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COMMENTARY

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Special Collection:
U.S. Climate Collection: Informing Assessment of Risks and Solutions

Key Points:

- A network of climate assessments plays a critical role in synthesizing the state of science to support evidence-based decision-making
- To support future U.S. and sub-national climate assessments, we identify scientific advancements and research needs important to synthesize
- We encourage submissions to the AGU/AMS U.S. Climate Collection to advance syntheses of climate systems, risks, impacts and solutions

Supporting Information:

Supporting Information may be found in the online version of this article.

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Research Priorities for Robust Climate Assessments in the United States

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Abstract Scientific assessments play a critical role in synthesizing evidence to support evidence-based decision-making in many sectors and topics. For climate change, large-scale assessments like the Intergovernmental Panel on Climate Change (IPCC) and the United States (U.S.) National Climate Assessment (NCA) reports help many different users—from national government to local governments, Indigenous Peoples and communities, the private sector, the social sector, and the scientific community itself—navigate the complex field of climate risks, impacts, and integrated solutions. While co-creation with users is essential to developing actionable assessments, this paper lays the groundwork for future processes by identifying many advancing and emerging areas of relevant knowledge ready for assessment or additional near-term research. Drawing on the expertise of many scholars who were formerly tasked with producing the Sixth NCA and authors of other national or sub-national climate assessment reports, this paper highlights select U.S.-relevant topics in which research advances since the 2023 Fifth NCA make new syntheses particularly valuable for future national, sub-national, and sectoral climate assessments. It also identifies critical research topics in those select areas that would be useful for future climate assessment efforts. Overall, this research priorities roadmap aims to catalyze collaborations, research, and a network of climate assessments to synthesize the state of climate impacts, risks, and responses and to provide widely accessible and foundational information for sectoral, regional, and cross-cutting climate action plans and decisions in the U.S.

Plain Language Summary Scientific assessments are critical in informing households, communities, businesses, institutions, and governments as they respond to intensifying climate hazards. As climate change impacts accelerate, the pace of assessment and integration of science with decision-making and action must accelerate as well. A network of U.S. climate assessment efforts could rapidly synthesize actionable science and case studies to inform climate response strategies. To support future processes, this paper presents a selection of foundational topics needing assessment and near-term research across climate impacts, risks, and actions from the perspective of the U.S. and some of its key regions, environments, and economic sectors. For example, assessment is needed for the increasing threats posed by compound extremes and cascading climate risks, which can overwhelm systems developed for independent events. The effectiveness of climate responses likewise requires continuous evaluation and improvement, with consideration of the broader impacts (e.g., economic, environmental, health) associated with those strategies. System-level understanding of integrated climate response strategies can be advanced by combining observations and modeling with mitigation, adaptation, climate interventions, disaster management, and resilience decision scenarios. Overall, these research priorities aim to encourage new research and future national, regional, local, and sectoral climate assessments that support climate-informed decision-making in the U.S.

1. Introduction

Human-caused greenhouse gas emissions are driving climate change and increasing the likelihood, frequency, and/or intensity of many types of extreme weather events and other climate hazards (Marvel et al., 2023). These changes are already harming people, economies, infrastructure, and ecosystems globally and across the United States (U.S.) (IPCC, 2023; USGCRP, 2023). Limiting human-caused global warming requires greenhouse gas mitigation efforts to reach global net-zero emissions, with the amount of future warming tied to the timing of when net-zero is reached and the lifespan of cumulative emissions released during that period (IPCC, 2023). Adaptation and resilience strategies are equally urgent to manage and reduce current and future risks, reduce inequities, and support recovery (IPCC, 2023; USGCRP, 2023).

Decisions on both how and when to reduce greenhouse gas emissions and invest in adaptation have current and future implications for the U.S., whether those decisions are made by individuals, businesses, local governments, states and territories, Federally Recognized Tribes (Grade et al., 2023), the federal government, or the U.S. as a whole. These decisions affect environmental quality and health, the economy and livelihoods, the safety of communities, the infrastructure that shapes society, and the future of the nation. Proactive, evidence-based decisions about climate change have greater potential to cost-effectively deliver benefits and reduce current and long-term harm, as well as the risks of catastrophic impacts (IPCC, 2023; USGCRP, 2023).

Scientific assessments provide a comprehensive understanding of the evidence and knowledges essential to support sound decision-making (Kirchhoff et al., 2019). Assessments synthesize existing research and lessons learned from practice; they define the state of knowledge, clarify uncertainties, and can reveal where more evidence is needed to support scientific understanding and decision-making (Avery et al., 2025). Assessments can also highlight barriers or enablers to the uptake of evidence and practice, and help guide approaches that facilitate greater use of evidence in decision-making (Hartwell et al., 2023). Assessments are conducted across scales—from local and state initiatives (e.g., Bedsworth et al., 2018; New York City Panel on Climate Change, 2019) to national (USGCRP, 2000, 2009, 2014, 2018, 2023), Indigenous Peoples (e.g., ANTHC, 2024; Grade et al., 2023) to global initiatives (IPBES, 2019; IPCC, 2023). They also evaluate sectoral systems and place-based considerations in the context of a changing climate (California Ocean Protection Council et al., 2024; USGCRP, 2016, 2018; Wamsher et al., 2024). While assessments have tended to be large, static reports produced on a periodic basis, many user challenges can be better served through a sustained assessment process, allowing for smaller, more frequent updates and contextualized information (e.g., Moss et al., 2019). Whether sustained or discrete, assessments inform and are a scientific reference for public policy, planning, infrastructure, investments, and industry (Avery et al., 2025).

The Global Change Research Act of 1990, signed into law by U.S. President George H.W. Bush, established the U.S. Global Change Research Program (USGCRP) and mandates that it coordinate and publish a National Climate Assessment (NCA) every 4 years. The USGCRP's stated purpose is *"to provide for development and coordination of a comprehensive and integrated United States research program which will assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change"* (Global Change Research Act of 1990, 15 U.S.C. § 2921 *et seq*, 1990). The Fourth NCA, released in 2017 and 2018, noted the role of assessments to *"help inform decision-makers, utility and natural resource managers, public health officials, emergency planners, and other stakeholders by providing a thorough examination of the effects of climate change on the United States"* (USGCRP, 2018, p. 1). As a few examples, NCAs have informed: New Hampshire flood risk management policies (S. Alexander & Crawford, 2019); Boston, MA, flood management plans (City of Boston, 2019); the North Carolina Resilience Exchange (Nicholson et al., 2020); Northeast Ohio Regional Sewer District projects (Northeast Ohio Regional Sewer District, 2012); West-Central Minnesota regional planning (West Central Initiative, 2023); Dallas, TX, Comprehensive Environmental and Climate Action Plan (City of Dallas, 2020); San Antonio, TX, Climate Ready plan (City of San Antonio, 2019); Washington state's resilience strategy (Washington State Department of Ecology, 2024); and Hawai'i bird protections and sea level rise planning (Raine et al., 2024).

As society determines how to respond to observed and anticipated changes in the climate, decision-makers will continue to seek information to help them understand the changes they may face. Assessments help fill this need by making the latest scientific research and cutting-edge practices accessible and actionable for decision-makers. Assessments, however, can be labor- and data-intensive, and all assessments benefit from strong engagement and co-design processes to enhance their relevance and usability (Crimmins et al., 2025). The Fifth NCA (NCA5), for example, engaged more than 500 authors and 260 technical contributors from federal, state, tribal and local government agencies, non-profits, private companies, and academia to assess and synthesize more than 8,200 studies, reports, shared Indigenous Knowledges and local knowledge, and other references (Chu et al., 2025; Grade et al., 2023). The more than 8,000 references are as critical as the more than 700 people: effective assessments need data, research, reports, and practices to assess.

Climate assessments depend on a robust body of research that can be assessed, synthesized, and translated into actionable information to support decision-making (Avery et al., 2025). In this commentary, jointly published in *Earth's Future* and *Bulletin of the American Meteorological Society*, we propose a roadmap to catalyze synthesis research and scientific priorities that can inform sub-national (e.g., state or municipal), national, or international assessments, as well as assessments focused on particular systems or sectors (Figure 1). Section 2 covers major global systems (physical, social, ecological, and economic) and their interactions; Section 3 provides examples of social-ecological systems, sectors, and regions; Section 4 considers climate responses (adaptation, mitigation, and climate interventions); and Section 5 concludes with a discussion about the path forward for U.S. climate assessments. These sections include a selection of topics relevant to synthesis and the authors' expertise, but are not intended to be a comprehensive representation of all relevant climate assessment research topics (Figure 2).

We call on the research community to work with communities, Indigenous Peoples, the private sector, non-governmental organizations, and government actors to conduct synthesis research and co-create assessments that directly inform decision-making, multiple climate response pathways, and climate risk reduction measures across the U.S. We encourage submissions to the AGU/AMS *U.S. Climate Collection: Informing Climate Assessment in the United States* that address the proposed synthesis research opportunities outlined here as well as other priorities identified by the broader scientific and practitioner communities, and hope this commentary can help shape future assessments of climate risks, impacts, and solutions within the U.S.

2. Major Global Systems

This section includes the major global systems—physical, ecological, social, and economic—that are impacted by and impact climate change.

2.1. Physical Systems

The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) and NCA5 concluded that the evidence for climate change driven by emissions of greenhouse gases from human activities is

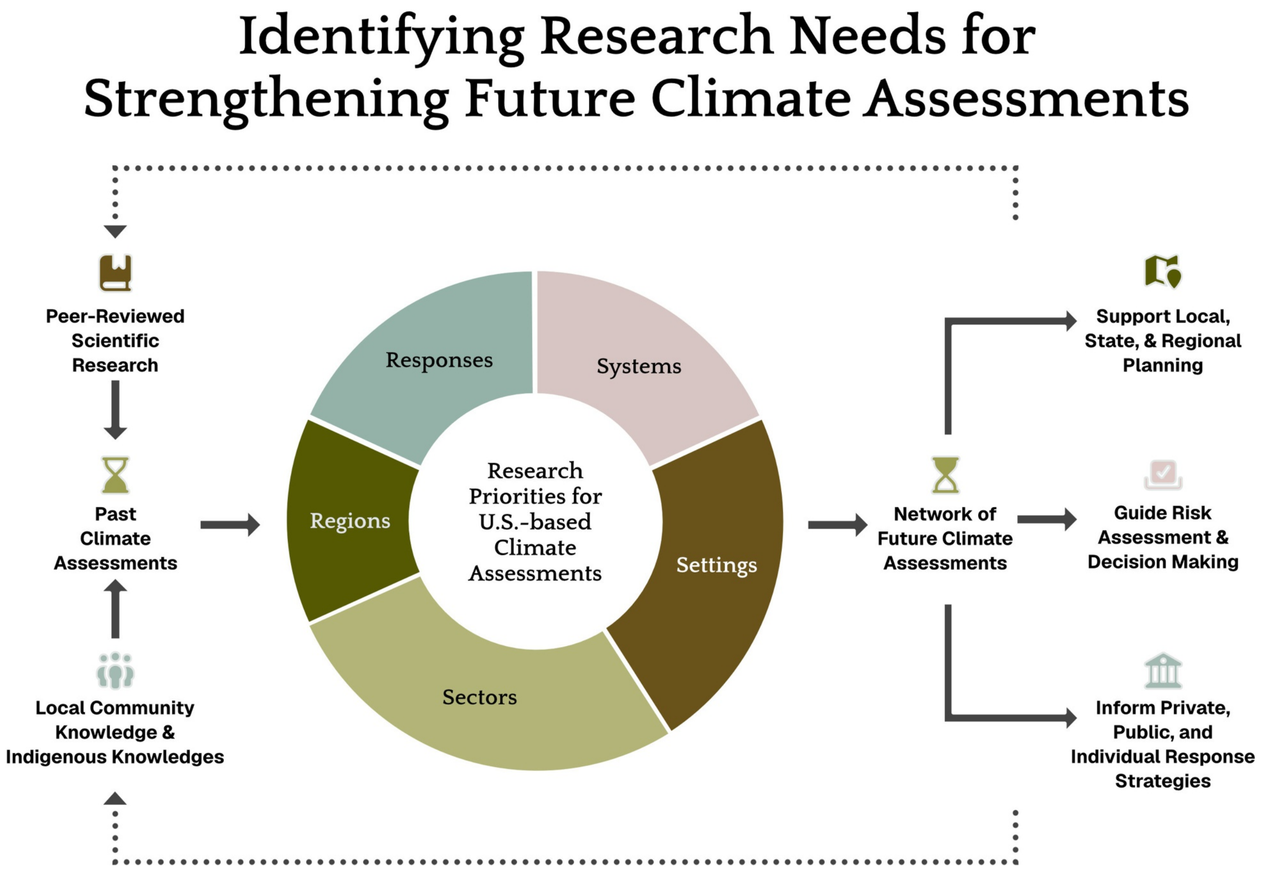

Figure 1. Conceptual positioning of this commentary within the broader climate research landscape. Peer-reviewed studies, local community knowledge and Indigenous Knowledges, and past sub-national to international climate assessments (left) inform the research priorities for future climate assessments as synthesized in this paper (center). These identified priorities, in turn, guide a network of future climate assessments (right), which can support local, state, and regional planning, strengthen risk assessment and decision-making, and inform sub-national to national public and private sector planning, risk assessments, and decision-making strategies. This figure represents one phase of an iterative process where the network of future climate assessments provides insights for future knowledge creation (gray arrows). Icons are from Font Awesome under a perpetual license agreement.

unequivocal (IPCC, 2023; USGCRP, 2023). Beyond warming, the fingerprints of human activities have been detected across the atmosphere, oceans, cryosphere, and biosphere (Queen et al., 2025; Santer et al., 2023). Several types of extreme weather events, including heat waves, extreme precipitation events, agricultural and ecological droughts, tropical cyclones, and fire weather, are increasing in likelihood, frequency, and/or intensity as a result (Marvel et al., 2023; National Academies of Sciences, Engineering, and Medicine, 2026; Seneviratne et al., 2021). Moreover, the extent, pace, and nature of future changes depend on the trajectory of future emissions (Leung et al., 2023; Marvel et al., 2023). While these scientific foundations are robust, many areas of physical science have advanced since the NCA5 and require synthesis and assessment to better characterize the climate future of the U.S. and the Earth to provide insights to policymakers, communities, and other stakeholders and rights-holders on using climate science to support decision-making.

2.1.1. Assessment Research Priorities

- **Comparing trends in Earth system model projections with observations:** Climate model projections have accurately predicted observed trends in global mean surface temperature (Hausfather et al., 2020). With clearer climate change signals emerging from longer observational records, it is now possible to evaluate models against observed trends—not just mean states—across a widening set of variables and at increased spatial resolution, while better accounting for internal variability (I. R. Simpson et al., 2025). Model evaluations can increase confidence in projections of future climate risks that are used to guide policy, planning, and preparedness. Relevant variables include but are not limited to those related to changes and trends in the

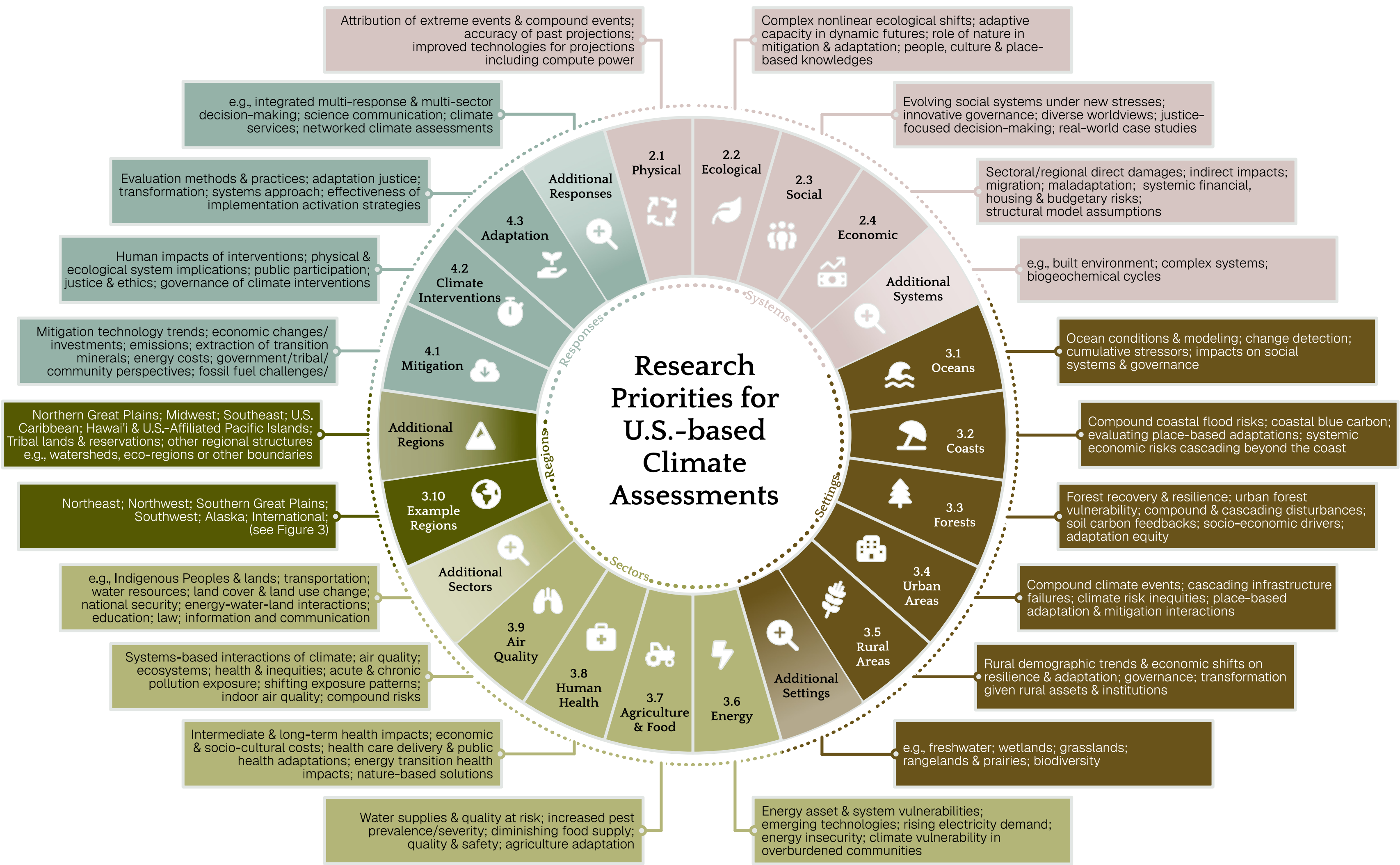

Figure 2. Overview of the key research priorities identified in this commentary. The paper has 22 sections, organized into 5 groups—systems, settings, sectors, regions, and responses. These groups are reflected in the wheel, illustrating how research priorities are connected as part of a system that can span multiple research dimensions. Each section within the systems, settings, sectors, and responses groups has a text box summarizing core future research needs, as well as a box highlighting additional research priorities not covered in this commentary ("Additional Priorities"). The regions group highlights the geographic areas covered in this paper and acknowledges regional gaps; research priorities of included regions are presented in Figure 3. Icons are from Font Awesome under a perpetual license agreement.

carbon cycle, such as ocean and land sink dynamics (Collier et al., 2018; Fu et al., 2022; M. Liu et al., 2024), regional temperature (Blackport et al., 2024), and precipitation (Klavans et al., 2025; Kuo et al., 2025), near-surface humidity (N. Simpson et al., 2023), atmospheric circulation (Grise et al., 2019), and top of atmosphere energy balance (Schmidt, 2024). Because adaptation typically occurs at regional and local scales, projections need to be evaluated at high spatial resolution across different regions of the U.S. A robust partitioning of regional climate trends into forced changes and internal variability allows better understanding of changes over time.

- **Improvements in high-resolution projections:** Coupled Model Intercomparison Project Phase 6 (CMIP6)-class models, with typical spatial resolutions of ∼100 km, are not always sufficient to capture important physical processes or to provide detailed local information to support decision-making. Higher-resolution models (∼10–25 km), convection-permitting simulations, dynamic downscaling methods, and statistical/hybrid-statistical/machine learning (ML)-based downscaling techniques offer finer-scale insights. There is an urgent need to assess the "added value" of these products for decision support (Office of Science and Technology Policy, 2024; U.S. Department of Energy, 2024). Similarly, the growing suite of downscaled CMIP6 products, including new ML-based data sets, requires a critical assessment of "fitness for purpose" (Hartke et al., 2025) and the quantification of uncertainty and confidence across metrics to help decision-makers assess the relevance of different products for their needs.
- **Assessments of past emissions scenarios:** It is important to assess how well earlier generations of emissions scenarios (e.g., the CMIP6-generation Shared Socioeconomic Pathway scenarios) capture current trends. Key examples include recent shifts in aerosol emissions (e.g., from shipping emissions and rapid reductions in global air pollution), short-lived climate forcers (e.g., methane), land use changes, and land and ocean carbon sinks (Schoeberl et al., 2024; Yuan et al., 2024). Do these developments fall within the CMIP6-based scenario envelope? If not, what are the implications for differences between models and observed changes in aspects of the climate system (Schmidt, 2024; I. R. Simpson et al., 2025)?

Two additional emerging extreme event topics merit synthesis.

- **Climate and extreme event attribution:** Attribution science continues to grow, with climate change signals emerging and human fingerprints being detected as contributing to additional aspects of the Earth system, such as the atmospheric circulation (Shaw et al., 2024), seasonal cycle (Santer et al., 2022; J.-R. Shi et al., 2024), upper-tropospheric ozone trends (X. Yu et al., 2024), and daily weather (Gilford et al., 2024). Further, a growing range of extreme event types is being studied within detection and attribution frameworks, including new links to health, agriculture, and economic impacts (Callahan & Mankin, 2025). Since the National Academies of Sciences, Engineering and Medicine (2016)'s Report on Extreme Event Attribution, confidence has grown in attributing climate change contributions to many types of extremes, including extreme fire weather, hurricane rainfall, marine heat waves, and certain types of droughts (National Academies of Sciences, Engineering, and Medicine, 2026; Perkins-Kirkpatrick et al., 2024). Confidence in attributing certain characteristics, such as hurricane frequency, and other event types, such as severe convective storms, meteorological droughts, and extratropical cyclones, remains relatively low and requires additional methodological and applied research to advance research and operational capability in attributing such events. In addition, unprecedented extremes, such as the 2021 Pacific Northwest heat wave, which shattered temperature records in the U.S. and Canada, pose novel challenges for attributing even widely studied event types using traditional approaches (Fleishman et al., 2025; National Academies of Sciences, Engineering, and Medicine, 2026). Understanding the climate change contribution to such record-shattering events requires methodological advances—for example, leveraging larger ensembles or new ML techniques—as well as advances in knowledge of their drivers and process-based evaluation of model capabilities in simulating such events.
- **Compound events:** Compound events—where multiple stressors overlap, interact with pre-existing conditions, or cascade—remain underexamined (AghaKouchak et al., 2020; Zscheischler et al., 2020; D. Singh et al., 2023). Some events, such as co-occurring hot and dry conditions or hot and humid conditions, have been the topic of many studies (e.g., Buzan & Huber, 2020; Matthews et al., 2025; Rogers et al., 2021). Other events have caused severe societal damage, but their understanding is still limited. These include, for instance, heat waves following hurricane- or winter-storm-induced blackouts (K. Feng et al., 2022, 2025), sequential hurricanes (Xi et al., 2023), and compounding drought–wildfire-flood events (Dulin et al., 2025; Richardson et al., 2022; Touma et al., 2022). Such events can pose outsized risks beyond those expected from individual

events alone and demand integrative assessment frameworks (Jézéquel et al., 2024). There is also a need to evaluate human responses to such extremes and how those feedbacks amplify, reduce, or create novel cascading risks (Hatchett et al., 2021). Finally, numerous mixed physical-biogeochemical compound events are understudied, for example, marine heat waves that reduce carbon dioxide (CO_2) uptake in the Mid-Atlantic Bight by increasing the seawater partial pressure of CO_2 (pCO_2) (Edwing et al., 2024).

2.2. Ecological Systems

Climate-driven ecological change is accelerating and becoming more complex, with emerging evidence of nonlinear responses, thresholds, and cascading effects on vital services and the many people, businesses, communities, and economies that depend on them. Recent research reveals striking differences in how species and ecosystems respond to similar changes in climate across space and time, illustrating that generalizations across geography or taxa are unreliable (Beever et al., 2023; Diffenbaugh & Burke, 2019; Perret et al., 2024; M. I. Smith et al., 2024). Advances in genomics, remote sensing, and ecosystem modeling may enable a more precise understanding of where and how ecological thresholds—values of environmental attributes beyond which stark changes in ecosystem states occur—may be crossed (Lenton et al., 2024; J. H. Thorne et al., 2023).

Growing evidence indicates that protecting and restoring ecosystems can yield substantial benefits for species, their habitats, and human health, enhancing the resilience of systems to wildfire, drought, floods, sea-level rise, and other stressors (Chaplin-Kramer et al., 2023; Griscom et al., 2017). Ecosystems with limited human influence not only sequester carbon but also contribute to climate resilience by buffering communities from climate extremes, supporting native species and ecosystem functions, and sustaining cultural values (Fargione et al., 2018; Goldstein et al., 2020). Recognition of these benefits is reflected in an increased emphasis on nature-based solutions, although challenges remain in quantifying the benefits, trade-offs, and effectiveness of these solutions under future climate conditions (Dunlop et al., 2024; Nelson & Reed, 2025; Palomo et al., 2021; B. Turner et al., 2022). Key research syntheses to support climate assessments needs include evaluating the effectiveness of ecosystem protection and restoration under extreme events, quantifying durable total amounts of carbon sequestration (Tölgyesi et al., 2025), developing metrics to assess co-benefits and trade-offs between carbon sequestration and adaptation outcomes, and understanding implications for reserved and treaty rights of Indigenous Peoples and for other communities that have a strong reliance on water and land.

2.2.1. Assessment Research Priorities

- **Complex and context-specific ecological shifts:** Local environmental conditions and interactions with other species affect how the physiology or behavior of a given species responds to the same change in climate (Williams et al., 2022). These responses can be nonlinear and may trigger abrupt shifts in community composition or function of the entire system. Such complexity calls for action to be informed by projections that incorporate local adaptation, time lags, feedbacks, and compound disturbances (Millar et al., 2007; M. G. Turner & Seidl, 2023). Key synthesis and research needs relate to the mechanisms of trait-based responses and species interactions under climate change, as well as identification and early indicators of irreversible ecological state shifts or ecological tipping transitions. Research needs to include appropriate attention to Indigenous Knowledges and data sovereignty.
- **Adaptive capacity and management implications:** The ability of ecological populations to persist under climate change depends on their adaptive capacity—a function of genetic diversity, demographic factors, ecological context, and exposure to other stressors (Pacifici et al., 2015; Thompson et al., 2023; Thurman et al., 2020). Recent studies highlight mismatches between observed ecological change and existing conservation strategies, underscoring the need for frameworks that accommodate dynamic futures (Schuurman et al., 2022). Addressing these gaps requires place-based approaches that integrate species-specific adaptation potential with landscape-level connectivity and draw on Indigenous Knowledges, including conservation strategies that emphasize long-term relationships with ecosystems. Research and synthesis needs relate to meta-analyses of population-level adaptive traits, as well as comparative assessments of management that is responsive to environmental variation and non-stationarity within and among ecosystems.
- **Nature's role in climate mitigation and adaptation:** Growing evidence indicates that protecting and restoring ecosystems can yield substantial benefits for species, their habitats, and human health, enhancing the resilience of systems to wildfire, drought, flood, sea-level rise, and other stressors. Trade-offs may exist

among maximizing carbon storage, species conservation, water availability, and recognizing diverse cultural perspectives and values. Moreover, major challenges remain in quantifying permanence, leakage, and additionality of ecosystem protection and restoration. Key synthesis needs include evaluating the effectiveness of ecosystem protection and restoration under extreme events, quantifying the durable total amount of carbon sequestration (Tölgyesi et al., 2025), developing metrics to assess co-benefits and trade-offs between carbon sequestration and adaptation outcomes, and understanding the implications for reserved and treaty rights of Federally Recognized Tribes and Indigenous Peoples.

- **People, culture, and place-based knowledges:** Climate change impacts the relationships between people and nature, particularly for Indigenous Peoples and other communities with strong place-based cultural ties. Changes in phenology, range shifts, and ecosystem structure, composition, and function can disrupt cultural practices, subsistence activities, and identity (Chisholm Hatfield et al., 2018; Farrell et al., 2021). At the same time, Indigenous Knowledges and relational worldviews offer valuable insights for adaptation and stewardship (Daigle et al., 2019; Whyte, 2017). Synthesis research needs include co-created adaptation strategies guided by Indigenous Knowledges or local knowledge, as well as evaluation of how values influence and are affected by ecological transformation.

Nature is both affected by and can buffer human systems as climate changes. Future assessments will be more useful if they go beyond species inventories to focus on dynamic processes, adaptive capacity, integrated system-level responses, and social and ecological feedbacks. By synthesizing insights from ecological, cultural, and governance domains, the scientific community can better anticipate, manage, and leverage ecological transformation as climate change accelerates.

2.3. Social Systems

Social systems structure what climate responses are possible—and which are not—through political, legal, economic, and cultural mechanisms. Moreover, social systems shape incremental shifts and transformative changes in societal, political, cultural, values, and economic systems that affect future societal and climate impact pathways. NCA5 assessed how social systems and processes influence the distribution of climate impacts and risks, amplify vulnerability among historically under-resourced and overburdened groups, mediate communication and knowledge about climate change, and influence the range and effectiveness of responses to climate-related extremes (Marino et al., 2023; Whyte et al., 2023). Future assessments should strive to weave together a wider range of research foci and methodological approaches, including place-based, participatory, and community-engaged studies and lived experiences with large-scale, generalizable approaches to studying societal phenomena and drivers, and integrate these into a more comprehensive understanding of climate change, impacts, and responses.

2.3.1. Assessment Research Priorities

- **Societal factors:** Emerging research identifies shifts in social cohesion, markets, insurance, education, demographics, political orientation, security, technology, and governance as key factors influencing climate outcomes (Cattino & Reckien, 2021; International Science Council, 2023; Lezak & Rock, 2024; Raymond et al., 2025). Social systems confront new stress from increasingly frequent and intense extreme weather events, combined with ongoing non-climate-related stressors and shrinking recovery windows as events occur concurrently or in near succession. At the same time, privatization of climate services and the risk of reduced data accessibility are reshaping who can plan and respond (Bradshaw et al., 2024; Congressional Budget Office, 2024). Studies are also advancing the scientific understanding of how policy mismatches across scales, governance inefficiencies, limitations of social vulnerability indices, and spatial disparities in exposure constrain adaptive capacity (Koslov et al., 2021; Painter et al., 2024; Samoray et al., 2024; Winkler & Mockrin, 2025).
- **Innovative forms of climate governance:** Alternative governance models (e.g., commons-based governance, cooperatives, co-governance) are gaining traction. These approaches aim to redistribute responsibilities, risks, and benefits more equitably than conventional frameworks, particularly when grounded in local knowledge and ethics of care (Barger et al., 2025; Ficara & Wheeler, 2023; Lezak & Rock, 2024). A central element is co-creation, which brings scientists, policymakers, and communities, including Indigenous Peoples and communities, into sustained collaboration. Co-creation can enhance legitimacy, foster shared ownership of

decisions, and generate innovative strategies that are better aligned with diverse values and dynamic socio-ecological conditions.

- **Worldviews and social connectivity:** Diverse worldviews and ways of knowing—including but not limited to Indigenous Knowledges, traditional knowledges, and local/experiential knowledge—shape awareness and understanding of climate risks and participation in responses as well as expand the creativity, depth, and robustness of climate responses (Whyte et al., 2023). Justice-focused approaches to decision-making (Jean et al., 2024; Méndez et al., 2025; Sultana, 2024) emphasize the importance of civic engagement, repair, accountability, community cohesion, reciprocity, and relational perspectives in shaping climate actions and building resilience.
- **Case studies in practice:** A growing body of evidence from climate programs and partnerships underscores the value—and limitations—of current implementation models. Synthesis of these cases can reveal conditions for success across public-private partnerships, research-practice collaborations, and efforts to include Indigenous Knowledges (Bethel et al., 2022; Bizer et al., 2025; Climate and Traditional Knowledges Workgroup, 2014; Lazrus et al., 2025; Maldonado et al., 2013). Case studies on the adoption of adaptation technologies and strategies can inform actions to reduce risks (A. Jones et al., 2023).
- **Disproportionate exposure and future equitable pathways:** Historic legacies—such as redlining and exclusionary housing practices—continue to shape climate risk exposure. For example, people living in formerly redlined areas face disproportionate exposure to extreme heat and may face greater financial burdens from higher energy and more frequent health bills, thus exacerbating the long-term and historical inequities of climate change (Hoffman et al., 2020). Climate resilience and adaptation decisions can either reinforce or alleviate inequitable climate burdens for low-income households, racial minorities, and other vulnerable groups (Sovacool & Linnér, 2016).

Additionally, three cross-cutting areas—emissions, impacts and adaptation, and climate services—frame the role of social systems in climate science. Cutting across these topics are the social structures that shape responses, which can simultaneously influence emissions, impacts, and knowledge.

- **Emissions drivers and social constraints on mitigation:** Greenhouse gas emissions result from a cascade of decisions and actions by governments, corporations, communities, and individuals, and continue to be shaped by evolving incentives and institutional structures in the U.S. and globally. Geopolitical conflicts (e.g., Ukraine, Iran) can create constraints, are difficult to predict, and can shift emission trajectories (Block et al., 2025). Any assessment of emissions scenarios should account for these historic, current, and future drivers and social contexts (Meinshausen et al., 2024; Nielsen et al., 2024).
- **Impacts and adaptation:** Social systems mediate the translation of physical climate impacts into societal consequences. Climate impacts lead to different outcomes depending on where and to whom they happen (Farrell et al., 2021; Waters et al., 2024). Gaining insights into these linkages provides a clearer framework for understanding the reasons behind the uneven distribution of impacts. This knowledge is essential for developing societal strategies—including adaptation, mitigation, and response strategies—that can reduce impacts for all, while also ensuring a fair distribution of responsibilities, risks, and benefits.
- **Valuing climate knowledge and services**: The generation and dissemination of usable information on climate change and its consequences are important enablers of climate adaptation. Navigating rapidly changing access to and the landscape of climate data, tools, and information useful for specific contexts remains challenging. Assessing research on boundary-spanning organizations and people who serve in science translation roles could provide useful insights into decision-making contexts and the usability of such decision-support tools (Moss et al., 2014). Additionally, assessing the value of climate knowledge and the effectiveness of climate services can support research on the return on investment generated by climate services, in calculations of the avoidance of climate losses, or to improve decisions for individual or integrated climate response strategies (Hewitt & Stone, 2021).

2.4. Economic Systems

Economic impacts due to anthropogenic climate change stem partly from direct physical effects of changing weather patterns on exposed market (e.g., energy, agriculture) and non-market (e.g., mortality, biodiversity) sectors. Impacts also arise indirectly, both via the transition risk to stranded assets during a clean energy transition and through intermediate pathways that affect the physical, human, and natural capital underlying economic activity, in both the short and the long run (National Academies of Sciences, Engineering, and Medicine, 2024a). Individuals, firms, communities, and policymakers make decisions under uncertainty and imperfect information, without public policies that fully internalize the positive and negative externalities that their actions impose. Thus, adaptation to current and expected climate change is inherently imperfect, especially for unanticipated events, making quantification of expected damages difficult. A further unknown is the degree of future innovation in, and adoption and diffusion of, adaptation and mitigation technologies. The distribution of damages across communities is difficult to assess, as migration has historically been a primary human response to environmental change. These identification challenges are further compounded by the unprecedented rate of climate change relative to human historical experience, as well as by the increasing complexity of modern societies. With considerable progress in the economic literature since NCA5 (Hsiang et al., 2023), several themes are emerging as priorities for research synthesis.

2.4.1. Assessment Research Priorities

- **Improved resolution, sectoral, and regional estimates of direct economic damages:** Recent studies have refined estimates of direct climate damages at sectoral, national, and global levels. Bottom-up, sector-based damage estimates continue to improve in accuracy and spatial resolution with more granular data, but remain mostly limited to market, temperature-driven, and lower-uncertainty impacts (Environmental Protection Agency, 2023; Waidelich et al., 2024). Economy-wide damage estimation methods with a focus on GDP have also advanced, as evidence grows of persistent, long-lasting effects of climate on economic growth (Burke et al., 2015; Dell et al., 2012; Howard & Sterner, 2025; Hsiang, 2026; Kopits et al., 2025).

  Critical needs include determining whether higher-quality estimates are now available for well-studied impacts, with a particular focus on whether new estimates better capture the relevant set of climatic impact drivers beyond temperature alone. With the growing availability of downscaled climate projections, linking climate stressors with health and economic data at consistent spatial scales is key to producing spatially resolved damage estimates that inform local adaptation, resilience planning, and cost-benefit analyses of specific interventions. Also critical is identifying previously omitted impacts for which estimates are now available, such as biodiversity, oceans, and air pollution impacts, including wildfire smoke (Waidelich et al., 2024). Structural gaps—including systemic risks and regional spillovers from migration, trade, security, and finance—also warrant attention (Pankratz & Schiller, 2024).

- **Indirect climate impacts, including planned adaptation, maladaptation, indirect benefits, systemic risks, and unplanned migration:** Knowledge of indirect climate impacts remains less developed, though the literature is expanding, particularly for planned adaptation and unplanned migration. A comprehensive assessment is needed on adaptation rates, costs and frictions, systemic financial risks, and asset adjustments (Giglio & Stroebel, 2024), potential maladaptation (X. Li et al., 2024), and the potential co-benefits of nature-based solutions for climate impacts (such as ecosystem services) (Ellis et al., 2024; Moreira et al., 2025). Understanding the links between bottom-up, local case studies, and top-down statistical methodologies for analyzing adaptation would advance the field.

- **Climate risks to housing, insurance markets, public budgets, and municipal credit:** Large-scale behavioral responses and shifts in macroeconomic dynamics, such as inflation, investment, and employment, can alter asset values and cause financial instability, such as banking crises and shrinking insurance markets (Giglio & Stroebel, 2024; Reissl et al., 2025; L. Shi et al., 2024). For example, internalization of flood risks could shock the overvalued property markets, thereby destabilizing banks, mortgage markets, and local government revenues (Gourevitch et al., 2023). Local governments face credit constraints and budgetary pressures from threats to their local property tax bases, limiting their ability to adapt under current structures, although public pressure could lead to alternative fiscal measures (Diezmartínez & Short Gianotti, 2024). A lack of disclosure of long-run climate risks to municipalities increases the potential for feedback into the broader financial markets (Davidson & Cooper, 2025). Despite an increasing need for wider risk sharing, insurance premiums are rising, and availability is declining in high-risk areas, posing further risks to regional

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governments as public pressure increases for them to fill the service gap (Gourevitch & Kousky, 2025; Kousky et al., 2024).

A synthesis of these systemic risks and an assessment of potential distributional impacts across communities is critical to identifying potential adaptation and policy options. Moreover, current climate-economic models broadly omit financial markets and their links to the wider economy, leading to an underrepresentation of these systemic risks (Reissl et al., 2025). Efforts are necessary to include the possibility of rapid structural change and disorderly transitions, and their associated costs (Stern et al., 2022).

- **Climate-economic models and their structural assumptions:** Social-cost integrated assessment models now incorporate improved calibration of damage functions, more accurate physical climate emulators, probabilistic socioeconomic and emissions scenarios, and lower discount rates that account for uncertainty and risk. Overall, these improvements have led to increases in their key policy output: estimates of the social costs of greenhouse gases (Barrage & Nordhaus, 2024; Environmental Protection Agency, 2023; Kopits et al., 2025). Simultaneously, advances in general-equilibrium integrated assessment models enable simulations of sector and individual adaptive responses beyond production, capturing migration and technological innovation (Desmet & Rossi-Hansberg, 2024; Reissl et al., 2025). Nonetheless, challenges—including omitted impacts and structural uncertainty—remain, with important implications for key policy metrics and simulations of behavioral responses (Howard & Sterner, 2025; Moore et al., 2024).

  The structural assumptions underlying climate-economic models have changed little over time. A synthesis and inter-model comparison of these assumptions is needed, with attention to empirical foundations. For example, panel estimates increasingly support persistent, long-lasting effects of climate on growth, challenging the standard assumption of transient impacts (Moore, 2025). Other structural assumptions needing critical synthesis include limited substitutability of market goods and ecosystem services for consumers and producers (Drupp et al., 2024), nonlinear changes in physical and social systems (e.g., "tipping points"; Dietz et al., 2021; Kopp et al., 2016), financial risks (Lamperti et al., 2019), improved treatment of adaptation (Filatova et al., 2025), and interactions across regions and damage pathways (T. R. Carter et al., 2021; A. Feng et al., 2025; Howard & Schwartz, 2017).

3. Examples of Social-Ecological-Technical Systems, Sectors, and Regions

System-wide assessments, as discussed above, are needed for large-scale and integrated issues (e.g., global models). Yet the effects of climate change differ among sectors and regions. Continued assessment and synthesis on these topics are essential for national, state, and local decision-making. To cover topics in greater depth, assessments often focus on smaller systems (e.g., coasts), geographic regions (e.g., the Northeast), or topical sectors (e.g., health), as has been done in the U.S. National Climate Assessments (USGCRP, 2023). There are numerous ways systems, regions, and sectors can be defined and organized, so the roadmap here is not comprehensive but rather illustrative of the type of research needed at the systems, regional, or sectoral levels to inform future assessments.

In this section, we highlight synthesis priorities across several socio-ecological systems, sectors, and regions. The topics covered here are selective, based on the authors' expertise, and are not comprehensive. There are critical communities, such as sovereign Federally Recognized Tribes and Indigenous Peoples, and sectors, such as transportation, water, national security, information and communication systems, education, and law, not included as sections. Similarly, we highlight examples from some but not all U.S. regions defined in the NCA (e.g., excluding the Southeast, Midwest, Northern Great Plains, the US Caribbean, and Hawai'i and U.S.-affiliated Pacific Islands). Though the coverage is not exhaustive, in sharing these examples, we aim to spur the scientific community to conduct synthesis research on the priorities highlighted, as well as to address other climate assessment research gaps relevant to communities, sectors, regions, and nationally important decisions.

3.1. Oceans

Rising atmospheric temperatures are driving increases in ocean heat content and more frequent marine heat waves, altering stratification, and reducing the ocean's ability to store gases such as oxygen and CO_2. Rising CO_2

in the atmosphere is altering the chemistry of the ocean, causing pH to decline; aragonite saturation had by 2020 declined by more than 20% compared to the pre-industrial era over much of the ocean, crossing a planetary boundary for ocean acidification and reducing habitat for calcifying species (Findlay et al., 2025). These multistressors are changing concurrently, or in close concert, generating more compound events (Gruber et al., 2021). Climate-mediated changes increasingly threaten food supplies, biodiversity, disaster preparedness, public health, coastal infrastructure, national security, and economic stability (Mills et al., 2023). A deeper understanding of the ocean, changing marine ecosystems, and the people that depend on them is critical to effective strategic resilience, adaptation, and mitigation efforts.

3.1.1. Assessment Research Priorities

- **Simulations of ocean conditions:** Models have become increasingly sophisticated, with high-resolution models now coupling ocean, ice, atmosphere, biogeochemistry, and sediment feedbacks (Mathis et al., 2022; Ross et al., 2023; Ye et al., 2025). These models span climate-relevant timescales, preserve key coastal dynamics, and support forecasts from sub-daily to decadal scales. Integrated forecasting systems now link weather, seasonal, and climate projections, revealing important global-to-local interactions (Tommasi et al., 2017). As models grow in complexity, the demand for accurate, near-real-time coastal forecasts is driving advances in ML-powered pattern recognition and in identifying persistent gaps, particularly in subsurface observations (McAdam et al., 2023; Mogen et al., 2023; Siedlecki et al., 2021). The land-ocean interface remains a critical frontier, with coastal hazards increasingly shaped by interactions at this boundary and increasingly influenced by global-scale processes that have localized impacts (e.g., El Niño-Southern Oscillation, atmospheric rivers). Key priorities for future assessment include evaluating how coupled systems reduce or revise estimates of sources of uncertainty and how to deliver more timely near-term forecasts to support dynamic ocean management and climate adaptation.
- **Rapid innovation in ocean observation and data science:** Advances in ocean observations and data analysis are reshaping the detection, interpretation, and response to change. Advances in satellites, autonomous platforms, and ML and artificial intelligence (AI) enable tracking of biological, chemical, and human activity in the ocean. Long-duration, in situ technologies such as gliders and profiling floats now expand observation capacity in the deep ocean, remote regions, and across all seasons. Tools like *Global Fishing Watch* (Global Fishing Watch, 2026) provide unprecedented visibility into global fishing efforts, transforming governance, enforcement, and understanding of fleet behavior (Kroodsma et al., 2018; Park et al., 2023). Future assessments will need to evaluate the relative value of emerging technologies for improving detection and attribution, as well as whether those innovations can be reliably integrated with existing ocean observing systems.
- **Stressors affecting ocean ecosystems:** Ocean ecosystems are facing intensifying stress not only from climate-associated biological and ecological shifts, but also from human use (Findlay et al., 2025; Vargas-Fonseca et al., 2024) and from weakening of the ocean carbon sink (Müller et al., 2023). However, understanding of the cumulative effects of co-occurring stressors remains limited. Marine heat waves, mass mortality events, and disease outbreaks occur against a backdrop of stressors like ocean acidification, deoxygenation, habitat loss, and resource competition (Muhling et al., 2025). In the Bering Sea, for example, anomalous warming has driven northward species shifts, outbreaks of harmful algal blooms, changes in food web dynamics, and mass mortalities of crabs (Szuwalski et al., 2023), seabirds, and marine mammals (Duffy-Anderson et al., 2017). Advances in data integration, modeling, and prediction will allow novel syntheses of diverse data, including human dimensions, that can improve understanding of compound risks and vulnerabilities and inform forward-looking decisions (Lezama-Ochoa et al., 2025). Future assessments will need to evaluate how coupled stressors affect ecosystem resilience potential, including synergistic effects, thresholds and tipping points, and cascading consequences.
- **Consequences of ecological change for coastal communities**: Particularly urgent are the risks faced by low-lying communities dependent on natural marine resources, where the impacts of sea level rise, shifting fisheries, and infrastructure vulnerability can co-occur (Halpern et al., 2025). Uneven capacity for adaptation and exposure to cumulative environmental stressors amplify existing disparities in access to resources, economic development, and vulnerability to environmental hazards (Mills et al., 2023). These challenges are compounded by the complex and intertwined ecological and socioeconomic pathways through which changes unfold (Koehn et al., 2022; Micheli et al., 2024).

- **Innovative approaches to ocean governance:** Governance innovations are needed to address growing natural, social, and economic problems. Traditional management approaches to key issues such as overfishing, habitat destruction, and marine plastic pollution struggle to succeed, and are complicated by emerging and growing industries like offshore wind and deep-sea mining (Dorrell et al., 2022; Levin et al., 2020). As the science and knowledge around the impacts and tradeoffs of these sectors mature, so will the challenges and contestations around governing the ocean. Yet there are opportunities for more adaptive, inclusive, and transformative ocean governance (Eurich et al., 2024; Mason et al., 2022). Efforts like those at the first Indigenous-nominated national marine sanctuary, the Chumash Heritage National Marine Sanctuary, provide roadmaps for success (Laughlin, 2024; Plunkett, 2025). Local and regional approaches offer collaborative opportunities for effective resource management with changes in species distribution (spatial and temporal) and abundance. Further, incorporating social and cultural dimensions is crucial (McKinley et al., 2020), particularly for Indigenous Peoples whose dynamic ocean governance systems are often overlooked.
- **Integration of physical and ecological information with social and economic models:** Thoughtful, integrative syntheses will help evaluate trade-offs among ecological sustainability, economic viability, and community well-being (Holsman et al., 2020; Sandifer & Scott, 2021). The frameworks necessary to address these and other complex problems rely on (a) co-developing management strategies with rights-holders and stakeholders, (b) quantifying economic and cultural impacts, and (c) incorporating ecosystem service valuation into scenario planning (Galparsoro et al., 2025; Rovellini et al., 2025). Next-generation assessments should examine the tradeoffs among economic viability, ecological sustainability, and social well-being using alternative management scenarios.

3.2. Coasts

NCA5 assessed the risk and severity of coastal hazards, which are increasing due to accelerating sea level rise and changing storm patterns, resulting in more frequent and damaging flooding events and chronic tidal flooding. It also evaluated the changing resilience of natural and human coastal systems, due to both climate change and human modifications, as well as both incremental and transformative coastal adaptation approaches (May et al., 2023). NCA5 noted that, while coastal ecosystem impacts and their climate feedbacks were key knowledge gaps, human modifications, including some flood risk reduction measures, can both limit natural ecosystem adaptation and compound climate change- and extreme event-driven ecosystem losses (May et al., 2023; McElwee et al., 2023).

3.2.1. Assessment Research Priorities

- **Advancing characterization of compound coastal flood risks:** Since NCA5, flood-risk drivers like land subsidence (Ohenhen et al., 2024), sub-decadal sea-level changes (O. Wang et al., 2024), and rapid hurricane intensification (Bhatia et al., 2022) are being better characterized. Compound flood modeling is considering not just coastal water levels (including tides, storm surge, and waves), but also fluvial discharge and rainfall, with increasing attention to factors like subsurface geology, groundwater, soil saturation, urbanization, and stormwater systems (Jafarzadegan et al., 2023). Research is also investigating how coastal erosion feeds back onto future coastal flood risk (Toimil et al., 2023) and how sea-level rise drives changes in coastal groundwater levels and saltwater intrusion, damaging agriculture and below-ground infrastructure (Befus et al., 2020; Habel et al., 2024). While incorporating all the relevant factors to project compound flood risk over large spatial scales remains challenging, computational and data improvements are paving the way for more comprehensive and scalable approaches (Barnard et al., 2025), and a new synthesis on this topic would be a useful contribution to assessment.
- **Assessing coastal blue carbon:** Climate change and human landscape modifications are impacting biogeochemical cycling along the land-to-ocean aquatic continuum; this is a major source of uncertainty in quantifying carbon fluxes that hinder estimates of North American greenhouse gas emissions (Poulter et al., 2025). Faster carbon cycling along this continuum and dampened uptake of atmospheric CO_2 by coastal blue carbon ecosystems may have led to a ~20% loss of terrestrial carbon to the ocean (Regnier et al., 2022). More process-based and regionally specific assessments would improve understanding of such climate-sensitive feedbacks.

- **Evaluating place-based coastal adaptations:** In response to the impacts of climate change, coastal communities are implementing incremental place-based adaptation projects and strategies, defined as adaptation actions tailored to the specific scale and characteristics of the places in which impacts occur (e.g., structural elevations, large-scale risk-reduction infrastructure, nature-based solutions, and buyouts). However, incremental adaptations are not sufficient in some locations given the accelerating pace and scale of coastal change. For example, coastal hardening measures can exacerbate beach loss and prove maladaptive (Nawarat et al., 2024). Transformative adaptations that involve fundamental attributes of human and ecological systems, governance, and institutions can be necessary and remain an emerging area of research. For example, recent research is exploring how societal perceptions of risk tolerance and values shape proactive implementation of transformative adaptations (e.g., Haasnoot et al., 2021; Moser, 2024; L. Shi & Moser, 2021).

  The key roles of financial resources, population size, and future risks in determining which coastal communities pursue adaptation measures, and which measures are pursued, are ripe for assessment (Grandage et al., 2024). While adaptation processes are increasingly attentive to questions of how to ensure the benefits are shared fairly, including with historically marginalized and lower-resourced communities (Foster et al., 2024), the degree to which coastal adaptation projects engage these communities and successfully implement equitable principles needs long-term monitoring and analysis (Domingue et al., 2024; Pollack et al., 2025). For example, some flood-prone communities pursue buyout programs, yet program requirements, structural factors, and market forces generate inequities as disadvantaged households often suffer higher relocation burdens and struggle to access safe housing elsewhere (L. Shi et al., 2022). Funding availability plays a critical role in the types of place-based adaptation pursued, and localities are increasingly using novel approaches to finance and pay for projects (Palinkas et al., 2023).

  Additionally, as nature-based strategies like living shorelines and ecosystem restoration become more common, synthesis is needed to evaluate their long-term benefits and their effectiveness to facilitate broader acceptance and effective implementation (Palinkas et al., 2023). Overall synthesis of place-based adaptation evaluation can also help inform more realistic economic modeling of the aggregate costs and tradeoffs of coastal adaptation (Depsky et al., 2023; Diaz, 2016).
- **Characterizing and managing compounding and systemic economic risks beyond the coast:** Just as climate impacts in general can have indirect effects that extend systematically, coastal climate impacts can have systemic effects that extend beyond the coast. For example, growing evidence demonstrates that coastal hazards are affecting insurance, mortgage, and property markets, as well as infrastructure costs, property tax bases, and municipal bond markets (Keys & Mulder, 2024; U.S. Department of the Treasury, 2025). While rising property insurance premiums and curtailed insurance availability are already being observed in some places, climate risks are still not fully reflected in market outcomes (Gourevitch et al., 2023; Hino & Burke, 2021). Failure to address mispricing through policy (including transparent climate risk disclosure), risk reduction measures, and insurance-market innovations could have highly inequitable outcomes and/or lay the groundwork for a future crash (Kousky et al., 2024), with ensuing outflows of population and capital.

  Coastal impacts can also have systemic effects through migration, including generational population declines in highly exposed coastal areas, rapid displacement following natural disasters, and purposeful out-migration—all of which occur in the context of and feed back upon broader demographic trends (Hauer et al., 2024; Tagtachian & Balk, 2023). Avoiding maladaptation is a crucial area for assessment, as out-migration diminishes local tax resources and in-migration places added strain on housing, school systems, and infrastructure (Gilmore et al., 2022). Systemic economic risk arising from growing coastal climate risk, and potential solutions, would benefit from synthesis, as would the sequencing and scaling-up of equitable strategies for community-led relocation, considering effects on both sending and receiving communities.

3.3. Forests

U.S. forests are increasingly impacted by climate change and related disturbances, with cascading effects on ecosystem services and human well-being (Domke et al., 2023). Rising temperatures and altered precipitation patterns have intensified disturbances, including wildfires, insect outbreaks, pathogen epidemics, and droughts, contributing to widespread tree mortality, forest degradation, and shifts in forest structure and species composition. These disturbances diminish the ability of forests to provide vital ecosystem services, including carbon sequestration, water regulation, air quality maintenance, recreation, and cultural and economic values, and particularly affect Indigenous and disadvantaged communities. In some cases, cumulative disturbance and climate stress may reduce forest carbon sink strength and, under certain future scenarios, could push forests past a carbon sink–source threshold such that they emit more carbon than they sequester, with significant implications for climate mitigation (Marcos-Martinez et al., 2022). There are several forest system adaptation strategies—such as fuel management and prescribed burning that promote species and trait diversity—that can integrate Indigenous Knowledges in the management practices (Domke et al., 2023). NCA5 also acknowledged uncertainties regarding the long-term effectiveness of these strategies given compounding disturbances and limited long-term monitoring (Domke et al., 2023).

3.3.1. Assessment Research Priorities

- **Forest recovery and resilience mechanisms**: Climate change not only intensifies forest disturbances but also alters recovery trajectories after disturbance (M. G. Turner & Seidl, 2023). Forest regeneration is increasingly uncertain, with many Western U.S. ecosystems potentially crossing thresholds into non-forest states (Tepley et al., 2017). With larger and more severe fires, non-forest patches are themselves becoming larger (Coop et al., 2020), with significant influences on future fire sizes and their frequency. Understanding these trajectories—and the conditions that support or undermine resilience—is vital for adaptive management and scenario planning (Hessburg et al., 2019). Assessing Indigenous Peoples' management and co-management of forests across varying ecoregions, alongside existing climate adaptation strategies, may help inform federal and state forest management. Syntheses should integrate knowledge of alternative stable states and critical thresholds, ecological tipping transitions, species regeneration traits, and post-disturbance trajectories under climate stressors. This includes evaluating the permanence of forest loss and the conditions under which recovery is feasible.
- **Impacts of compound and cascading extreme events on forests:** Extreme events are changing not only in frequency but also in type and intensity (Parks et al., 2023). Novel "hot droughts" (Leeper et al., 2025), fire spread into urban zones (Ghanbari et al., 2023), and compounding disturbance events (e.g., insects, pathogens, wind and wildfire) (M. Liu et al., 2024) are reshaping forest dynamics. These new disturbance regimes require updated conceptual models, multi-disturbance simulation models, and risk-based assessment tools. A cross-cutting synthesis of how multiple disturbances interact (e.g., fire-insect-drought feedbacks) to change forest trajectories would significantly advance predictive capabilities beyond single disturbances.
- **Urban forests as a crucial forest type:** As over 80% of the U.S. population resides in urban areas, the climate threats to urban trees (Kaur et al., 2024; Nowak et al., 2022)—including heat stress, pests, drought, fire, and sea-level rise—have broad implications for public health, equity, and infrastructure resilience. Urban forests not only mitigate climate change by sequestering carbon and reducing urban heat islands, but also serve as critical refugia for vulnerable people during extreme weather events (W. Zhou et al., 2021). Urban forests that incorporate biodiversity-supporting elements—such as larger park patches, tree canopy, and habitat diversity—are associated with improved mental and physical health, increased physical activity and social cohesion, reduced exposure to air pollution, heat, and noise, and in some cases lower mortality risk (Spotswood et al., 2025). An interdisciplinary assessment that links urban ecology, public health, social vulnerability, and forest management would provide critical insights for municipal planning and climate adaptation.
- **Forest soils as an important component of forest ecosystems:** Globally, soils store more carbon than aboveground biomass and support key ecosystem processes, yet they remain underrepresented in assessments. Their response to elevated atmospheric carbon dioxide, warming, and shifts in precipitation—responses that may differ from those of plants (Terrer et al., 2021)—could significantly affect overall forest function. New integrative reviews should assess how soil biogeochemistry (e.g., carbon and nutrient cycling, microbial dynamics) and biogeophysics (water and heat content, erosion) respond to increasingly varied warming, drying, wetting, and disturbance, especially in comparison to aboveground changes.
- **Economic dimensions of forest dynamics:** Socioeconomic drivers and equity in forest management need a sharper focus. Shifts in economic returns to forest land—due to changes in productivity, risk exposure, and market forces—are increasingly affecting land-use decisions (Y. Wang & Lewis, 2024). These dynamics

influence forest extent, management, and resilience, and deserve more integrated treatment in climate assessments. This is particularly important where urban communities that depend on forestry, harvesting, and milling operations are heavily affected. The widespread financialization of commercial timberlands has led to shortened planning horizons and fewer long-term investments in forests (Mei & Clutter, 2023). Syntheses that incorporate landowner decision-making, urban community impacts, market trends, and social equity, especially in the context of adaptation incentives and barriers, would support more inclusive policy frameworks.

3.4. Urban Regions

Urban and suburban regions are the material manifestation of complex social, infrastructural, economic, and ecological systems that mediate both climate risks and opportunities (Chu et al., 2023). As densely interconnected hubs that house a disproportionate share of the population, they shape how climate impacts propagate across neighborhoods, metropolitan systems, national supply chains, and global markets. Urban regions can also amplify hazards through interactions between climate drivers, urban conditions, and environmental stressors (e.g., heat waves interacting with urban heat island effects, extreme precipitation interacting with impervious surfaces to increase runoff and flood risk, and compound heat and air pollution events). These compounding effects increase the need for adaptation (Cheval et al., 2024; Oke, 1982; Ortiz et al., 2018; C. Wang et al., 2025). In addition, urban form and infrastructure can modify climatic hazards themselves, with implications for heat, precipitation, air quality, and associated risks (Rahman et al., 2024; J. Singh et al., 2020). At the same time, urban regions are critical sites for assessing where mitigation and adaptation strategies reinforce one another, where they create trade-offs, and how their benefits, costs, and risks are distributed across communities. This complexity makes them uniquely suited for advancing integrative climate research that spans disciplines and sectors. The intersection of climatic and non-climatic stressors creates an urgent demand for new syntheses and assessments that can inform adaptive planning, infrastructure investment, and governance in the context of accelerating global change.

3.4.1. Assessment Research Priorities

- **Urban dynamics amid changes in climate, governance, demography, and affordability:** Climate risks are escalating faster than the capacity of local, state, and federal institutions to respond. Some cities have taken leading roles in mitigation and adaptation, yet many others remain far behind (Cohen et al., 2025). The increasing frequency, intensity, geographic distribution, and complexity of compound events—such as concurrent heat waves, fires, droughts, and/or floods—expose critical vulnerabilities in public services, infrastructure systems, and local populations. These stressors are no longer confined to seasonal or historical patterns, creating new fiscal pressures on local governments—just as federal support for hazard mitigation and disaster recovery is being reduced (Keenan & Panfil, 2025). Meanwhile, demographic shifts, rising cost burdens, and growing interdependence across metropolitan regions require more refined assessments of vulnerability and adaptive capacity (Brunner et al., 2024; Reilly et al., 2021). Importantly, the cities facing the greatest climate risks often have the fewest resources to adapt, and even within cities, adaptation and mitigation resources are unevenly distributed. Hurricane Katrina—now over 20 years past—offers a stark reminder of how intra-city disparities in climate adaptation and mitigation can persist for decades after a major natural disaster. However, urban dynamics and changes in urban landscapes are not well represented in national assessments. To better represent these dynamics in national assessments, global socioeconomic pathways should be translated into spatially explicit, locally differentiated scenarios of urban development, migration, infrastructure exposure and investment, and climate vulnerability distribution (Balk et al., 2022; Lino et al., 2019; Rohat et al., 2021).
- **Interdependencies and cascading risk in urban systems:** Urban infrastructure systems—energy, water, wastewater, housing, communications, and transportation—are increasingly interdependent, amplifying hazards and variability in loads, and heightening the risk of cascading failures under climate stress (Helmrich et al., 2023). For example, new research highlights risks posed by climate-driven groundwater fluctuations, particularly in cities with dense populations and extensive underground infrastructure (Habel et al., 2024; Rasmussen et al., 2023). Despite growing evidence of cascading risk, planning and management practices rarely account for these interconnections or their health outcomes, especially across jurisdictional and agency boundaries (J. L. Jones & White, 2022; T. Yu et al., 2025). Recent events like Hurricane Helene's flooding of

Appalachian communities demonstrate that roadways, water supply, power, wastewater, and communications infrastructure can fail simultaneously, with cascading effects on food security and health (Amorim et al., 2025).

Additionally, physical interdependencies extend to financial systems. Risk perception and valuation shifts already affect municipal credit ratings, insurance, and access to capital (Kovacs et al., 2025; Zahnow et al., 2025). Coordinated cross-sectoral synthesis is needed to identify vulnerabilities, support integrated planning, and spur innovation in governance and implementation (S. S. Clark et al., 2019; Lawrence et al., 2020).

- **Urban decision-making amid fragmented information:** Most market actors still lack reliable climate analytics, disclosures, and hazard maps to support decisions across households, governments, and firms (Schubert et al., 2024). Divergent time horizons, risk tolerances, and planning goals further complicate coordination: insurance companies evaluate risk on policy timescales (i.e., 1–2 years), local governments prioritize short-term development, and federal agencies focus on long-term asset performance. These misalignments may widen as budget cuts erode authoritative climate information—reducing projections, risk assessments, and the integration of future climate data. Without federal coordination, state and local entities are left to develop their own tools, often without credible data, or to rely on limited and costly proprietary data—underscoring the need for research on decision-making and emerging challenges amid fragmented information and deep uncertainty (Condon, 2023).
- **Toward integrated, adaptive urban solutions:** Systems-based, forward-looking approaches to land-use and infrastructure planning can address both long-term climate trajectories and growing uncertainty around extreme events. Strategic decommissioning of aging infrastructure can be integrated within broader, flexible land-use visions. Adaptation investments—such as nature-based solutions—are gaining traction in urban planning, yet evidence of their long-term, stress-tested performance remains limited (Cook et al., 2025; Ferrario et al., 2024; Grimm et al., 2023; Kabisch et al., 2017). Current evaluations often focus on single-agency benefits, neglecting system-wide effectiveness, lifecycle costs, and zoning alternatives. In dense urban areas, limited space further constrains interventions (Seidu et al., 2025). Scenario planning and updated zoning are needed to identify transitional areas for decommissioning, conservation, or housing shifts—and to preserve optionality for future needs. Fragmented monitoring hampers evaluation across social, ecological, and infrastructure dimensions (Hobbie & Grimm, 2020; J. Li et al., 2025; Seddon et al., 2020). Advancing integrated, adaptive solutions will require comparative evaluations and standardized protocols to assess multifunctionality over time (Lehmann et al., 2025).

  Cities can seize opportunities where adaptation and mitigation align—such as nature-based solutions, building retrofits, weatherization, and distributed renewables—to deliver climate and socioeconomic co-benefits (Galvin & Healy, 2020; Privitera & La Rosa, 2021; Wijesuriya et al., 2024). These approaches require integrated assessments of future climates, local development pathways, co-benefits, trade-offs, and governance models (Kalafatis, 2017). A next-generation research agenda must build on these insights to guide planning, investment, and cross-sector collaboration within increasingly complex and interconnected urban systems (Pickett et al., 2024; Sharifi et al., 2022).

3.5. Rural Communities

Rural communities continue to be on the front lines of the social, environmental, and economic impacts of climate change and other drivers of change (Akamani, 2023; Deslatte et al., 2023; Vasseur, 2021). Compared to urban communities, which are often presented as the default, rural communities' lack of resilience to climate change tends to be shaped by low population density, a low or seasonal tax base, remoteness, insufficient public and communications infrastructure, low capacity for planning or emergency response, economic dependence on natural resources, aging populations, a self-reliant culture, and low incomes (Allred et al., 2022; Andrews & Reiblich, 2020; Fergen et al., 2024; Lal et al., 2011; Winkler & Mockrin, 2025). Yet rural communities are diverse in their demographics, economic drivers, ecological settings, and specific climate risks (Ulrich-Schad & Duncan, 2018). Rural communities are unique places where individual and community characteristics intersect with climate-change risks, creating variation in both vulnerabilities and opportunities for resilience. As such, changing conditions and research approaches in rural communities are important to investigate and assess.

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3.5.1. Assessment Research Priorities

- **Rural community dynamics amid climate and socioeconomic change:** Demographic and economic conditions in rural communities are changing in ways that require assessment to understand how these changes interact with climate change, contribute to vulnerabilities, and shape opportunities and challenges for resilience. Rural communities are aging rapidly (Farrigan et al., 2023; Jensen et al., 2020) and could yield insights into broader population aging trends across the U.S., yet the interrelationships between aging and climate risks warrant assessment research (Tipaldo et al., 2024). Similarly, the ways in which racial, ethnic, and linguistic vulnerabilities intersect with climate risks and resilience across rural areas have not been fully assessed, particularly in those places experiencing rapid demographic change. Many rural communities remain dependent on natural resources for economic well-being and livelihoods, yet the nature of dependency in some places is shifting with economic diversification and away from more reliance on extractive industries (i.e., agriculture, forestry, fishing, mining) to non-extractive industries, including tourism and recreation (Mueller, 2021), which introduces different and complex vulnerabilities as well as opportunities for building resilience through, for example, distributed renewable energy production (Horowitz et al., 2019) and diverse food systems (Prokopy et al., 2020).
- **Rural community adaptive capacity, governance, and resilience:** Rural communities tend to be overburdened and under-resourced (in terms of funding, technical expertise, data, staffing, and other infrastructure) for planning, grant procurement, health care, emergency services, and other resources that are critical for supporting resilience (Allred et al., 2022; Vo et al., 2022). However, research examining the interaction between climate risks and capacity and evaluating policy mechanisms aimed at supporting resilience in at-risk rural communities is lacking. New tools and frameworks to build resilience to climate change must recognize that rural communities across the U.S. do not all experience the same risks nor do they experience the same opportunities or options to build resilience.

  Understanding and characterizing community adaptive capacity and resilience to climate change across different rural settings requires examining how communities cope, adapt, and transform. This includes the study of pathways for guided transformations that incorporate diverse perspectives and prioritize community and environmental well-being (Herbert et al., 2025; Morgan et al., 2024). Given that climate change is already manifesting in particular localities in the form of specific hazards, such as flooding, drought, wildland and wildland-urban-interface fires, and heat waves (Berrang-Ford et al., 2021; Vasseur, 2021), there is the need to move beyond the focus of the existing literature on general community resilience to gaining a deeper understanding of the mechanisms by which communities build resilience to particular threats, including the growing incidence of concurrent and compound climate extreme events (N. Simpson et al., 2023). Equally important are the governance requirements for building different types of capacities (e.g., coping, adaptation, and transformation), as well as the need for valid and reliable indicators for assessing resilience outcomes across scales (Gerst et al., 2025; Kenney et al., 2020).

New syntheses of information on climate change impacts are particularly valuable to rural communities, given how frequently they are understudied. Such assessments need to consider the following three major themes: (a) key demographic trends in rural communities and how they interact with climate vulnerability and resilience; (b) the dependency of major economic sectors on natural resources, opportunities and vulnerabilities, and implications for adaptation and mitigation (e.g., renewable energy); and, (c) the effects of assets and institutions on community capacity to cope (react), adapt (anticipate), and transform (enact change). This kind of novel accounting is essential to preparing and responding to climate change for the most at-risk residents in frequently overlooked rural places.

3.6. Energy

Assessments of climate impacts to energy systems provide critical information to energy system planners, builders, and operators, enabling them to conduct climate vulnerability assessments, develop resilience plans, and adjust to a constantly evolving set of climate hazards. Assessments also help communities better prepare for and adapt to extreme weather conditions and a changing climate, and inform researchers and technology developers about opportunities for energy system innovations.

3.6.1. Assessment Research Priorities

- **Region-specific energy system vulnerabilities to extreme weather:** Extreme weather and climate events can damage energy infrastructure and other services, sometimes extending to previously less vulnerable (e.g., more inland) areas and striking with greater severity. The U.S. is continuing to see an increase in the frequency and severity of climate-related events, further exposing vulnerabilities in the U.S. energy system. Hurricane Helene caused over 4.7 million power outages across the southeastern U.S. (Micek et al., 2024) and resulted in catastrophic flooding from Florida to North Carolina (NOAA NCEI, 2024). The resulting devastation of inland communities such as Asheville, North Carolina, illustrates the expanding geographic reach of extreme weather events. Hurricane Francine forced the shutdown of 39% of oil and half of gas production in the Gulf of Mexico, not only halting offshore drilling and refinery operations but also disrupting regional and global supply chains, spiking fuel prices, and exposing critical infrastructure to flooding, wind damage, and prolonged recovery delays (Mcwilliams & Parraga, 2024). Systems in relatively temperate or inland areas may now face flood risks, high winds, or prolonged heat waves that were once considered unlikely. Wildfires continue testing the resilience of the infrastructure, leading to an increase in public safety-power shutoffs (C. Huang et al., 2023). Ongoing efforts focus on assessing the changes produced by climate change in hazards that impact structural and infrastructure systems (Barsugli et al., 2025). Moreover, energy infrastructure is increasingly exposed to compound climate risks that can damage assets directly and threaten the reliable provision of energy services. Unreliable energy services can have devastating effects on people who depend on electronic medical devices, acute medical procedures, or other critical energy-dependent services. Future assessments could explore national as well as region-specific vulnerabilities of energy systems and update compound and cascading hazard mapping for energy infrastructures to examine the potential for related stress and failures.
- **Climate and geopolitical risks of emerging energy technologies:** Emerging energy technologies may require reconsidering energy system planning, particularly in light of increasing climate and geopolitical risk. Traditional energy system planning has relied heavily on historical climate data and long-standing approaches to reliably meet consumers' demands for goods and services. Existing infrastructure designed for past climate conditions may face operational challenges under increasingly uncertain and changing future conditions. Furthermore, the accelerating impacts of climate change, geopolitical risks, and developments in energy technologies may render those assumptions obsolete (Chester & Allenby, 2024). Infrastructure built today, such as power plants, transmission lines, or natural gas delivery systems, will operate for decades under increasingly uncertain and changing conditions. For instance, the shift toward renewable and distributed energy sources, increased frequency and severity of extreme weather events, the uncertain and fast evolving integration of sectors (such as vehicle electrification, the shift to electric home heating and new energy transformation pathways and technologies) add further planning and operational complexity and new risks of inadequate resources, while also offering opportunities to flexibly meet energy services and reduce emissions. These technological shifts are occurring alongside growing geopolitical risks, including disruptions in energy supplies, critical mineral geopolitical pressures, cyber threats, and energy and materials trade volatility (Cheng et al., 2025). Aging infrastructure and limited system redundancy further exacerbate these vulnerabilities. Future assessments could explore the uncertainties around integrating emerging technologies and evolving risks into energy system design, operations, and investment decisions.
- **Impacts of changing electricity demand on the grid:** New sources of electricity demand are placing a strain on regional electricity grids. The U.S. has experienced a surge in electricity demand, driven primarily by new investments in manufacturing, building, transportation electrification, and the rapid expansion of data centers. This recent growth marks a significant departure from the relatively flat electricity demand over the last two decades (Electric Power Research Institute, 2024; King et al., 2025). At the same time, however, the nation's aging grid infrastructure, supply chain challenges for critical grid components such as transformers (McKenna et al., 2024), and long siting/permitting timelines for new generation (Rand et al., 2024) create compounding challenges for meeting new electricity demand while maintaining reliability and cost effectiveness. Climate-driven changes in electricity demand are highly heterogeneous across urban areas, underscoring the risk of relying on aggregated analyses when evaluating grid stress (C. Wang et al., 2023). Future assessments could examine the implications of increasing electricity demand at regional and distribution system scales, as well as opportunities for demand-side efficiency and flexibility.

- **Energy insecurity and climate vulnerability in overburdened communities:** Overburdened communities face compounding stressors, including greater vulnerability to climate impacts and greater energy insecurity. NCA5 found that overburdened communities suffer more from urban heat islands, power outages, longer restoration times after a storm, higher energy prices, and increased health concerns from pollution and waste from incumbent energy systems. These communities also have less access to energy choices and high-quality infrastructure (e.g., air conditioning, efficient buildings) that can improve their resilience to climate impacts (A. Jones et al., 2023). Recent research points to policy and market design that can help low-income and vulnerable groups both reduce their energy burden and improve their climate resilience. For example, federal and state programs for home electrification and energy efficiency help reduce emissions and energy bills for low-income households (J. M. Joseph et al., 2025; Massachusetts Interagency Rates Working Group, 2024). Future assessments could inventory federal, state, local, Indigenous Peoples, and utility programs and examine how energy expansion and resilience policies address the needs of these communities, as well as the barriers to expanding or improving the desired benefits.

3.7. Agriculture and Food

Risks to agricultural production and food systems from climate change continue to increase due to changes in extreme event frequency and severity with ongoing temperature increases and shifts in precipitation patterns (Bolster et al., 2023). This increases the frequency and intensity of drought, flooding and erosion, and wildfire hazards. Increased variability of temperature and precipitation in time and space also exacerbates pests in plant- and animal-based agricultural systems, leading to economic losses. This includes the increased production losses from insects, diseases, and weeds, as well as reduced beneficial ecosystem services such as pollination and biological pest control. Other climate impacts on food systems (both land and aquatic) and consequently on consumers include changes in food safety, access, and supply. This includes reduced nutritional value of some staple crops due to increased carbon dioxide (Ter Haar et al., 2025), and increased food safety hazards, pathogens, and chemical contaminants. Finally, while agriculture can contribute to climate mitigation via carbon sequestration, adaptation strategies to maintain food security are needed. Evidence strongly suggests that no single adaptive approach will negate the impacts of climate change on agriculture and food systems. Instead, multiple approaches implementable across scales (genes to whole-system management) are needed to buffer or accommodate the impacts of both extreme events and ongoing change. Combinations of adaptation strategies provide improved risk management choices to producers, consumers, and other stakeholders, but these may conflict with mitigation goals and are likely to vary geographically and temporally, and to be system-dependent (Barbieri et al., 2024; Hultgren et al., 2025).

3.7.1. Assessment Research Priorities

- **Precipitation changes threatening water supplies underpinning agriculture:** Recent research that is ripe for synthesis includes how the positive and unwavering link between the availability of high-quality freshwater and plant growth defines the spatial distribution of terrestrial, aquatic, and marine food production (He & Rosa, 2023). The magnitude of consumptive water use in agriculture is significant, with water requirements ranging from 300 to over 2,000 kg of water needed per kg of plant dry matter produced. Proper temporal water distribution during the growing season is as critical as the quantity. Across the Western U.S., climate change is widening the temporal gap between demand and supply, a trend that is particularly relevant in regions with limited reservoir storage capacity. There is high confidence in projected declines in snowpack critical for agricultural water resources in the Western U.S. (Norris et al., 2025; Schmitt et al., 2024). However, there remains disagreement and uncertainty regarding the magnitude and direction of surface and groundwater availability for agriculture due, in part, to knowledge gaps in quantifying groundwater recharge, soil moisture levels, temporal and spatial variation in precipitation, and a poor understanding of a suite of anthropogenic factors, including population distribution, water policy, crop species choices, and irrigation. Model results suggest that adaptation strategies such as adding tiles to drain excess water and/or increasing nitrogen fertilization rates to mitigate reduced crop yields under a changing climate may negatively impact water quality in rural areas unless coupled with improved nutrient management strategies (Niroula et al., 2023). Research should also include the challenges and possibilities of ongoing and increased aquaculture in freshwater and marine environments (Hossain et al., 2025), and an evaluation of water use, access, and availability to Indigenous Peoples for reserved and treaty rights purposes in a changing climate.

- **Climate change impacts to insect, disease, and weed pests in agriculture:** Addressing the impacts of climate change-induced environmental variations on insect, pathogen, and weed pests in plant- and animal-based agricultural systems is critical to protect food security and sustainable agriculture (Verma et al., 2025). Increasing CO_2 levels will alter the growth and morphology of many crop species, affecting competition and crop-pest interactions (Eigenbrode & Adhikari, 2023; B. K. Singh et al., 2023). Temperature shifts and altered precipitation patterns impair crop and animal defenses. These changes alter pest ecology, including range, life cycles, and phenology. Climate change further contributes to the biodiversity crisis (e.g., species extinction and decline in abundance), affecting the loss of ecosystem services such as pollination, biological control, and microbiome functions (Ma et al., 2025; Moreira et al., 2025; B. K. Singh et al., 2023). Innovative, predictive, and adaptive management strategies can assist in protecting agriculture from pests and improve food security in a changing climate (Verma et al., 2025).
- **Climate change impacts to food safety, access, and supply:** Climate change is intensifying multifaceted risks to food security, encompassing food safety, availability, and accessibility, with particularly pronounced effects in aquatic food systems where shifts in environmental parameters are driving the emergence of seafood hazards (Cao et al., 2023). This includes reduction in nutrient (Fe, Ca, protein, omega-3 fatty acids) availability in seafoods (Cheung et al., 2023), amplification of neurotoxins such as methylmercury in aquatic food webs (M. Wu et al., 2025), rising incidence of *Vibrio* bacterial contamination of seafood in the U.S. (Brauge et al., 2024), and prevalence of cyanotoxins resulting from more frequent and expansive cyanobacterial blooms associated with climate change (Lee et al., 2025). On land, climate change and CO_2 fertilization are also diminishing micronutrient profiles and disrupting the spatial and temporal patterns of production. For example, Ter Haar et al. (2025) reported declines in most mineral nutrients in edible parts of 43 crop species, with the largest reductions occurring in Zn, Fe, and N. These dynamics pose substantial challenges to the nutritional quality of diets and the economic viability of producer communities (Mirzabaev et al., 2023). Vulnerabilities are particularly acute in certain U.S. populations, including Indigenous Peoples and those in geographically isolated regions, where climate-driven disruptions can compromise locally and culturally significant food sources. Furthermore, climate-induced yield declines and input cost increases affect food prices, disproportionately impacting low-income, food-insecure populations. Advancing science-based, adaptive strategies that account for emerging hazards (e.g., harmful algal bloom toxins, pathogens, and chemical contaminants such as heavy metals, pesticides/aquaculture drug residues, and PFAS), as well as historic and ongoing food access inequities, can bolster the resilience of food systems and inform adaptive risk management frameworks for food safety (Mu et al., 2024).
- **Emergent strategies for agricultural adaptation:** Agriculture has the potential to mitigate climate change by sequestering carbon in soils, but uncertainty exists about the rate of carbon accumulation under various management systems, and the forms and permanence of soil carbon pools (Paul et al., 2023). By comparison, adaptation strategies within U.S. agriculture and food systems can help reduce the impacts of climate change across temporal and spatial scales, as well as the environmental impacts of agriculture (Yang et al., 2024). Short-term responses focus on buffering disruptions to productivity and stability from extreme events, while long-term strategies aim to enhance system resilience. Key approaches include developing climate-resilient crops, adaptive livestock management systems, and integrative agronomic practices such as diversified crop rotations, habitat enhancement, and predictive pest and disease management (Ishtiaque, 2023). These interventions, however, may introduce trade-offs (Barbieri et al., 2024); for instance, improved irrigation efficiency can inadvertently intensify hydrological stress. Alaska, where agriculture is currently climate-limited in the types of crops that can be grown, is a unique assessment research priority because of the increased near-term agricultural opportunities created by warmer, expanding growing seasons, while also understanding the unique challenges posed by thawing permafrost (Ward Jones et al., 2022). Widespread adoption of climate-smart practices is contingent upon addressing institutional, structural, and economic barriers, including incentives, access to data and interoperable platforms, and transdisciplinary efforts that explicitly account for socioeconomic and environmental interactions and trade-offs, as well as the reserved and treaty rights of Federally Recognized Tribes and Indigenous Peoples.

3.8. Human Health

Climate change impacts physical and mental human health directly and indirectly. NCA5 highlighted the diversity of health impacts due to climate change, with particular attention to the role of systemic racism and discrimination and the inequitable burden on historically and socioeconomically marginalized communities (Hayden et al., 2023). It emphasized the importance of effective and culturally appropriate adaptation and mitigation efforts to protect human health, defined broadly as encompassing physical and mental health, and including transitioning to climate-resilient care delivery systems with reduced greenhouse gas emissions, highlighting the short- and long-term benefits of reducing greenhouse gas emissions.

Since NCA5, climate and human health research has expanded rapidly. An early and critical focus has been on the health impacts of extreme weather events, like hurricanes, heat waves, floods, and destructive wildfires. The short time frame, intensity of exposure, and substantial public attention drawn to these acute episodes allow for rapid knowledge generation that is critical to understanding the immediate impacts and best defenses. Still, these studies often underestimate the true health impacts, as acute events may have cascading effects and trigger health outcomes, such as mental health conditions, reduced fertility, and long-term mortality risk, that emerge long after the acute event has ended (Purtle et al., 2025; Segal & Giudice, 2022; R. Young & Hsiang, 2024). A more holistic understanding of health as it relates to climate change and to a broader range of climate-sensitive weather exposures over time and place is critical (Etzel et al., 2024). Advancing understanding of the connections between public health and climate change mitigation and adaptation measures is also needed.

3.8.1. Assessment Research Priorities

- **Intermediate- and long-term, cumulative health impacts of climate trends and extremes, including compound events:** Growing evidence on the independent and cumulative health impacts of slower and more gradual climate trends (e.g., droughts, sea level rise, rising temperatures), the intermediate and long-term health impacts of extreme weather events (Tipaldo et al., 2024), and impacts of combined exposures (heat and poor air quality), are in need of assessment. This research is advancing with new methods that allow for a more complex accounting of human–climate interactions and changes in exposures over time, including for outdoor workers (Chunga Pizarro et al., 2024), as well as the impacts of responses to climate change on human health. The growing field of omics reveals how molecular compounds direct and modify the way the body functions. Identifying (epi)genomic changes associated with climate-related exposures can provide additional insight into what it takes to age healthfully in a changing environment (Choi & Ailshire, 2025; Ni et al., 2023). A more thorough understanding of the multiple drivers of climate change and climate hazard-related health risk over time and across populations, as well as cumulative impacts, is also needed.
- **Economic and sociocultural costs of health impacts:** Measuring the direct and indirect costs of climate change on health is another critical area for research. Examples are myriad, from the direct costs of clinical care due to heat-related illness (Schmeltz et al., 2016), to the accumulating impact of climate-eroded infrastructure that is required to support healthy populations (e.g., housing, transportation, employment, healthcare services, etc) (Nordeng et al., 2025) and opportunity costs associated with recovery from extreme events. These studies often engage a broader field of stakeholders and sectors in the health conversation and, as such, may reveal formerly unappreciated consequences of climate change, for example, cultural losses.
- **Strategies for advancing adaptation in health care delivery and public health systems:** Prior assessments have identified multiple gaps in preparedness, ongoing surveillance (beyond extreme events), and the prevention and control of climate impacts on individuals and populations (Remigio et al., 2023), and opportunities to scale adaptation more effectively to fill these gaps. Updates to and innovations in health surveillance systems are needed, for example, to monitor and assess the direct and indirect, immediate, intermediate, and long-term risks for evaluating the impact of interventions (Angell, 2025; H. A. Joseph et al., 2023; Lemon et al., 2023), and to take full advantage of available environmental information. Investigations using big data benefit from the inclusion of electronic health records, which allows linking of individual health, environmental, and other patient-specific contextual and geographic measures. When combined with modern ML and causal inference approaches, these novel big data resources can generate insights previously hidden to researchers and policymakers. Research that uses these insights is needed to explore new interventions and assess policy and programming impacts. Examples of such interventions include programming directed to

high-risk individuals through the health care delivery system, such as provision of air conditioners, early warning systems that deliver tailored information, and on-demand resources through state and local public health entities to communities

- **Health care interventions for populations at increased risk:** Research is needed to better identify current and future populations at increased risk and climate-impacted health interventions. Communities are impacted by historic policy inequities (e.g., clean water access for Indigenous Peoples (Grijalva, 2016; U.S. Commission on Civil Rights, 2018)) and by demographic certainties (e.g., aging population and rural population declines). To understand the effectiveness of programs for a range of populations, it is important to focus on older adults on fixed incomes or in precarious housing (Bukvic et al., 2018; Molinsky & Forsyth, 2023), address the potential for climate related interactions with medical devices or medications (Sorensen & Hess, 2022), and understand gaps in emergency services in hazard-prone locations where adults are aging in place (Winkler & Mockrin, 2025), and explore the resilience of healthcare systems in areas that are especially vulnerable to regular impacts (e.g., tidal flooding access impacts to healthcare services (Hauer et al., 2023)).
- **Health outcomes of nature-based solutions for adaptation:** The health effects of nature-based solutions should continue to be studied (Balk et al., 2024; Seddon, 2022; Vora et al., 2024). For example, expanding tree canopies in urban areas and other changes in the physical environment are being developed and tested, with potential for spread and scale (Dean et al., 2024; McDonald et al., 2024). Assessment of strategies for identifying locations that would benefit most from enhanced tree canopy investments and implementing protective nature-based solutions are important next steps (Spotswood et al., 2025).
- **The health impacts of energy system transitions:** Energy system transitions and deep decarbonization pathways have direct and indirect health effects, including which scenarios could lead to more equitable outcomes, and are an important area for assessment (Spurlock et al., 2022). For example, emissions from fossil-fuel-powered vehicles include greenhouse gases that drive climate change and pollutants that are linked to adverse health outcomes. Therefore, reducing reliance on fossil fuel-powered transportation (e.g., electric vehicles, public transportation) can benefit both climate and public health (Matte et al., 2024). A synthesis of potential health benefits as well as spatio-temporal health disparities arising from this transition is needed (Bell & Gillingham, 2025; Peng et al., 2025). This includes understanding the potential of clean energy technologies to reduce or generate pollution during their production and disposal, and monitoring to ensure that environmental health risks are not being shifted to the extraction, manufacturing, and disposal phases of the supply chain, which may disproportionately impact lower-income and more rural counties and communities.

3.9. Air Quality

Climate change affects and interacts with both ecological and human health, requiring systems-based approaches to provide usable insights into the consequences of changes in the frequency and duration of acute and long-term chronic exposures to air pollution (e.g., rising concentrations of wildfire smoke). NCA5 concluded that climate change will worsen air pollution due to increases in wildfire smoke, dust, ozone, and pollen, thereby negatively impacting both human health and air quality goals. Particularly vulnerable groups include children, people who are pregnant, people with chronic disease(s), and under-resourced communities (West et al., 2023). Research has continued on these and related topics, providing new insights into risks and responses associated with climate-sensitive air pollutants. Because indoor spaces serve as a first-line shelter from climate-related air pollution events such as smoke events, dust storms, and weather events, they—and their interaction with outdoor environments during and after extreme events—warrant further investigation (National Academies of Sciences, Engineering, and Medicine, 2022c). Continued exploration on the health consequences of exposures over the life course, simultaneous exposures from multiple pollutants, and ecological-human interactions can provide new insights to increase resilience and sustainability to the air quality consequences of climate change.

Emerging areas of research include using more systems-based approaches that further clarify: (a) the interconnected nature of climate, air quality, ecosystems, and health; (b) changes in the magnitude and pattern of exposure to air pollution; (c) the extent to which climate change is altering indoor air quality; and (d) new air quality concerns including, for example, the impacts of compound exposures to heat and air pollution (Rau et al., 2025; Stafoggia et al., 2023). Research using systems-based concepts such as "One Health," which takes into account environmental, animal, and human interactions in manifestations of ill health and serves as an example of a systems-based approach to understanding human health, continues to expand knowledge of climate-driven air pollution consequences (Winkler & Mockrin, 2025; R. Zhang et al., 2022). Taken as a whole, four themes emerge as being particularly high-yield for assessment.

3.9.1. Assessment Research Priorities

- **Cumulative impact of meteorological, chemical, biological, and other exposure factors**: Emerging research suggests climate-driven changes in meteorology, directly from climate change and indirectly from the consequences of climate change for ecosystems, may increase population-level exposure to air pollution. These changes include increases in the frequency, intensity, and duration of wildfires, longer duration and intensity of allergy seasons (Anderegg et al., 2021), and impacts on anthropogenic sources of air pollution (e.g., transition to electric vehicles) (West et al., 2023). Additional synthesis research priorities include how changes in the concentration and mixtures of air pollutants and exposures—including chemical and meteorological interactions (e.g., pesticides and heat)—may influence population health (Ferguson et al., 2019). A One Health-based approach, for instance, can incorporate the cascading effects of climate change-influenced air pollution, spanning different habitats and species (Winkler & Mockrin, 2025). Developing similar methods for other factors remains crucial.
- **Differential and inequitable effects of climate change on air pollution:** As the concentrations of air pollutants shift with climate change, exposures of vulnerable groups also will likely change. Residential location, regional features, housing infrastructure, occupation, cost of living that drives relocation, and other factors can impact how indoor and outdoor exposure would differ, with increasing concentrations putting larger numbers of people at risk. This variation in how people experience exposure, particularly when compounded by social, economic, and environmental exposure factors, will affect not just health and well-being, but also the economy and society as a whole. Research needs to further explore the "climate penalty"—that is, negative impacts from climate change that offset health gains from reducing air pollution—based on regional, geographic, and socioeconomic differences.
- **Extreme event impacts on outdoor and indoor air pollution:** The quality of indoor air is being affected by trends in outdoor air pollution that are caused by climate change-driven increases in the frequency and intensity of extreme events (Nazaroff, 2013). Changing outdoor air quality influences indoor conditions in complex ways as indoor air quality is affected by emissions, chemistry, and environmental conditions (Institute of Medicine, 2011; National Academies of Sciences, Engineering, and Medicine, 2022c). For example, outdoor ozone production can change infiltration rates of ozone in indoor spaces, and indoor ozone can react with some household cleaning products to generate substantial particle concentrations (Rosales et al., 2022). Changes in indoor temperature and humidity linked to increasingly extreme outdoor conditions can strongly influence indoor exposures to semi-volatile organic compounds, which can partition between the gas, particle, and indoor surface phases (National Academies of Sciences, Engineering, and Medicine, 2022c).
- **Building adaptations for power grid disruptions and indoor air quality:** Climate change may also disrupt power grids, resulting in more use of less efficient and/or polluting means to meet heating, cooling, cooking, or other household needs. These methods can generate air pollution inside and near buildings (e.g., solid fuels). Building codes and practices affect indoor air quality and are being modified in response to a changing climate. Recently, for instance, researchers developed building-scale mitigation efforts that aim to protect occupants from wildfire smoke by changing building envelopes and/or mechanical systems (ASHRAE, 2024). Because most people spend significant time indoors, research on the effectiveness of climate-ready and indoor air pollution building adaptations, human behaviors, and outdoor exposure dynamics could identify the magnitude of exposure pathways, hotspots of vulnerability, and assess the effectiveness of different adaptation strategies.

3.10. Regional Examples

This section is structured as regional examples organized around large multi-state regional boundaries that have been used since NCA3 (USGCRP, 2014). Figure 3 presents these regional boundaries and highlights the example regions included in this paper. Though the NCA regions have been useful for large-scale regional-to-national climate assessment processes, there are other useful and arguably hydrologically, ecologically, geopolitically, or culturally more natural ways of structuring regions that may cross governmental or national boundaries (e.g., cultural regions like Appalachia, hydrologic units like the Columbia River Basin, ecoregions like Marine

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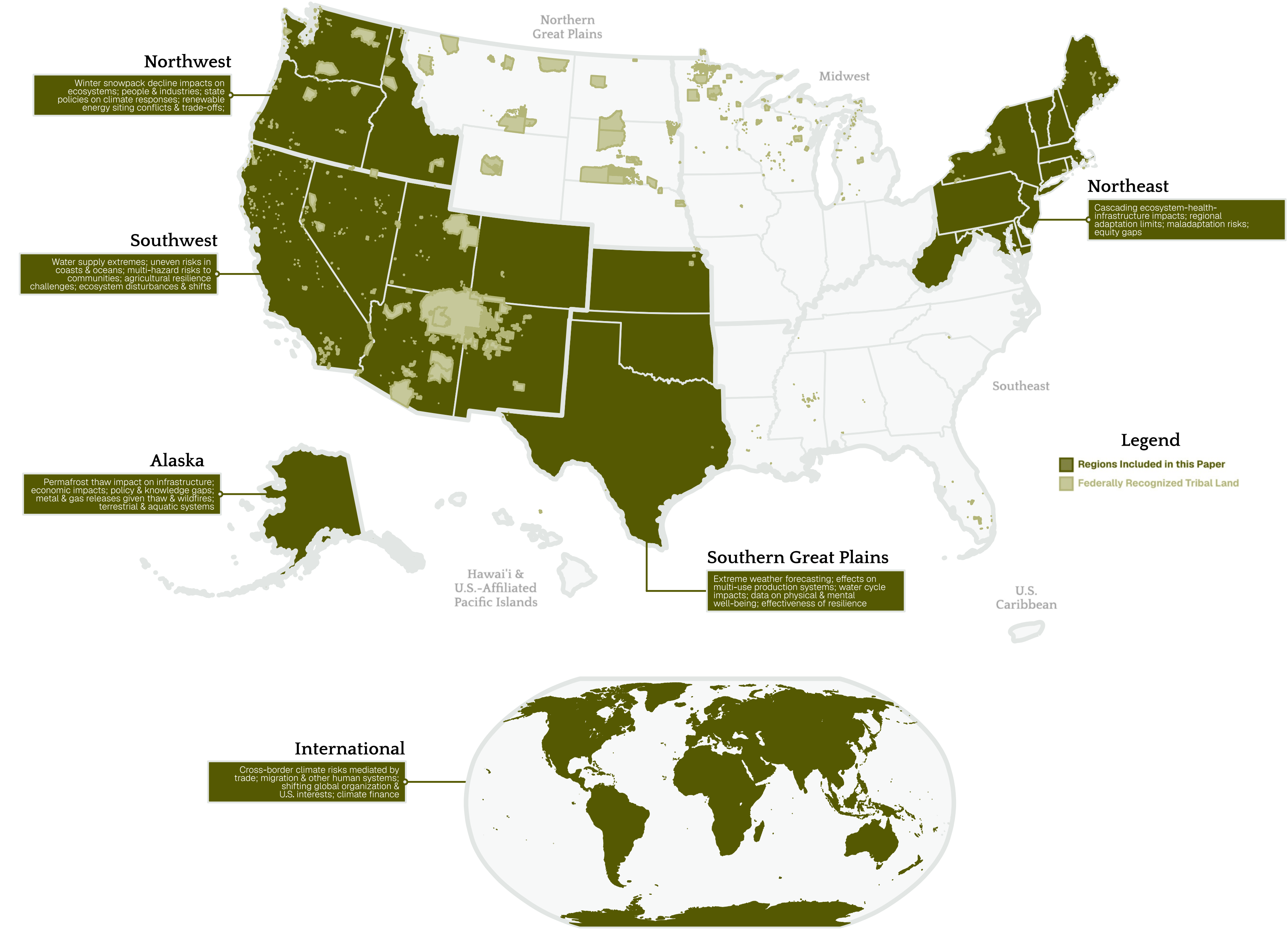

Figure 3. Map with key research priorities for regions included in this commentary. Map highlighting (in green) the regions included in this commentary; grayed regions are not included. Dark green indicates the regional boundaries, while light green denotes the land of Federally Recognized Tribes within those larger regional boundaries (*Note: this does not represent lands of all Indigenous Peoples within the U.S. and its territories*). Regions are based on NCA5; other climate assessments may adopt different place-based boundaries. Paired with each included region is a text box summarizing its core future research needs. Additionally, a global map highlights the international section and the associated summary of key research priorities. U.S. map adapted from NCA5 Figure 1 (USGCRP, 2023). Tribal land boundaries sourced from the Bureau of Indian Affairs (BIA) American Indian and Alaska Native Land Area Representation (AIAN-LAR); available at https://www.conservation.gov/datasets/245ffcb63a0b44cb9ed467bbd5f9d7ea_0/about. *Note*: maps are not to scale.

West Coast Forest, Native land territories). Climate assessments that adopt different regional structures may find relevant research priorities in more than one regional section.

3.10.1. Northeast

The Northeast region of the U.S. includes New England and the Mid-Atlantic states, the District of Columbia, and 18 Federally Recognized Tribes. It boasts a rich natural environment, a mix of large urban centers and small towns, and a diverse economy. The Northeast has experienced regional climate and weather shifts including a dramatic increase in the intensity and frequency of extreme precipitation (Henny et al., 2022; H. Huang et al., 2021), shifts in streamflow and flooding (Pal et al., 2023), drought (Xue & Ullrich, 2022), rapid mean sea level rise and increasing frequency of coastal flood events (Sweet et al., 2022), and rising temperatures and shifts in temperature extremes in both marine and terrestrial environments (S. S. Young & Young, 2021). Below are five assessment research priorities for the Northeast region.

3.10.1.1. Assessment Research Priorities

- **Emerging regional extreme events and hazards:** Shifts in snowpack and runoff have implications for ecosystems and water supplies (Hale et al., 2025; Khodaee et al., 2022; Shakhawat et al., 2024), while temperature and relative sea level rise are likely to diminish the performance of coastal infrastructure (Knott, 2019; Mayo & Lin, 2022; Ohenhen et al., 2024; Sweet et al., 2022). Research is needed to understand future changes in frequency and pathways of severe extratropical storms and tropical hurricanes, relative contributions of the processes that drive local sea level rise, and potential impacts of a slowing Atlantic Meridional Overturning Circulation on the region.
- **Non-linear and indirect ecological responses:** The direct and compounding impacts of climate change on ecosystems are becoming more visible. For example, marine warming affects fish species, which in turn affects the survival of dependent bird species (O. Smith & Craig, 2023), while rising seas are decimating saltmarsh sparrow populations (Johnston et al., 2025). Changing precipitation and shifting pathogen or herbivore damage affect Northeastern tree senescence (Garretson & Forkner, 2021). Understanding non-linear and indirect ecological responses to variable and extreme climate in the Northeast, as well as how climate interacts with multiple stressors to affect Northeast ecosystems, is an assessment research priority.
- **Adaptation interactions and effectiveness:** The Northeast continues to pursue adaptation efforts (McGann et al., 2023), although there may be limits stemming from differences in adaptive capacity and potential maladaptation outcomes. For example, fishers adjust their behavior to shifts in the distribution and abundance of fish, but some responses may leave communities more vulnerable (Papaioannou et al., 2021). Agricultural adaptations, such as crop diversification, are more effective when accompanied by market, technology, and/or policy changes (Medellín-Azuara et al., 2024). Finally, efforts to mitigate and manage coastal forest dieback by preserving marsh and upland system migration (Sacatelli et al., 2023) may result in trade-offs with human systems migration. Clarifying the interacting and compounding effects of both climate change and responses to it is urgently needed to better inform adaptation efforts, including understanding adaptation effectiveness and limits, and the rates of impact versus the rates of response of human and natural communities. This also includes understanding how capacities (e.g., human/natural/technological) shape vulnerabilities and adaptation, including maladaptive or unjust outcomes, and how these change over time.
- **Mitigation and energy transition pathways:** The Northeast continues to pursue mitigation efforts. However, assessment research is needed to better understand climate mitigation and the energy transition in the Northeast, how sustainable development interacts with mitigation and adaptation goals, and how informal, autonomous, and everyday mitigation and adaptation actions shape both energy transitions and responses.
- **Regional climate change impacts on human health:** Emerging hazards like the 2023 Canadian wildfire event substantially increased PM2.5 levels (up to 317 μg/m^3 in New York City; Cedeño Laurent et al., 2024), increasing asthma-related emergencies in New York City (Chen et al., 2023; Thurston et al., 2023), and cardiac-related clinical visits in Baltimore, MD (Maldarelli et al., 2024). Climate-driven cyanobacterial algal blooms (Wiley & McPherson, 2024) increase algal toxins in drinking water, increasing respiratory illness in Greater Boston (J. Wu et al., 2021). Articulating the associations between environmental hazards attributable to climate change and adverse human health outcomes in the Northeast is an important assessment priority.

3.10.2. Northwest

Accelerating and emerging climate changes increasingly challenge human communities, economies, and ecosystems in the Northwest, an area that includes Idaho, Oregon, Washington, and 43 Federally Recognized Tribes. The Northwest relies on winter snowpack to support many water uses, including agricultural irrigation, household, commercial, and industrial needs, hydroelectric generation, and sufficient streamflow for salmonids and other freshwater species. Declines in winter snowpack have already intensified drought conditions across the region and affected regional water supplies. Additionally, the Northwest historically experiences more temperate weather than the rest of the U.S., making communities less prepared and more sensitive to the impacts of extreme heat events, such as the 2021 heat dome (White et al., 2023). As individuals, communities, and governments respond, mitigation and adaptation efforts are creating opportunities as well as tradeoffs and conflicts.

3.10.2.1. Assessment Research Priorities

- **Social and economic systems are affected by climate:** Hazard exposure will increase as jurisdictions invest in development to accommodate anticipated population growth. Extreme events put new and existing housing at risk, and changes in homeowners' insurance are affecting coverage (U.S. Senate Budget Committee, 2024). While Northwest agriculture may experience less disruption than other regions, there are increasing concerns about impacts on food production and supply chains (Washington State Department of Agriculture, 2025). Understanding effects on public health, such as occupational heat and smoke exposure (Hyland et al., 2024), has increased. Future research should continue to evaluate the hazards, exposure, and vulnerability of communities and their responses.
- **Climate change is altering natural systems:** Recent studies document impacts on a range of Northwest ecosystems, from alpine to marine (Crozier & Siegel, 2023; R. B. Harris et al., 2024). Droughts, severe wildfires, floods, heat waves, and other events have transformed some ecosystems and led to declines in species populations. Other ecosystems, such as coastal forests and upwelling zones, are instead showing evidence of resilience to extreme events. Model advances are improving understanding of how physical processes are restructuring ecosystems (Nederhoff et al., 2024) and the ability to project future changes. Research should continue to assess impacts on natural systems and clarify the mechanisms through which climate change alters terrestrial, freshwater, and marine ecosystems.
- **Effectiveness of adaptation and mitigation actions:** State- and local-level action has facilitated adaptation and mitigation investments in the region (Panwar & Barnett, 2025; Washington State Department of Commerce, 2024). Examples include requiring or incentivizing local governments to integrate adaptation and mitigation into land use plans and a cap-and-invest program. Potential adaptations are also being explored within impacted sectors, such as water needs (Adiga et al., 2024; Kondal et al., 2024; B. Singh et al., 2024). Adaptation remains a challenge for many sectors, including natural resource-based industries (Koehn et al., 2022). Innovative frameworks, such as those developed by Northwest Indigenous Peoples, integrate environmental changes with community priorities (O'Rourke et al., 2024). Future research should evaluate the effectiveness of adaptation and mitigation strategies and assess the monitoring, implementation, and enforcement of policy interventions.
- **Co-benefits, vulnerabilities, and trade-offs of adaptation and mitigation strategies:** Northwest forests have significant carbon storage potential (Hall et al., 2024) but are also expected to experience more frequent disturbances. Utilities rely on hydropower for energy generation, which is vulnerable to climate change and has had deleterious effects on aquatic ecosystems and cultural sites. Investments in renewable energy may be impeded by existing and new use conflicts that can affect Indigenous Peoples (Janowitz, 2025; Washington State Department of Commerce, 2024), fish, ecosystems (Galparsoro et al., 2022), and traditional fishing grounds (Warlick et al., 2025). Future research should analyze these issues and interactions of mitigation and adaptation.
- **Imminent hazards and emerging interactions:** A research focus should include assessing imminent hazards that could drive adaptation efforts, including public health responses, relocation of infrastructure, or expansion of engineered protections (e.g., at shorelines or within floodplains). A better understanding of interactions

among emerging industries and climate change, such as the growing water and electricity demands of data centers across the Northwest, is needed.

3.10.3. Southern Great Plains

The Southern Great Plains—encompassing the states of Kansas, Oklahoma, and Texas, and 46 Federally Recognized Tribes—is a large and highly diverse region of the U.S. spanning multiple climatological and ecological regions, sociological and economic sectors, and human demographic categories. This region experiences one of the highest frequencies of U.S. billion-dollar weather and climate disasters, particularly for severe storm events, creating high regional risk and vulnerability (Climate Central, 2026). The Southern Great Plains also produces the largest share of U.S. energy (U.S. EIA, 2022). Thus, climate resilience and governance are critical topics that must be addressed within the Southern Great Plains. Regional climate assessments provide essential information needed to ensure that people can respond and adapt to ongoing and future climate change (Frazier et al., 2025).

The region has continued to change over the past decades (Kloesel et al., 2018; McPherson et al., 2023; Shafer et al., 2014), as has the science for identifying, adapting to, and mitigating the impacts of climate change. There are five priority areas for assessment within this region.

3.10.3.1. Assessment Research Priorities

- **Regional extreme event forecasts and projections:** New data and improved computational resources have improved decision-relevant climate projections at finer spatio-temporal scales (U.S. Department of Energy, 2024). This is critical for stakeholders within the Southern Great Plains, who have different information needs depending on their sector of interest, location, and planning timeframe. Climate assessments can provide summaries of these data for different stakeholder groups, facilitating a connection between developers and end users.
- **Productivity impacts on multiple land uses:** Land use in the Southern Great Plains is changing, with a notable shift toward implementing multi-use production systems that integrate forms of agricultural, ranching, and energy production. The adoption of multi-use systems will also have direct impacts on climate, as they may drive greater variety in production across sectors. An assessment to explore the intersection between changing land use and climate across the Southern Great Plains is pivotal.
- **Sectoral impacts of climate-induced water cycle impacts:** Water is a critical resource within the Southern Great Plains, with varying concerns across the region, including the drier western sub-region, the wetter eastern sub-region, and the southern coastal sub-region. Climate change affects water availability differently across these sub-regions (Seager et al., 2018). Greater variability in precipitation and temperature is increasing uncertainties about water availability and water quality, with enhanced extraction of nonrenewable groundwater in drier portions of the region an especially critical issue (Reyes et al., 2020). The changing nature of water resources within the Southern Great Plains under climate change requires a new assessment.
- **Physical and mental wellbeing of different communities:** Climate change continues to negatively affect human health in the Southern Great Plains (McPherson et al., 2023), straining the region's people and infrastructure. The impacts include greater heat stress, declining air quality, and increasing vector-borne diseases. The effects are widespread but disproportionately affect communities with the fewest resources. Communities need to develop innovative ways to address these challenges, and these solutions can be communicated more widely through an assessment.
- **Compilation and evaluation of climate resilience effectiveness strategies:** Climatic challenges continue to impact the Southern Great Plains. Local resilience planning and strategies are rapidly emerging within the region, primarily in higher-capacity, larger cities (e.g., adaptOKC, Dallas Comprehensive Environmental and Climate Action, San Antonio Climate Action and Adaptation Plan, Austin Climate Equity Plan, Tulsa Climate Action Plan). In the Southern Great Plains in particular, Indigenous communities also play a large regional role (Bray et al., 2024). However, smaller communities with less capacity often struggle to identify suitable actions to reduce their risks. An assessment can explore and publicize successful local strategies for further development in these communities or at larger scales, while also examining their effectiveness (Owen, 2020).

3.10.4. Southwest

The Southwest region encompasses the economically, geographically, and socio-culturally diverse states of Arizona, California, Colorado, Nevada, New Mexico, and Utah, and 192 Federally Recognized Tribes. While regional climate and weather have long been characterized by high variability, recent research indicates trends in increasing temperature and precipitation extremes (Liang & Zhang, 2022; Swain et al., 2018; Williams et al., 2022; Zamora-Reyes et al., 2022), as well as increasing risk associated with simultaneous and sequential extreme events (Touma et al., 2022; Y. Zhou et al., 2024). New evidence better explains the specific weather and climate drivers of regionally relevant hazards, such as wildfires (Brown et al., 2024; W. Zhang et al., 2025), as well as how pre-existing societal conditions, arrangements, and inequalities influence their effects on communities (Sanchez et al., 2025), resulting in uneven adaptation (Silber-Coats et al., 2024).

3.10.4.1. Assessment Research Priorities

- **Managing water supply extremes**: The Southwest is experiencing declines in surface and groundwater availability (Bass et al., 2023; Carroll et al., 2024), driven by prolonged drought and expected to continue as the region aridifies (Hall et al., 2024; Whitney et al., 2023). At the same time, the region has experienced more extreme precipitation events, such as longer-lasting clusters of atmospheric rivers (Slinskey et al., 2023), though more research is needed to better understand and model long-term trends in regional precipitation (Kuo et al., 2025; Todd et al., 2025). A key research priority is to better understand how these changes, including heightened variability, impact regional water management (Scanlon et al., 2025), as well as how differences in communities' vulnerability and adaptive capacity affect their resilience to impacts. Research should also analyze the effects of water-related adaptation measures across scales (e.g., water recycling, desalination, irrigation, climate-resilient crops, new forecasting and management tools) to inform community and regional decision-making.
- **Uneven risks and uncertainties in coasts and oceans:** The Southwest's coastal areas experience a diversity of hazards, including compounding and cascading events (e.g., extreme precipitation, sea level rise, coastal flooding, erosion, marine heat waves) (K. M. Thorne et al., 2025), many of which are projected to intensify (Ohenhen et al., 2024), with uneven impacts on communities (Sanders et al., 2022). It is therefore critical to understand how these hazards, combined with growing exposure of aging infrastructure, create risk to ecosystems, communities, and economies, both regionally and beyond. Additionally, substantial uncertainty exists around the future of marine fog, which is vital to regional agricultural economies, ecosystems, and the human health–energy nexus (Oliphant et al., 2021). Future research should focus on how communities can overcome fiscal, political, and practical challenges in adapting to coastal and oceanic hazards.
- **Multihazard risks to community infrastructure and well-being**: As regional population growth increases and shifts to exurban areas (U.S. Census Bureau, 2024), land development choices increase exposure to hazards, such as wildfires (Shives et al., 2025). Communities increasingly face compounding hazards, such as exposure to both wildfire smoke and extreme heat (Walker et al., 2025), and cascading hazards, such as post-wildfire flooding (Dilshan et al., 2025; Pastor et al., 2024). Extreme heat poses uneven, increasing risks to vulnerable populations, such as outdoor laborers (Bandala et al., 2023), unhoused people (Gabbe et al., 2023), people in poorer quality housing (Kear et al., 2023), and people in correctional facilities (Ovienmhada et al., 2024). While heat governance has advanced in well-resourced cities (Meerow & Keith, 2024), progress is uneven. Research should focus on multihazard planning and multiscalar heat governance, particularly in smaller and rural communities and in communities that experience multiple inequalities.
- **Agricultural resilience to climate pressures given structural barriers:** Rising temperatures and prolonged drought, coupled with existing water overallocation and urban growth, impact agriculture through multiple pathways, including declining water availability, soil degradation, pests and disease, increased dust generation, and thermal stress across the growing cycle (Guan & Mascaro, 2023; Tong et al., 2023). These local-scale impacts have implications for national food systems and supply chains (Medellín-Azuara et al., 2024; Schneider, 2023). Existing research outlines adaptation options, but overlapping barriers (i.e., high upfront costs, lack of training, support, and access to information, and cultural resistance) hinder uptake (Nabhan et al., 2023). Research should focus on better understanding adaptive capacities and actions (e.g., adoption of conservation practices, technological innovation, economic diversification), climate mitigation potential, and

relevant institutional barriers to facilitate resilience in the agricultural sector (Bennett et al., 2023; Eash et al., 2024).

- **Tracking ecosystem shifts, disturbances, and restoration:** Coupled with weather variability, background warming, and increasing aridity contribute to ecosystem shifts and disturbance (e.g., drought, wildfire, invasive species, pests, disease, development) across Southwestern landscapes (G. M. Harris et al., 2023). These potentially irreversible impacts threaten general ecosystem function across scales, with wide-ranging impacts on agriculture, recreation, human health, and ecosystem services (Briske et al., 2023; Costanza et al., 2023). Additionally, continued development in the Southwest region, including renewable energy infrastructure crucial for mitigating climate change, can negatively affect critical ecosystems (G. C. Wu et al., 2023). Research should focus on assessing the implementation and monitoring of restoration treatments, as well as tradeoffs and tensions associated with the complexities of multiple land uses, socio-political pressures, and neighboring/overlapping jurisdictions.

3.10.5. Alaska

Alaska and the 229 Federally Recognized Tribes in the state are unique, as the only Arctic region containing the most extensive types of ice (e.g., sea ice, ground ice in permafrost, glaciers, and river ice) within the U.S. It also has the greatest volume of freshwater and the longest coastlines of any state. Alaska has already warmed far more than other states as well, between 1.22°C and 3.4°C since 1971, depending on the region (Thoman & McFarland, 2024). Warming and associated changes cause reductions in all types of ice, affecting interconnected ecological, social, cultural, and economic systems. Currently, several topics surrounding thawing ice and soil require further study, and threats to Arctic and Indigenous communities' subsistence economies remain. Below are topics where the knowledge has advanced to a stage where assessment research is particularly valuable.

3.10.5.1. Assessment Research Priorities

- **Permafrost and ground ice—Planning:** The current state of knowledge about permafrost and ground ice does not meet the planning and management needs of local communities and regulatory agencies (Spero et al., 2025). Eighty percent of Alaska lies within a permafrost zone (Jorgenson et al., 2008), and permafrost temperatures were the second warmest on record in 2024 (Natali et al., 2024). Thawing ice-rich permafrost causes ground-surface collapse (i.e., subsidence), which presents extensive challenges for infrastructure, including sewer, water, transportation, energy, and communications (Brown et al., 2024). For example, ice-wedges were only recently confirmed (B. M. Jones et al., 2025) for the first time in the Yukon-Kuskokwim Delta, highlighting how the hidden nature of below-surface ground-ice conditions exacerbates the lack of available data in the state.
- **Permafrost and ground ice—Costs:** Recent studies estimate costs of permafrost thaw hazards to Alaska at $37B to $51B by 2064 (Manos et al., 2025). Permafrost subsidence mitigation has cost individual homeowners up to approximately $31,500 (Schwoerer et al., 2024). On Alaska's Arctic Coastal Plain, 45%–65% of infrastructure could be damaged by 2100 without mitigation measures, including 10%–20% of oilfield infrastructure (Creel et al., 2024). Permafrost thaw, later freeze-up, and larger storms are also driving village relocation. Over 73 Alaska communities face severe flooding or erosion threats (U. S. Government Accountability Office, 2024). Of these, Newtok is the first village to complete relocation, with an estimated cost of over $150 million and many challenges, including failures in new infrastructure (Schwing, 2025). Aging colonial-era buildings (Brown et al., 2024), policy gaps, insufficient community consultation (Gini et al., 2024), and a lack of coordinated policy interventions (U. S. Government Accountability Office, 2024) all contribute to ongoing risk for communities.

  Permafrost thaw is also affecting Alaska tourism (a landslide in Denali National Park closed the only access road; reopening is expected to cost $102 million (Rosen, 2023)). Loss of glacial ice has caused deadly dam bursts in Juneau (2024) and increased precipitation-caused deadly mudslides in Haines (2020) and Wrangell (2023). None of this damage is included in the National Risk Assessment used by federal agencies (Manos et al., 2025; Sullivan et al., 2025; Zuzak et al., 2022).
- **Thawing permafrost and wildfire activity—Release of metals and gases:** Thawing permafrost and wildfire activity have been shown to release mercury into rivers (M. I. Smith et al., 2024; Zolkos et al., 2024), as well as

mobilize iron and heavy metals that cause streams to turn orange (Gulfam-E-Jannat et al., 2025; O'Donnell et al., 2024). Evaluation of these processes and the extent of mercury and other contaminant releases is needed to assess changes in water quality that affect drinking water and subsistence food sources.

The contribution of permafrost thaw to emissions of methane, nitrous oxide, and carbon dioxide from certain landforms, like deep lake sediments, particularly those that contain Yedoma (an ancient type of permafrost), needs examination and is not currently included in global emission models (Freitas et al., 2025). Recently, permafrost has shifted from a carbon sink to a source of emissions when accounting for permafrost thaw caused by wildfires (Natali et al., 2024). Mitigation methods need exploration, such as the historic practice of Indigenous forest management through cultural burning (E. Alexander, 2025; Christianson et al., 2022). Indigenous burning practices have been used to effectively manage fire in other places around the world, and their effectiveness and protective impacts need to be evaluated.

- **Effects of warming air and water temperatures:** Warming air temperatures are affecting terrestrial habitats. Spruce bark beetle expansion from the Kenai Peninsula to just south of Denali National Park has impacted thousands of acres of forest. Expansion of this species and others has yet to be fully examined, but advances in mapping dead trees (Zwieback et al., 2024) will support future efforts. Beavers expanded northward above the tree line as a result of increased shrubification (Diamond et al., 2024; Tape & Speed, 2025), changing water dynamics that increase permafrost thaw and the release of methane (J. A. Clark et al., 2023), but with benefits to some communities as a new source of food and economic revenue (Rosen, 2024). The impacts of other species expansion and the increased risk of zoonotic infections and pathogens need to be evaluated (e.g., H1N1 (Andersen-Ranberg et al., 2024); ticks (Hahn et al., 2020; McCoy et al., 2023)). Work is just beginning on evaluating the risks of potential reemergence of ancient pathogens from thawing permafrost (D. Kim et al., 2025; Mackelprang et al., 2025).

  Warming waters and melting ice are also affecting Alaska's oceans and coastlines (Lefebvre et al., 2025; Overland et al., 2024). Fish have been documented moving from the Pacific into the southern Bering Sea (Stafford et al., 2022). Marine species stocks have collapsed (e.g., snow crab (Litzow et al., 2024)), unusual multi-species bird mortality events have occurred, and western Alaska salmon have been shown to be sensitive to warmer temperatures (Schoen et al., 2023). The collapse of the Chinook salmon fishery along the Yukon River has had devastating impacts on Indigenous communities' food security and cultural practices. (Ebertz & Demuth, 2024; Feddern et al., 2023). Communities and fisheries managers need adaptation plans to help adjust to ecosystem changes driven by warming air and sea temperatures (DeMaster et al., 2025; Hollowed et al., 2025; Overland & M. Wang, 2025).

3.11. International

Previous NCAs have focused on assessing the nature of climate risk to U.S. interests in the global context—including national security—along with understanding the impacts and opportunities for sustainable development under near-term climate change and the role for climate information services to serve U.S. interests abroad. Since NCA5, the scientific literature has increasingly recognized the disconnect between administrative boundaries and political jurisdictions and the manner in which climate impacts and responses are actually unfolding, transcending borders. This includes the reality that U.S. citizens, assets, and networks are dispersed around the globe and thus interconnected with environmental conditions, populations, and decision-making elsewhere. In that context, we identify here key areas for systematic assessment and where new research would be timely and impactful.

3.11.1. Assessment Research Priorities

- **Interconnected natural system risk:** Recent years have seen new, detailed studies of the interconnected nature of physical climate risk (National Academies of Sciences, Engineering, and Medicine, 2024c), including the potential for state shifts that cascade across systems. In the international context, this emerges in the governance and management of transboundary flows—including water, air pollution, invasive species, and pathogens—that are altered or impacted by shifting climate patterns. Simultaneously, a growing understanding of the role of human system response in complex systems (Higuera Roa et al., 2025; N. Simpson et al., 2023) has begun to identify effective approaches for characterizing vulnerability and its associated uncertainties in a more nuanced and actionable way. The U.S. role as source, receptor, and connector in this interlinked system is overdue for rigorous scientific assessment.

- **Risk mediated by human networks:** In addition to direct physical transboundary risk, global social, economic, and political networks can propagate climate impacts from one location to another. New research has shown how trade can act as both a buffer and a new channel of exposure to climate risks, with food and supply chains as prime examples (Baldwin & Freeman, 2022; Haqiqi, 2024; Karakoc & Konar, 2024; Y. Sun et al., 2024). Increased mobility of humans around the world has shifted the landscape for climate-driven health risks, including exposure to physical risks like extreme heat and new infectious disease exposure and transmission risks. Climate-driven conflict and climate-driven migration have become urgent areas for both research and assessment (Caligiuri, 2022; Cantor et al., 2024; Raleigh et al., 2024), along with challenges posed to human rights, international law, and the international legal order by climate-driven changes to habitability, borders, exclusive economic zones, and statehood (Fry, 2023). More broadly, governments around the world now recognize climate change as a potential threat to political stability, including via impacts on radicalization, democracy, and participation in the international order (Buhaug et al., 2023); a synthesis of this literature would be especially impactful.
- **Shifting global organization and U.S. interests:** Around the world, national economies are retooling and realigning to deal with their own climate risks, responses, and sustainable development agendas. This has shifted the economic and geopolitical landscape for U.S. economic response, domestic investment, and trade opportunities and risks (including supply chains and exports) in ways that have yet to be fully understood. Moreover, a systematic assessment of the impacts of the U.S. political pendulum within the formal UNFCCC framework (and the IPCC) is urgently needed to understand both the future of U.S. interests and the future of global and regional climate governance under different potential U.S. positions. In the climate arena itself—concurrent with rapidly shifting U.S. positions over the past decade—there has been both an evolving and enhanced role of sub-national actors within the UNFCCC context (e.g., the Arctic Council, Coalition for High Ambition Multilevel Partnerships) and a rise in collaboration schemes outside the formal international context. These include movements focused on just economic and energy system transformation, climate adaptation finance organized outside state structures, and the inclusion of Indigenous Peoples and youth in climate research and governance.

  Finally, the global economic and climate finance landscape has matured (even as overall finance has lagged), and now includes taxes, carbon pricing (regional markets), and border tax adjustments, as well as mechanisms to address climate-driven increases in debt through mitigation, adaptation, or recovery (e.g., the Bridgetown Initiative). This rapidly evolving climate cooperation landscape and its implications for U.S. interests—as well as U.S. responsibility in global solutions and governance—is especially in need of both research and assessment, as much of the innovation is documented in gray literature and policy documents outside the formal peer-review context.

4. Responses

Deliberate responses to climate change take three principal forms: mitigation, climate intervention, and adaptation. Mitigation reduces climate hazards by limiting the emissions of greenhouse gases into the atmosphere, principally through decarbonization. Climate intervention refers to measures that "produce a targeted change in some aspect of the climate" (National Research Council, 2015, Box S.1)—for example, changing planetary albedo or capturing greenhouse gases from the atmosphere—as well as to measures that deliberately reduce the ecological consequences of climate change (National Research Council, 2015). Adaptation reduces climate risk by decreasing exposure and vulnerability and increasing resilience, and operates at a variety of scales—from household-level decisions about where and how to live and work, to state and national decisions about long-term community planning and disaster response, policy, and investment. This section presents research priorities in these response action categories.

4.1. Mitigation

The costs of solar power, wind energy, and battery technologies have fallen substantially over the past decade, making them among the cheapest forms of new energy capacity to install in many places on a levelized cost basis (Lazard, 2026). In addition, distributed energy resources such as rooftop solar and energy storage can also reduce household energy costs while providing resilience services in the face of risks from extreme weather and an aging electricity grid (T. Sun et al., 2025). However, while in the years following the release of NCA5 in 2023 net U.S. greenhouse gas emissions fell by about 3.5% in 2023 and 0.5% in 2024, emissions are estimated to have grown by 2.4% from 2024 to 2025 (M. Gaffney & King, 2026). The recent rise in emissions is largely due to increases in power demand and increased coal power generation, and increased fossil fuel use for heating buildings (M. Gaffney & King, 2026). This result is consistent with scholarship that distinguishes between the addition of new, low-emissions energy supply and the displacement of legacy, higher-emissions energy assets (York & Bell, 2019). The rapid growth of electricity demand from AI is reshaping prior emissions trajectories. Data center electricity use doubled from 2% of U.S. electricity consumption in 2019 to about 5% in 2024, and is projected to consume between 9% and 15% by 2030 (LBNL, 2026). These projections carry considerable uncertainty, both in the future demand from data centers and in other, likely larger, future electricity demand from electric vehicles, home appliances, and industrial applications. In addition, reaching net-zero emissions in the U.S. and globally likely requires a considerable scale-up in the production and processing of minerals needed for decarbonization technologies (IEA, 2021). The extent of this scale-up, which can have adverse impacts on local and Indigenous communities (Sovacool et al., 2020), will vary depending on mitigation policy choices (Riofrancos et al., 2023). Those mitigation policy choices, and mitigation efforts broadly, are themselves shaped and conditioned by concerted opposition to both climate science and various decarbonization technologies (Roberts et al., 2025).

In 2024, U.S. greenhouse gas emissions were approximately 20% below 2005 levels. The Inflation Reduction Act of 2022 was projected to reduce the nation's projected greenhouse gas emissions by 39%–48% by 2035 from 2005 levels, as compared with 27%–35% without the Inflation Reduction Act (Bistline et al., 2026), and provided subsidies to reduce the costs of electrifying home heating systems and other residential appliances (J. M. Joseph et al., 2025). However, in 2025, major changes in federal energy policy, including the One Big Beautiful Bill Act (An act to provide for reconciliation pursuant to title II of H. Con. Res. 14, Pub. L. No. 119-21, 139 Stat. 1, 2025), scaled back or eliminated many energy, efficiency, and climate programs that were projected to lower the cost of mitigation technologies (Bistline et al., 2023, 2026) or reduce emissions directly. These changes, alongside new federal actions aimed at expanding fossil fuel production, highlight the substantial role of policy in shaping future emissions trajectories and introduce added uncertainty regarding progress toward achieving long-term emission reduction goals.

4.1.1. Assessment Research Priorities

- **Increase the synthesis speed and scope of mitigation trends, costs, and assumptions:** With the costs and performance of many mitigation technologies advancing quickly, and national to local-level policies that affect emissions continuously changing, open source research is needed to synthesize and understand major U.S. trends in mitigation technologies, economic outcomes, and emissions across sectors, as well as assess governmental (federal, state, Indigenous Peoples, municipal), private-sector, and organizational mitigation-related laws, policies, plans, targets, and incentives. In addition, documenting and understanding U.S. extraction trends and projections of transition minerals and materials can affect mitigation pathways, trade balances, and security (Samaras, 2025). Cost changes and investment levels for the deployment of energy generation, energy storage, and demand mitigation options are often inputs to climate mitigation models and systems-level assessments that affect decisions, and up-to-date and relevant data can help align model outputs with decision-maker intentions. Advanced computing and AI tools may enable researchers to quickly summarize changes in technology costs and performance indicators, assess the greenhouse gas reduction rates and pace and scale required to reach net-zero emissions, and enable new technologies and strategies for mitigation. At the same time, AI and the increased electricity and resource use from the growth of data centers are likely to result in new near-term emissions and environmental challenges (T. Carter et al., 2026). This highlights the need to concurrently assess the emissions and environmental impacts from increasing use of AI and the potential for these tools to analyze and accelerate mitigation efforts (Kaack et al., 2022), as well as new institutional approaches to considering AI in climate policy and assessments (Buck et al., 2026; O. Gaffney et al., 2025).

- **Improve the understanding of community engagement, community-based research, and public perception of mitigation strategies:** Community-based engagement and social sciences research can build trust and durability for mitigation efforts (J. Smith et al., 2025). New social science synthesis research on the role and best practices of Indigenous community consultation, free prior and informed consent, and community engagement in decarbonization, as well as on public perception of mitigation technologies and the impacts of energy transitions on customer affordability, can elucidate successful mitigation strategies.
- **Characterize existing and emerging risks:** Mitigation choices are affected by regional and national energy transitions and climate risks (National Academies of Sciences, Engineering, and Medicine, 2024a) and, at the same time, can introduce new risks. Synthesis research is needed to assess the state of the science, research strategies, technology readiness, life cycle impacts, cost, accounting and verification issues, and potential distributional impacts on communities and Indigenous Peoples for the extraction and processing of transition minerals and metals, as well as prospective mitigation strategies (e.g., carbon dioxide removal, advanced nuclear, hydrogen, geothermal, long-duration energy storage).
- **Understand new fossil fuel trends and liabilities:** Synthesis research on the management of fossil energy systems can enable safer, more resilient, and more successful mitigation pathways. This can include research that characterizes projections of U.S. fossil fuel production, consumption, and exports, as well as evaluates unfunded liabilities and the challenges and trade-offs of state and federal decommissioning, remediation, reclamation, and abandonment policies for energy infrastructure under declining throughput (Grubert & Hastings-Simon, 2022; Lappen & Grubert, 2026).

4.2. Climate Interventions

Climate interventions range from reforestation or afforestation, which change the Earth's surface properties (e.g., albedo) as well as sequester carbon dioxide (e.g., Hasler et al., 2024), to solar radiation modification, which modifies the amount of solar radiation that either reaches the surface (e.g., via stratospheric aerosol injection) or escapes (e.g., via cirrus cloud thinning) the troposphere (National Academies of Sciences, Engineering, and Medicine, 2021). Recent National Academies reports have examined marine or land carbon uptake interventions like ocean liming or enhanced rock weathering (National Academies of Sciences, Engineering, and Medicine, 2022b), solar radiation management via stratospheric aerosol injection or marine cloud brightening (National Academies of Sciences, Engineering, and Medicine, 2021), and forms of atmospheric methane removal such as atmospheric oxidation enhancement (National Academies of Sciences, Engineering, and Medicine, 2024b). Some researchers are also investigating cryosphere interventions aimed at ice sheet stabilization (MacAyeal et al., 2024). In relation to mitigation and adaptation, climate intervention has generally received comparatively little attention in expansive climate assessments like the NCA. However, the recent explosion in research, field testing, governance discussions, and public awareness demands rigorous assessment.

4.2.1. Assessment Research Priorities

- **Physical and ecological consequences of climate interventions:** Earth system modeling experiments, like those of the Geoengineering Model Intercomparison Project (Kravitz et al., 2015) for solar radiation management, regional marine cloud brightening studies (Wan et al., 2024), and CDR-MIP for negative emissions technologies (Keller et al., 2018), provide part of an evidence base for evaluating the physical and ecological consequences of certain climate interventions. The implications of such interventions in a dynamic climate system and their impacts on humans, particularly in the U.S., are not well understood and need to be assessed (Harding et al., 2020, 2024).

  These implications are often complex. For example, marine carbon dioxide removal—such as ocean alkalinity enhancement, seaweed cultivation, and ecosystem recovery—could augment natural carbon sinks but has substantial uncertainties, including uncertain effectiveness, unintended environmental impacts, and financial and technological limitations (National Academies of Sciences, Engineering, and Medicine, 2022b). While intended to mitigate ocean acidification and support decarbonization, some marine carbon dioxide removal approaches also have significant risks, including habitat disruption, cascading ecological consequences for fisheries or marine biological processes, and scaling uncertainties. More comprehensive synthesis of the trade-offs and carbon removal potentials, including integrating physical and ecological information with social and economic models, could inform management options.

- **Climate intervention governance:** Many climate intervention approaches, such as solar radiation modification, are inherently international in their climate impacts, yet they might be undertaken unilaterally or by private companies, nations, or non-state actors; research illustrates that solar radiation modification and strategic aerosol injection in particular are currently insufficiently governed, both in terms of frameworks for deployment and oversight of research itself (Jinnah et al., 2024). Despite a plethora of research calling for governance to ensure responsible innovation—including possible decisions to halt research if it is determined that risks outweigh benefits or if broad publics object to technological development on moral or other grounds—the prospect of unregulated research and deployment activities looms large (National Research Council, 2015). For these reasons and many others, the rapid increase in climate intervention research and development activities poses critical questions for public participation, justice, ethics, governance, and oversight at all stages of the process from initial design through implementation as deserving of systematic attention (AGU, 2022; Baum et al., 2024; Dove et al., 2024; McKinnon, 2019; Sugiyama et al., 2020).

4.3. Adaptation

A major gap is growing between U.S. adaptation in practice and in research (Tietjen et al., 2024). Although U.S. adaptation practices have expanded dramatically in the past decade, they remain largely sector- and hazard-specific, incremental, and insufficient to address either current or future risks (Burke et al., 2024). Meanwhile, U.S. adaptation research over the same time period has shifted toward more transformative, equity-centered approaches that address root causes of vulnerability, integrate multiple benefits, and center climate justice, although the shift is incomplete (Deubelli & Mechler, 2021; T. Liu & Fan, 2023; L. Shi & Moser, 2021; Taylor et al., 2025). Critical research priorities to support future climate assessments include efforts to understand why the gap between adaptation research and practice persists, and how to provide useful and usable information and tools to practitioners to close it.

4.3.1. Assessment Research Priorities

- **Activation of adaptation actions:** Future climate assessments are needed to provide practitioners and communities with evidence-based guidance on when, where, and how adaptation actions can be implemented most effectively. Research is needed to synthesize what is known about the economic and political conditions under which various actors (e.g., federal, state and local government, Indigenous Peoples, civil society, private sector, individuals) engage in adaptation and to address gaps in knowledge to support further adaptation actions (Mezei et al., 2023). Relevant factors that should be assessed and addressed in future adaptation guidance include sources of funding, organizational conditions, adaptation-as-planning versus adaptation-as-disaster-response paradigms, technocratic versus participatory approaches, access to climate services, and the timescales actors consider (e.g., 30-year mortgage, projections to 2100, intergenerational) (Grandage et al., 2024; Palinkas et al., 2023). Such work could usefully explore discount rates, future generations, life cycle analyses, and how community values or funding priorities shape the timescales considered.

  Ongoing changes in U.S. federal adaptation and disaster policy present natural experiment opportunities for evaluation. The shift of responsibility for resilience efforts to state and local governments, for example, as outlined in Executive Order 14239 (2025), presents an opportunity for research on multi-level governance (Knauer, 2022; Nevitt, 2024). Changes in state and federal laws on financial risk disclosure (both emerging and disappearing) present opportunities for pre- and post-comparisons (J.-B. Kim et al., 2023). Variations in state and local zoning and building codes and planning frameworks also offer opportunities for comparative research to inform future assessments (Chang et al., 2025).

- **Advancing evaluation methods to support learning—Barriers to evaluation:** Adaptation evaluation research has progressed from conceptual frameworks to applied methods that assess sufficiency, efficiency, co-benefits, and maladaptation. In practice, adaptation evaluations are uncommon and, when done, tend to be short-term and focused on a single project, hazard, and a narrow set of stakeholders and outcomes. Research specifically on barriers to evaluation could increase the frequency and quality of evaluations, thereby improving the data available for future assessments. Investigation of feasible opportunities to further integrate and embed adaptation evaluation within existing legal, regulatory, and stakeholder decision processes might also facilitate valuable learning over time (Aldy, 2022). Without rigorous evaluations of adaptation actions, the guidance on how to adapt or efforts to increase adaptation actions risk being ineffective, inefficient, or maladaptive.

- **Advancing evaluation methods to support learning—Evaluation methods:** Evaluation methods have improved in numerous ways, and syntheses of these improvements, especially syntheses that compare the relative merits of different approaches, would be of practical use to decision-makers (e.g., new economic models) (Desmet & Rossi-Hansberg, 2024). Methods to quantify co-benefits, for example, have advanced, especially for biodiversity, flood mitigation, carbon sequestration, and, to a lesser degree, health and human well-being, although these last two remain areas for future improvement. Adaptation pathways methods have matured and been adopted widely enough to merit synthesis evaluations (Haasnoot et al., 2024; Muccione et al., 2024). Scenario planning, which previously focused on biophysical features (e.g., sea level rise), has integrated a wider range of social, economic, and political drivers, creating a need for updated syntheses. Evaluations of nature-based strategies could benefit from a similar shift: from a focus on biodiversity and conservation outcomes toward a broader, more integrated evaluation (Barry et al., 2025). Additionally, as scientific and technological advances increase both the volume and granularity of data, new evidence may be leveraged to assess adaptation actions at finer scales, potentially overcoming analytical pitfalls such as the "ecological fallacy"—errors where individuals are incorrectly assumed to be the same as those from the aggregate group—and improving inference (Khadke et al., 2024).

  Systems approach to evaluation. Single case studies that evaluate individual adaptation actions still vastly outnumber syntheses and comparisons. New methods are still needed to assess cumulative effects of adaptation actions over time and space and to address systems-wide outcomes (e.g., road network vs. single road elevation). Emerging methods (e.g., ML, AI, remote sensing, crowdsourcing) offer opportunities for large-scale assessments of adaptation actions, but these require data sets of comparable information for numerous adaptation actions, which largely do not currently exist for most adaptation strategies. Efforts to develop consistent reporting mechanisms and compile such data sets with metadata would greatly improve future assessments. It is critical for comparative and synthetic assessments to collect appropriate metadata when evaluating individual adaptation measures or locations. These data allow for analyses of the context for effective adaptation, for example, what geographic, economic, and social contexts lead to more effective implementation of specific adaptation approaches? In addition, the impact of the scale of adaptation implementation on effectiveness and potential maladaptation needs to be considered. For example, scaling up seawall installations can lead to erosion and negatively affect coastal ecosystems (Nunn et al., 2021). Community-wide approaches to wildfire adaptation can be much more effective than individual homeowners acting alone (Knapp et al., 2021).

- **Decision-making tools and approaches**: A range of methods and tools have been developed to support adaptation decision-makers in choosing how to allocate finite resources in response to a growing set of hazards and an expanding set of response options (Ulibarri et al., 2022). Examples include robust decision-making, triage-based planning, stakeholder elicitation, adaptation pathways, and econometric techniques (Orlove et al., 2020). A synthesis of options that helps decision-makers choose which approaches to use would be practical (Siders & Pierce, 2021). Additionally, research on how decision-makers *make decisions in practice* (and how they differ from formal methods) would yield useful insights to further advance these methods.

- **Adaptation justice in practice:** Decisions about when, where, and how to invest public resources affect which people benefit most from those investments, whose safety is prioritized, and who remains at greatest risk, which are all questions of justice. To inform these decisions, research on how adaptation relates to justice is critical for providing scientific evidence to decision-makers about the trade-offs, judgments, and ethical considerations they face with each adaptation effort. Studies have documented injustices arising from some adaptation actions (e.g., to communities left unprotected outside levees or disrupted by relocation) (Domingue et al., 2024; Pollack et al., 2025; L. Shi et al., 2022), and these efforts increase transparency and accountability but often fall short of providing guidance to practitioners on how to avoid such injustices. More recently, studies have begun to address that gap by empirically evaluating the benefits of adaptation processes that are not only participatory but involve power-sharing, co-production, recognition of historical and contemporary systems of oppression, and inclusion of diverse knowledge systems (Carman et al., 2025; Chu &

Cannon, 2021; Herreros-Cantis et al., 2025; L. Shi, 2021). Syntheses of these findings are needed to demonstrate how justice and equity scholarship informs and improves evidence-based governance (Brousseau et al., 2024; Foster et al., 2024).

- **Achieving transformation:** A growing body of research documents structural barriers to effective and just adaptation, such as property regimes, governance structures, and institutional and administrative rules, that may require substantial legal and institutional reforms to overcome (Bertana et al., 2022; Bizer et al., 2025; Dilling et al., 2023; Giovannettone et al., 2024; Nevitt, 2024; L. Shi & Moser, 2021; Taylor et al., 2025). If social systems are not transformed proactively, they may still be forced to change significantly due to increasing hazards in the future (e.g., the coastal real estate industry is likely to transform either through market forces or regulatory reforms), but with greater harms and fewer social benefits (Bizer et al., 2025; L. Shi & Moser, 2021). Recent changes in U.S. institutions provide important insights into the positive and negative consequences of rapid changes to fundamental systems and may provide nuance to transformation scholarship. Research on these contemporary changes and syntheses of research on structural barriers will be important sources for future assessments to understand the constraints and opportunities facing adaptation decision-makers.

5. Discussion

5.1. Common Themes

Across systems, sectors, and regions, several cross-cutting themes emerge as common priorities for assessment. Compounding extremes and cascading climate risks are increasingly salient threats to companies and communities, often overwhelming systems designed using outdated historical climate information (AghaKouchak et al., 2020; Amorim et al., 2025; Webber et al., 2025) (see Sections 2.1, 2.2, 3.1–3.11, and 4.2). Legacy policies, infrastructure, and institutional silos have the potential to amplify exposure and vulnerability, which could lock communities into path dependencies that complicate adaptation. Meanwhile, ongoing greenhouse gas emissions continue to alter and amplify climate hazards. Social systems critically shape both the distribution of climate impacts and the possibilities for climate responses (see Sections 2.3, 2.4, 3.1–3.11, and 4.1–4.3).

As communities implement climate response strategies, these efforts must be informed by high-quality information, with strategy effectiveness and adoption continually evaluated and improved. For example, in many different contexts, nature-based solutions may be valuable parts of adaptation strategies, with significant co-benefits for human and ecological health; both their potential and limitations require careful assessment (see Sections 2.2, 2.4, 3.2, 3.4, 3.8, and 4.3). To more comprehensively understand impacts, vulnerabilities, and responses, robust and rigorous climate assessments include both peer-reviewed science and a broader range of practitioner sources, as well as diverse ways of knowing, including local community knowledge and Indigenous Knowledges (see Sections 2.2, 2.3, 3.3, and 4.3). Weaving western science with Indigenous Knowledges—which are integrative, holistic, and relational (Deloria, 1997; Kimmerer, 2013; Kovach, 2021; Reid et al., 2021)—is essential for a more complete Earth systems understanding (Gazing Wolf et al., 2024; National Academies of Sciences, Engineering, and Medicine, 2022a) and for improving climate assessments (Huambachano et al., 2025). Future assessments should also feed actionable results back into communities more rapidly (see Sections 2.2, 2.3, and 4.3). Synthesis of local case studies is a crucial part of ensuring actionability (see Sections 2.2, 2.4, and 4.3). Together, these factors underscore the need for sustained and robust climate assessment (Buizer et al., 2016; Moss et al., 2019).

To support on-the-ground decisions, there is an increasing need for synthesis research to understand the governance processes and portfolio effectiveness of climate response decisions that integrate mitigation, adaptation, climate interventions, disaster management, and resilience planning and action. While individual or single organizational or governmental climate responses have been studied (see Sections 4.1 and 4.3), there is a need for a deeper understanding of the effectiveness of coordinated governance across jurisdictional boundaries (e.g., regional land management given municipal, state, Indigenous Peoples, federal, and private ownership). Future assessments should also evaluate how these integrated response portfolios interact—whether they create cascading benefits, tradeoffs, maladaptation, or unintended consequences—and how responses vary across governance levels, funding structures, and social and environmental contexts. Priorities include developing sustained indicators (Kenney & Janetos, 2020), assessing the role of public and private financing, examining incentives and institutional coordination in accelerating or impeding action, and understanding social and behavioral dimensions such as equity, justice, trust, risk perception, and agency. Addressing compounding hazards, cascading impacts, long-term financial risks, and inadequate data for confident decision-making under deep uncertainty will require new data sets, tools, and methods explicitly designed for ongoing assessments.

Additionally, tools that advance such integrated decisions include scenario analyses and integrated assessment models that help understand human–Earth system dynamics. Such large-scale coupled human–Earth system models must explicitly represent human behaviors, decision-making, and spatial heterogeneity, drawing on innovations in integrated assessment modeling, agent-based modeling, multi-agent microsimulation, and spatially explicit simulation frameworks to capture how individual and collective choices interact with land, energy, water, and climate processes (Beckage et al., 2022; Tan et al., 2023). At the same time, next-generation Earth system models need dynamic, multi-resolution frameworks that bridge global, regional, and local processes. Integrating physics-based approaches with data-driven methodologies, including ML and AI, may further enhance precision and efficiency by leveraging diverse data streams to overcome the limitations of traditional parameterizations (Ou et al., 2026). Attention needs to be given to the social data and drivers that are not represented by such data streams and may limit the parameterizations and conclusions that can be made for coupled human-Earth system models. Further representing feedbacks between people and Earth systems, however, will enable decision-makers to better understand and evaluate trade-offs and a range of climate and energy solution pathways (National Academies of Sciences, Engineering, and Medicine, 2022a; Pan et al., 2025).

5.2. The Need for Broader Engagement, Input, and Evaluation

In this commentary, we outline some foundational topics in need of assessment and near-term research across physical and ecological environments, socio-ecological-technical systems and sectors, communities and regions, and responses that reduce climate risks. The assessment and research priorities in this commentary reflect the collective expertise of a broad group of scholars and practitioners with diverse institutional affiliations, but it is not intended to be a comprehensive commentary on all the topics relevant to future assessments. As highlighted in Figures 2 and 3, there are a number of systems, settings, sectors, regions, and responses that were not covered and yet should be important areas for future work.

Furthermore, the scope of an effective assessment cannot be determined solely through deliberations by those experts with the time and resources to participate. It must be co-created with and accountable to the communities and institutions that depend on the knowledge produced in order to build capacity and a durable consensus to support change and action. Delivering credible, actionable knowledge requires deliberate integration of interdisciplinary scholarship, co-creation with diverse user communities, and a transparent prioritization of emerging challenges and decision needs (Jagannathan et al., 2023).

The credibility and legitimacy of climate assessments also depend on rigorous, inclusive review processes. Unlike standard peer review, scientific consensus assessment processes must span disciplines, sectors, and stakeholder perspectives. The U.S. NCA process, for example, has historically included multiple federal reviews, a National Academies of Sciences, Engineering, and Medicine review (e.g., National Academies of Sciences, Engineering, and Medicine, 2022a), and an open public comment period.

Past NCA reports have been widely cited in the scientific literature, federal, state, and local planning documents, company reports, and the media, underscoring their value as trusted sources of climate information. They have supported local, state, and regional adaptation planning, guided agency risk assessments, and informed legislation. Yet their uneven influence across sectors highlights the need to improve accessibility, relevance, adoption, and integration with decision-making contexts. Understanding how past assessments have been used—or not used—can inform improvements in engagement strategies, digital platforms, and evaluation frameworks for future assessments (Crimmins et al., 2025). This further emphasizes the importance of a range of climate assessment efforts that can effectively provide the information needed for the range of uses and contexts that such assessments inform.

Finally, in identifying research needs, we were inspired by the breadth of current national and sub-national climate assessment efforts, and also recognized the opportunity to encourage a wider range of right-sized, timely assessment efforts. Stronger networking among future national, sub-national, and sectoral assessment processes could help better address the range of local, state, and regional planning and implementation efforts, inform public and private sector response strategies, and guide a range of climate responses. It could also enable sub-national, sectoral, or special topic assessments that could better address place-based priorities, sectoral needs, or specific decision contexts. Such a network of climate assessments (Figure 1) could provide timely, contextualized syntheses of the current state of scientific knowledge and actionable insights to support decision-making.

6. Conclusion

Climate assessments in the U.S. are at a critical crossroads. Amid a complex public environment, future climate assessments must address the rapidly shifting climate landscape shaped by the convergence of accelerating risks, deepening inequities, and the urgency of coordinated action. Assessments must both synthesize knowledge and provide insights on navigating deep uncertainty and institutional, technical, and social barriers to climate solutions. As climate change impacts accelerate, the pace of assessment and the integration of science with decision-making and action must accelerate as well.

AI Tools Disclosure

AI tools were used by some authors for spelling and grammar checks. Six of the authors disclosed they used AI for minor tasks such as suggestions for paragraph editing for brevity and supplemental literature review.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

Data were neither used nor created for this research.

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