.\(^{27}\)

49. Produce Chemicals
Many chemical producing plants are on the Gulf Coast, making production vulnerable to high winds, storm surge, and excessive rainfall.\(^{35}\)

50. Provide Metals and Materials
Although climate change will affect all of manufacturing at least indirectly through supply chain linkages, the direct effect on metal and material production is likely minimal.\(^{31}\)

51. Provide Housing
Housing stock can be vulnerable to climate effects, depending on both the type of housing and the geographic location.\(^{44}\) Single-family and low-rise multifamily housing is likely more vulnerable to direct damage from storms and wildfire, given its smaller size and generally less stringent building codes.\(^{45}\)

52. Provide Information Technology Products and Services
Climate change likely poses a limited direct threat to the United States’ ability to provide IT products and services. Although supply chain disruptions caused by extreme weather would indirectly influence production of these products and services and environmental goals could limit the extraction of rare-earth materials required to produce these products and provide these services, there is likely little direct effect on this NCF.\(^{46,47}\)

53. Provide Materiel and Operational Support to Defense
DoD has considered climate change a threat to its operations since 2010. The defense industrial base, which provides critical material and support to DoD, is also likely vulnerable to climate change. NCA4 points out that DoD “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,” which suggests that defense operations are vulnerable to climate change.\(^{48,49}\)

54. Research and Development
The primary pathway by which climate change could disrupt the R&D enterprise would be through direct damage to research infrastructure, such as research facilities or equipment, or through disruption of materials, metals, and chemicals needed to support specific R&D activities. With the exception of some unique facilities and infrastructure, R&D tends to be a highly distributed activity, so disruption of R&D in one location can be replaced by efforts in other locations.

55. Supply Water
The ability to maintain the availability of both raw and treated water supply is intrinsically tied to climate, even in regions dependent on imported water supplies.\(^{59}\) Much of centuries of water management around the globe have focused on efforts to capture, store, and transport water to overcome short-term fluctuations in precipitation, streamflow, and snowmelt, as well as inter- and intra-annual changes in water demand caused by the single or combined effects of other climate (e.g., temperature), physical (e.g., crop water demand) or socioeconomic variables (e.g., urban growth and development).\(^{52}\)


\(^{23}\) Reidmiller et al., 2018.

\(^{26}\) Durairajan, Barford, and Barford, 2018.

\(^{27}\) National Academies of Sciences, Engineering, and Medicine, 2018.

\(^{31}\) Kose, Koytak, and Hascicek, 2012.

\(^{35}\) Seba et al., 2019.

\(^{37}\) Tan et al., 2017.

\(^{44}\) ASCE, 2021c.

\(^{48}\) EBP, undated; DOE, 2015; Sweet et al., 2017; President’s Council of Economic Advisers and DOE, 2013.

Table A.1—Continued

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<tbody>
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<td>1 National Academies of Sciences, Engineering, and Medicine, 2015.</td>
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<td>k Chinowsky, 2019, p. 183.</td>
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<td>m Becker, Ng, et al., 2018.</td>
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<td>o GAO, 2021.</td>
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<td>q Fischer et al., 2004.</td>
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<td>s ASCE, 2021a.</td>
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<td>t Hunt and Watkiss, 2011.</td>
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<td>u Muurlink and Matas, 2010.</td>
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<td>v Krishnamurthy et al., 2019.</td>
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<td>w Sheffield et al., 2017.</td>
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<td>x Heilmann, Kahn, and Tang, 2021.</td>
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<td>y Man et al., 2018.</td>
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<td>z Chowdhury et al., 2019; Ghazanchaey et al., 2021.</td>
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<td>a Wick et al., 2018.</td>
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<td>c ASCE, 2021f.</td>
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<td>d Kormann, 2019.</td>
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<td>e Campiglio et al., 2018.</td>
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<td>f Brunetti et al., 2021.</td>
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<td>g Carney, 2015.</td>
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<td>h Grimaldi et al., 2020.</td>
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<td>i Ebi, 2011.</td>
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<td>j Portier et al., 2010.</td>
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<td>k k EPA, 2021e.</td>
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<td>l Chang and Lin, 2006; GAO, 2014.</td>
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<td>m U.S. Energy Information Administration, undated.</td>
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<td>n Bjelkevik, 2005; Ford et al., 2010; IPCC, 2014; Mavrommatis, Damigos, and Mirasgedis, 2019.</td>
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<td>o Peterson et al., 2016.</td>
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<td>p Vose et al., 2017.</td>
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<tr>
<td>q Brown et al., 2015; Crane-Droesch et al., 2019.</td>
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<td>r Olson et al., 2018.</td>
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<td>u Beckettii, 2021.</td>
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<tr>
<td>v V Fung, 2019; HUD, 2014.</td>
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<td>w Lee, Lee, and Lim, 2018.</td>
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<tr>
<td>x Wuebbles et al., 2017, p. 651.</td>
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<tr>
<td>y Muth et al., 2018; GAO, 2020a.</td>
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<td>z Milly, 2008; ASCE, 2021b.</td>
</tr>
</tbody>
</table>
Abbreviations

ACC  American Chemistry Council
AR6  Sixth Assessment Report
ASCE American Society of Civil Engineers
CERCLA  Comprehensive Environmental Response, Compensation, and Liability Act of 1980
CISA  Cybersecurity and Infrastructure Security Agency
COVID-19  coronavirus disease 2019
DHS  U.S. Department of Homeland Security
DOE  U.S. Department of Energy
DOT  U.S. Department of Transportation
EMS  emergency medical services
EO  executive order
EPA  U.S. Environmental Protection Agency
EPCRA  Emergency Planning and Community Right-to-Know Act of 1986
FEMA  Federal Emergency Management Agency
GAO  U.S. Government Accountability Office
GHG  greenhouse gas
HSOAC  Homeland Security Operational Analysis Center
HUD  U.S. Department of Housing and Urban Development
IPCC  Intergovernmental Panel on Climate Change
IT  information technology
LOCA  localized constructed analogs
NCA4  Fourth National Climate Assessment
NCF  National Critical Function
NIOSH  National Institute for Occupational Safety and Health
NPL  National Priorities List
PNT  positioning, navigation, and timing
RCP  Representation Concentration Pathway
RCRA  Resource Conservation and Recovery Act
R&D  research and development
SDWA  Safe Drinking Water Act
TRI  Toxics Release Inventory
USDA  U.S. Department of Agriculture
USGCRP  U.S. Global Change Research Program
WHO  World Health Organization


ACC—See American Chemistry Council.


ASCE—See American Society of Civil Engineers.


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National Critical Functions (NCFs) are government and private-sector functions so vital that their disruption would debilitate security, the economy, public health, or safety. Researchers developed a risk management framework to assess and manage the risk that climate change poses to the NCFs and use the framework to assess 27 priority NCFs. This report details the risk assessment portions of the framework.

The team assessed risk based on a scale that the Cybersecurity and Infrastructure Security Agency uses that ranges from a rating of 1 (no disruption or normal operations) to 5 (critical disruption on a national scale). A rating of 3 (moderate disruption) on the national level, although it still allows normal functioning on a national scale, should be regarded as highly significant and includes the potential for major disruptions or failure of NCFs at a local or regional level and for significant economic loss, health and safety impacts, and other consequences.

Using this risk rating scale and projected changes in eight climate drivers identified in the analysis (drought, extreme cold, extreme heat, flooding, sea-level rise, severe storm systems, tropical cyclones and hurricanes, and wildfire), the researchers examined how NCFs could be affected by and at risk from climate change in three future time periods (by 2030, by 2050, and by 2100) and two future greenhouse gas emission scenarios (current and high).