National Climate Change Roadmap

A Research Framework for U.S. Agriculture, Forestry, and Working Lands

Colorado State University

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Preferred citation: National Climate Roadmap Working Group. 2023. National Climate Change Roadmap: A Research Framework for U.S. Agriculture, Forestry, and Working Lands. Colorado Agricultural Experiment Station. Mountain Scholar. 56 pp. https://doi.org/10.25675/10217/237190.

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ACKNOWLEDGMENTS

This report was co-authored by a team from Colorado State University, including Dr. Eugene Kelly, Associate Director of the Colorado Agricultural Experiment Station and Professor of Pedology, Soil & Crop Sciences; Dr. Jan Leach, Associate Dean for Research in the College of Agricultural Sciences and a University Distinguished Professor of Agricultural Biology; Dr. Courtney Schultz, Associate Professor and Director of the Public Lands Policy Group; and doctoral student Erin Jackson from the Graduate Degree Program in Ecology in the Department of Soil and Crop Sciences.

Research support was provided by the US Department of Agriculture's National Institute of Food and Agriculture (USDA-NIFA) award to Colorado State University (2023-67019-38845) and the Colorado State University Agricultural Experiment Station.

The findings and conclusions in this report have not been formally disseminated by the U. S. Department of Agriculture and should not be construed to represent any agency determination or policy.

The authors also thank the dedicated members of the National Climate Change Roadmap Horizon Scan Core Group and Working Group, whose invaluable contributions have been acknowledged in the appendices.

Furthermore, the authors wish to express deep appreciation to Carly Campana, Lindsay Cope, Tannera George, Heather Lair, and Laurie Ristino of Meridian Institute for their unwavering partnership in orchestrating and overseeing the development process of the Horizon Scan and National Climate Change Roadmap.

EXECUTIVE SUMMARY

DANIEL LLOYD BLUNK FERNANDEZ, UNSPLASH

Over the last decade, addressing climate change impacts facing agriculture and natural resources has been an increasing focus of the scientific community. Translation of science to solutions, however, requires national and international policies that support more sustainable forms of land use, efficient agricultural production, and community-engaged research globally.

With a grant from the U.S. Department of Agriculture National Institute of Food and Agriculture (USDA NIFA), the National Climate Change Roadmap (NCCR) was undertaken by scholars from Colorado State University (CSU) with support from Meridian Institute (Meridian) to develop a science agenda that is holistically designed to serve researchers, policymakers, farmers, and practitioners. The Horizon Scan methodology, an innovative visioning process, was used to gather input from 61 leading scientists to inform the NCCR via an expert Working Group. These researchers represented 51 institutions from across the U.S. and contributed expertise in a wide range of disciplines, including social and biophysical sciences, to ensure diverse, inclusive perspectives.

The inputs collected from the Working Group were organized as insights, which included a problem statement, critical science gaps, and model science questions aligned around a set of initial themes. These insights then informed revised thematic areas through a series of discussions and syntheses, resulting in the following focal thematic areas that serve as the backbone of the NCCR.

Seven Thematic Areas Form the Backbone of the National Climate Change Roadmap

1 **Systems-based innovations:** Cultivate and advance systems-based innovations and approaches that bridge biophysical and socioeconomic disciplines to build system resiliency to climate change.

2 **Participatory research processes:** Co-create a science continuum that bridges fundamental research to producer knowledge, practice, and experience and incorporates principles of environmental and social justice.

3 **Mitigation and adaptation through ecosystem management:** Adapt to and/or mitigate the impacts of climate change across diverse environments and land use systems via science-based management opportunities.

4 **Climate-informed water resource management:** Address earth system interactions and the growing challenges created with increasing agricultural water demand.

5 **Energy-smart agriculture and technology integration:** Integrate new energy technologies into diverse production systems to help achieve carbon neutrality.

6 **Strategic, sustainable, and regenerative agricultural practices:** Develop and promote practices that improve biodiversity and ecosystem health while strengthening resiliency to climate change.

7 **Socioeconomic and policy research:** Develop and evaluate models that assess impacts of markets, consumption patterns, socioeconomic conditions, and food systems on human well-being under a changing climate.

Within each of the themes, the NCCR sets forth exemplar insights derived from the Working Group's initial insights, which show the types of science needed to address the impacts of climate change on agriculture, food systems, forests, and natural resources.

The Horizon Scan process was agnostic as to outcomes and was designed to generate, winnow, and prioritize science needs into the future. However, a surprising and illuminating result of the Horizon Scan was that Working Group members emphasized principles such as the need for systems-based approaches and consideration for how science is conducted such as using participatory research approaches as much as the specific areas of science needed. Consequently, this report also presents a set of principles derived from the Horizon Scan process that guide the above focal thematic areas.

Nine Guiding Principles from the Horizon Scan Process

1. **Equity and justice:** Ensure that climate actions do not unfairly burden marginalized communities and rectify historical environmental injustices by fairly distributing both benefits and burdens.

2. **Policy relevance:** Align climate initiatives and policy objectives to maximize resources and outcomes.

3. **Contextual considerations:** Recognize diverse social and economic factors that affect communities and emphasize tailored solutions that consider cultural practices, socioeconomic conditions, and values.

4. **Risk and vulnerability:** Identify and understand the impact of climate-related hazards on communities and ecosystems to develop strategies for resilience and vulnerability reduction.

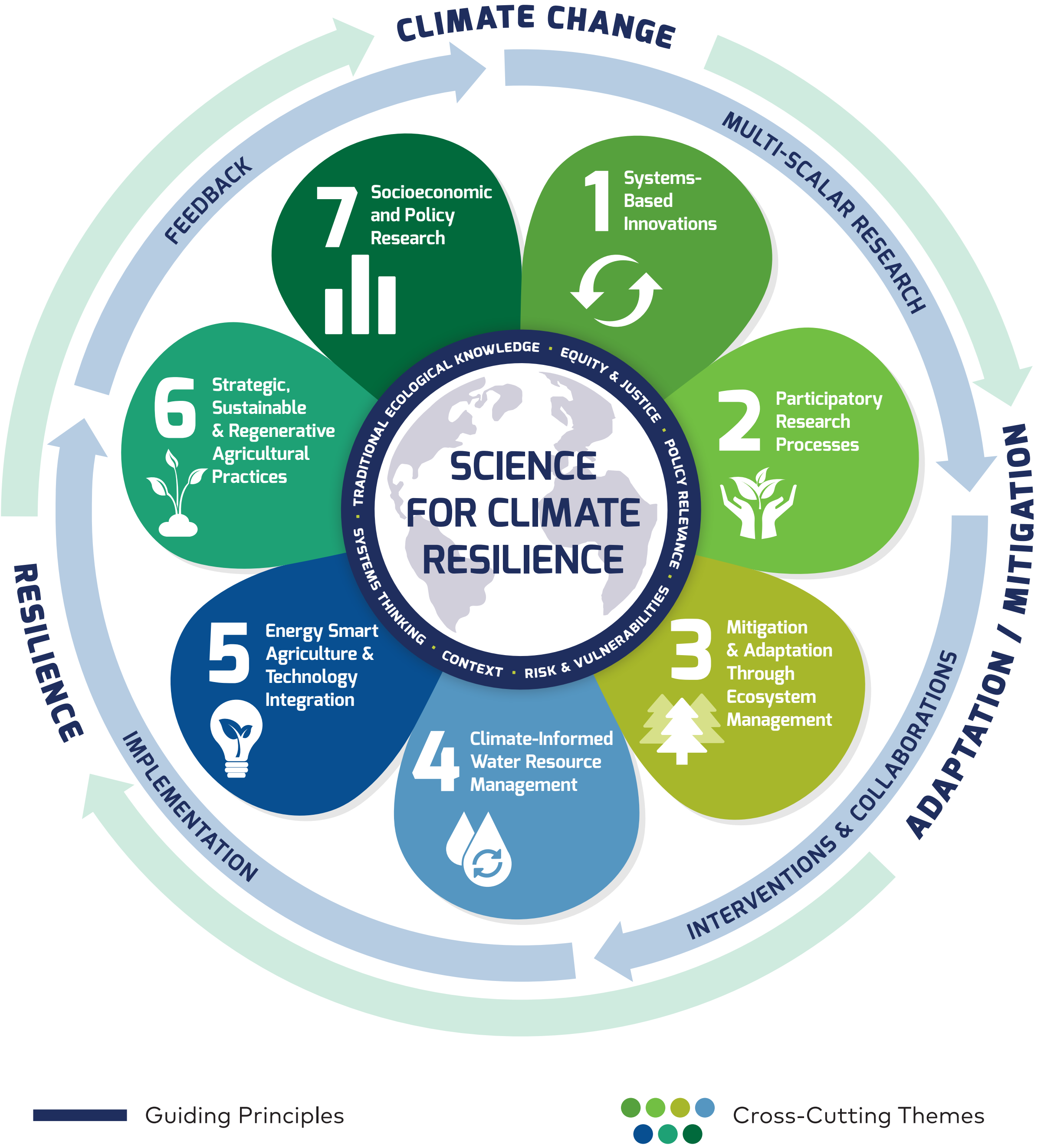
5. **Traditional ecological knowledge:** Value traditional ecological knowledge in partnership with indigenous and local communities to better adapt to environmental changes.

6. **Strategic communications:** Emphasize well-designed communication strategies to engage and inform interest holders about climate change impacts and mitigation/adaptation measures.

7. **Co-production with end-users:** Involve end-users in decision-making processes to ensure that climate actions meet their needs and preferences.

8. **Systems-thinking:** Study climate change comprehensively by examining interconnected systems (e.g., ecosystems, economies, societies) to identify synergies and trade-offs.

9. **User-centered:** Design user-friendly, accessible policies, technologies, and interventions that prioritize human needs, values, and behaviors in addressing climate change.



The themes and principles are visualized above with an emphasis on the system-based and continuous nature of the research endeavor. Through these components, the National Climate Change Roadmap provides a framework for science and funding grounded in a systems-based, highly participatory, and just approach, which acknowledges the ongoing, evolving challenges of climate change. This framework is not intended as an endpoint, but a place from which to evolve and refine to meet climate science challenges for the benefit of agriculture, working landscapes, and the communities that rely upon them.

INTRODUCTION

Addressing climate change impacts facing agriculture and natural resources has been an increasing focus of the scientific community. Translation of science to solutions, however, requires national and international policies that support more sustainable forms of land use and efficient agricultural production, and forest and natural resource management globally. Despite increased emphasis on evidence-based policy, decision-makers in most fields, including agriculture, forestry, and the environment, often base decisions on insufficient evidence. This is exacerbated by the complexity and scarcity of information flows among scientists, practitioners, and policymakers.

The key thematic areas presented in this report are intended to guide policymakers looking to support and direct the science needs of the coming years, as well as to fund agencies and other organizations seeking to strategically target their investments and resources in support of agricultural science, including forestry and the management of natural resources. With funding from the U.S. Department of Agriculture National Institute of Food and Agriculture (USDA NIFA), this National Climate Change Roadmap (NCCR) was created using an iterative process (the Horizon Scan) to provide a framework for developing science agendas that are holistically designed to serve researchers, policymakers, farmers, and practitioners. Through the Horizon Scan process, input from leading scientists and researchers across disciplines (Working Group) was gathered to inform the NCCR. These experts provided 84 science insights which were discussed and distilled during a series of virtual and in-person meetings. Twenty-four refined insights are included in this document as exemplars of the types of science that are needed to address the impacts of climate change on agriculture, food systems, forests, and natural resources.

Our intention in contextualizing these insights within high-order themes is to guide researchers as they prioritize their efforts and develop new, integrated science programs. In addition, we anticipate the themes and principles will assist policymakers in supporting and directing the science community's needs in the coming years, guiding funding agencies and other organizations to strategically target their investments and resources in support of agricultural and natural resource science. Improved dialogue and information flow among scientists, practitioners, and producers are vital to addressing the multiple drivers and system responses to climate change.

Focal Cross-Cutting Thematic Areas

Below are seven focal cross-cutting thematic areas derived from the Horizon Scan discussions and activities. These themes are intended to inspire new approaches to studying, managing, and promoting the adoption of practices that address climate change's impacts on natural, agricultural, and human resources. They are the "chapters" of the NCCR thesis – that the way we structure and carry out research programs is as important as the disciplines and scientific techniques employed. The list below is not a "menu" – it is a recipe that needs to be followed to ensure the health of our food, agricultural, and natural resource systems and the people who rely upon them.

1. **Systems-based innovations:** Cultivate and advance systems-based innovations and approaches that bridge biophysical and socioeconomic disciplines to build system resiliency to climate change.
2. **Participatory research processes:** Co-create a science continuum that bridges fundamental research to producer knowledge, practice, and experience and incorporates principles of environmental and social justice
3. **Mitigation and adaptation through ecosystem management:** Adapt to and/or mitigate the impacts of climate change across diverse environments and land use systems via science-based management opportunities.
4. **Climate-informed water resource management:** Address earth system interactions and the growing challenges created with increasing agricultural water demand.
5. **Energy-smart agriculture and technology integration:** Integrate new energy technologies into diverse production systems to help achieve carbon neutrality.
6. **Strategic, sustainable, and regenerative agricultural practices:** Develop and promote practices that improve biodiversity and ecosystem health while strengthening resiliency to climate change.
7. **Socioeconomic and policy research:** Develop and evaluate models that assess impacts of markets, consumption patterns, socioeconomic conditions, and food systems on human well-being under a changing climate.

PROCESS OVERVIEW

Input from leading scientists and researchers across disciplines was gathered using a Horizon Scan methodology to inform the NCCR. A Horizon Scan is a collaborative tool to identify trends, threats, opportunities, and emerging topics to facilitate proactive response to foreseen change. This iterative process collects diverse perspectives and expertise within an area of interest. The NCCR Horizon Scan engaged leading agricultural, forestry, and natural resources researchers and other professionals in extension, education, and engagement across disciplines to guide the NCCR and inform the most critical science priorities for agriculture, forestry, and natural resources management over the next decade.

The Horizon Scan was implemented by a Planning Group, comprised of Colorado State University (CSU) researchers and a team of facilitators and strategic advisors from Meridian Institute (Meridian). The CSU-Meridian Planning Group formed two bodies to carry out the Horizon Scan.

The Planning Group Formed Two Bodies to Carry Out the Horizon Scan

Core Group

Twenty directors from university research, teaching, and extension programs, as well as government and non-profit entities, advised on the Horizon Scan process and nominated members of the Working Group.

Working Group

Sixty-one experts in the sciences and social sciences generated scientific insights and identified knowledge gaps and key questions for the NCCR.

More information about the Core and Working Groups is shared in Appendices A-C.

HORIZON SCAN METHODOLOGY

As noted above, the Horizon Scan Methodology is a systematic assessment of trends, threats, opportunities, and emerging technologies within a domain of choice. For this assessment, the focus was on key climate change issues in agriculture, forestry, and natural resources. The Horizon Scan approach is designed to identify discontinuities, emerging issues, and other signals of change through cyclical scanning, analyzing, synthesizing, and communicating information.

Step 1 — Gathering Insights

The first step of the Horizon Scan was to gather data to subsequently refine through the iterative process of the scan. Members of the Working Group were asked to provide up to two insights on priority science topics on climate change science-related issues that are critical in their importance, emerging, or largely unknown, and likely to impact agriculture and natural resources in the next five to 10 years. Each insight included a problem/context statement, critical science gaps, and model research questions taking into consideration the original five themes of the roadmap that are listed below. Working group members were also asked to provide scientific citations.

To broaden the expertise involved beyond the 61 members of the Working Group, members were instructed to canvas their professional networks and draw upon the expertise of their colleagues to generate insights for the Horizon Scan. This six-week exercise generated 84 unique and far-ranging insights.

Original Roadmap Themes

- **Theme 1:** Advancing climate-smart agricultural and forestry approaches to adaptation and mitigation while building ecosystem resiliency.
- **Theme 2:** Advancing racial justice, equity, and opportunities in historically underserved communities.
- **Theme 3:** Developing value propositions to reward farmers, ranchers, foresters, and landowners for adopting climate-smart agriculture and forestry practices and facilitate better market opportunities for agricultural producers and rural communities.
- **Theme 4:** Increasing resilience of rural communities to withstand the impacts of climate change.
- **Theme 5:** Responding to cross-cutting issues such as nutrition security and workforce development.

The guiding principles are intended to guide efforts to address climate change comprehensively, equitably, and effectively while considering the needs and contexts of diverse communities.

Step 2 — Guiding Principles and Sorting Insights

The Planning Group reviewed the insights and sorted them into the five themes listed above. Working Group members were assigned to Expert Groups, each corresponding to one of the five themes. Each Expert Group reviewed the insights categorized into its corresponding theme and met virtually for 90 minutes to discuss the insights. The goal of the Expert Group discussions was to narrow down the collection of insights by combining those that were similar and identifying the most pressing areas of science. The Expert Groups were also charged with adding insights if gaps were identified.

While some insight sorting and combining took place in the Expert Groups, a significant outcome of the discussions was the elucidation of overarching guiding principles to frame the NCCR. These included a strong consensus regarding the need for a systems-based focus that integrates biophysical, social, and systems research questions that can address problems at various scales. Working Group members underscored the need to focus on people and affected communities when developing research proposals, emphasizing two-way information flows and holistic science approaches. Importantly, a clear call for centering equity and access across each theme's discussions was evident, and reflecting that such inclusion is essential to taking a true systems-based approach to research, education, and extension.

The guiding principles serve as a north star when designing science programs to address climate change. They are intended to guide efforts to address climate change comprehensively, equitably, and effectively while considering the needs and contexts of diverse communities and stakeholders.

Guiding Principles for the Roadmap

1. **Equity and justice:** Ensure that climate actions do not unfairly burden marginalized communities and rectify historical environmental injustices by fairly distributing both benefits and burdens.
2. **Policy relevance:** Align climate initiatives and policy objectives to maximize resources and outcomes.
3. **Contextual considerations:** Recognize diverse social and economic factors that affect communities and emphasize tailored solutions that consider cultural practices, socioeconomic conditions, and values.
4. **Risk and vulnerability:** Identify and understand the impact of climate-related hazards on communities and ecosystems to develop strategies for resilience and vulnerability reduction.
5. **Traditional ecological knowledge:** Value traditional ecological knowledge in partnership with indigenous and local communities to better adapt to environmental changes.
6. **Strategic communications:** Emphasize well-designed communication strategies to engage and inform stakeholders about climate change impacts and mitigation/adaptation measures.
7. **Co-production with end-users:** Involve end-users in decision-making processes to ensure that climate actions meet their needs and preferences.
8. **Systems-thinking:** Study climate change comprehensively by examining interconnected systems (e.g., ecosystems, economies, societies) to identify synergies and trade-offs.
9. **User-centered:** Design user-friendly, accessible policies, technologies, and interventions that prioritize human needs, values, and behaviors in addressing climate change.

Step 3 — Synthesizing Feedback and Revising Themes

Cross-cutting themes emerged during the Horizon Scan process as participants, representing a wide range of disciplines and cultural perspectives, engaged in discussions. They contributed insights from various fields, including environmental science, social science, economics, agriculture, engineering, policy, and more. This interdisciplinary approach enriched the process, allowing for a thorough exploration of climate change complexities, recognizing that resilience demands insights and approaches from diverse disciplines.

Facilitated discussions and interactions enabled participants to exchange ideas, spot trends, identify challenges, and uncover emerging topics that transcended conventional boundaries. This cross-fertilization of ideas led to overarching themes that bridge disciplinary divides, exploring connections between different facets of climate change resilience, such as the interplay between ecosystem health and socioeconomic factors or the relationship between energy efficiency and agricultural practices.

Cultural viewpoints were identified as critical given how they influenced how communities perceive and react to climate change. Engaging participants from diverse cultural backgrounds unveiled distinctive insights into the human dimensions of climate resilience, including traditional ecological knowledge and adaptive strategies.

The importance of diversity in disciplinary, institutional, and cultural perspectives in tackling climate change resilience cannot be overstated. It provided depth to the horizon scanning process, fostering a more holistic understanding of climate challenges, aiding in the identification of innovative solutions that account for the intricate web of factors influencing resilience, and spanning environmental, social, economic, and cultural dimensions. Diverse perspectives also champion inclusivity and equity in climate resilience endeavors, ensuring that strategies are effective and relevant across diverse communities and regions. Ultimately, addressing climate change resilience necessitates a comprehensive and collaborative approach achievable by embracing the diversity of human knowledge and experience.

A set of integrated themes, contextualized with narrative and mapped to exemplary insights, was produced by the Planning Group, and shared with the Working Group before the in-person workshop to gather feedback. These Revised Themes became a foundational document for discussions during an in-person Working Group workshop.

Revised Interim Themes

1. **Innovations for climate resiliency.** Cultivate and advance innovations and approaches directed towards system resiliency to climate change.
2. **Holistic research process.** Co-create a science continuum that bridges fundamental research to producer knowledge, practice, and experience and that incorporates principles of environmental and social justice.
3. **Management for mitigation and adaptation.** Adapt and/or mitigate the impacts of climate change across diverse environments and production systems via science-based management opportunities. (Forestry/ Cropping/Livestock/Urban Systems)
4. **Climate change impacts on water resources.** Address earth system interactions and the growing challenges with increasing agricultural water demand.
5. **Energy technologies.** Integrate new energy technologies into diverse production systems to help achieve carbon neutrality.
6. **Strategic and sustainable agricultural practices.** Promote practices that improve biodiversity and ecosystem health while strengthening resiliency to climate change.
7. **Targeted, appropriate regenerative approaches.** Incorporate regenerative practices to rehabilitate and conserve agroecosystems and communities impacted by climate change.
8. **Socioeconomic and policy research.** Develop and evaluate models that assess impacts of markets, consumption patterns, socioeconomic conditions, and food systems on human health and well-being under a changing climate.

The Planning Group produced a set of revised, integrated themes, contextualized with narrative and mapped to exemplary insights. The themes became a foundational document for discussions during an in-person Working Group workshop.

Step 4 — Testing the Themes and Exemplar Insights

Eighteen members of the larger Working Group attended an in-person workshop to help the Planning Group finalize the themes and recommendations that were outputs of the Horizon Scan process. A key takeaway from the discussion was that fundamental changes are needed in the way science is conducted to shift agricultural, forestry, and natural resource biophysical and social sciences to best address the highly variable conditions resulting from climate change. At the heart of these changes is to ensure that research is user-centric and engages producers and communities to develop technologies and approaches that respond to community needs. In addition, working with leadership from indigenous communities to incorporate indigenous wisdom and traditional ecological knowledge into western science efforts can help ensure research is deeply connected to the valuable insights of local producers and communities. It ensures that research becomes not only user-centric but also deeply connected to the insights and needs of local producers and communities. Such an approach enables the development of technologies and strategies that are culturally sensitive and contextually relevant.

Furthermore, this transformation calls for a multidisciplinary approach that can better account for the intricate web of social, ecological, and economic factors that shape agricultural and natural resource systems. Science needs to transcend traditional boundaries and silos, fostering collaboration across diverse fields of expertise. Additionally, recognizing the urgent nature of the climate crisis, science must encompass a wide range of scales and applications; it must address both the immediate challenges and the long-term consequences of climate change, providing insights and solutions that can adapt and evolve over time.

The final themes emerging from this process are the need for:

1. **Systems-based innovations:** Cultivate and advance systems-based innovations and approaches that bridge biophysical and socioeconomic disciplines to build system resiliency to climate change.
2. **Participatory research processes:** Co-create a science continuum that bridges fundamental research to producer knowledge, practice, and experience and incorporates principles of environmental and social justice.
3. **Mitigation and adaptation through ecosystem management:** Adapt to and/or mitigate the impacts of climate change across diverse environments and land use systems via science-based management opportunities.
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Evolution of the Thematic Areas

Original 5 Themes

- **Crosscutting themes covering anticipated gaps**

Revised 8 Themes

- **Updated to reflect the Expert Group session discussions**
- **Focus on systems and a holistic science process**

Final 7 Themes

- **Updated in response to feedback from the in-person workshop (July 2023)**

CROSS-CUTTING THEMES

& Exemplar Climate Change Insights

The seven cross-cutting focal themes provide a roadmap for navigating the complex landscape of climate change science within the context of agriculture, forestry, and natural resource management. In this section, each theme is introduced and illustrated by the inclusion of two to five "exemplar" insights - composite contributions from the Working Group highlighting important research opportunities within each theme. It is essential to approach these 24 insights with the understanding that they serve as exemplars rather than exhaustive lists of science priorities. Climate change presents multifaceted challenges, and these exemplar insights provide a glimpse into some of the critical areas where science and innovation are urgently needed. They are meant to inspire further exploration and action, recognizing that the quest to address climate change is dynamic and ever evolving. With this perspective in mind, we encourage you to explore these themes and exemplar insights, recognizing that they are part of a broader spectrum of science opportunities in the pursuit of a sustainable and resilient future.

THEME 1. Systems-Based Innovations

Resilience to climate change must constitute a fundamental attribute of sustainable ecosystems in the coming decades, particularly in regions projected to undergo profound ecological shifts due to a changing climate (Moore & Schindler, 2023; Raza and Bebber, 2022; Chaloner et al., 2021). Higher temperatures and the increasing frequency of prolonged droughts are increasing wildfires (Jones et al., 2022), causing both short- and long-term environmental and health effects (Blando et al., 2022; Rodney et al., 2021). Livestock, fisheries, and wildlife populations are also negatively impacted (Thornton et al., 2021; Cheung et al., 2021; Riddell et al., 2021). In addition, warming of nights and diminished frosts are driving increases in biological invasions (e.g., animal and plant diseases), which lead to increased use of herbicides, pesticides, and antibiotics and can threaten food security (Ristaino et al., 2021).

Addressing these challenges will require integrated approaches and innovations that encompass the realms of biology, agricultural sciences, economics, and social sciences. Science that integrates insights from diverse disciplines using a systems-based approach grounded in context may uncover comprehensive strategies for climate resilience. Breeding programs, for example, can develop crop varieties and animal breeds that are adapted to changing climatic conditions. These varieties may have traits such as drought tolerance, heat resistance, disease and pest resistance, and improved yield potential under altered environmental conditions (Lobell and Gourdji, 2012).

Developing accurate monitoring, evaluation, and reporting for climate-informed forestry and regenerative agricultural practices will require new technologies to ensure accurate metrics and reduce uncertainties that are crucial to prevent potential disparities in benefits and equitable outcomes across diverse communities.

Climate impacts and risks vary across different communities. Thus, the intersectionality of social inequalities, such as gender, race/ethnicity, and disabilities, must be addressed to ensure that practices and technological advancements benefit all members of our agricultural, food systems, and forestry communities.

Five exemplar insights were selected to demonstrate the types of systems-based science that are needed to support social and ecological resilience to climate change.

Insight 1.1 – Accelerate technology and innovation for precision monitoring, reporting, and verification in Climate-Smart Forestry (CSF) to foster resilient practices in a changing climate.

Science-based reforestation is a potent tool for climate change mitigation, outperforming other land management activities (Fargione et al., 2018; Van Winkle et al., 2017). However, the U.S. faces a growing backlog of reforestation needs (400,000+ hectares/year) due to disturbances such as fires, pests, and diseases (Dumroese et al., 2019). This has prompted initiatives such as the REPLANT Act (Balloffet & Dumroese, 2022) and Climate-Smart Forestry (CSF) practices, which were designed for climate adaptation, biodiversity conservation, and sustainable resource use, ultimately to bolster the forests' role in carbon sequestration and resilience against climate-induced threats. Although forests are renowned for long-term carbon storage, climate change impacts such as drought, wildfires, pests, and market dynamics, including carbon credit sales, complicate management decisions (Favero et al., 2023; Goodwin et al 2020). Uncertainty persists regarding forests' ability to absorb emissions under high carbon dioxide (CO_2) scenarios, with inadequate tree planting potentially raising CO_2 emissions and harming biodiversity, landscapes, and livelihoods (Alkama et al., 2022; Shi et al., 2021). Other research suggests that reforestation and afforestation may be curtailed due to unreliable growing conditions and increasing levels of disturbance. Overall, there is a pressing need for advancement in technology and innovation to create precise monitoring, reporting, and verification methods for CSF to properly employ high-resolution forest performance tracking in the face of shifting climate conditions.

Insight 1.2 - Diversity: Enhance biodiversity in food production and preserve genetic variation within crop species.

The continued reduction of crop diversity is increasing the vulnerability of our global food supply and reducing future crop options (Khoury et al., 2022). Underutilized and minor crops have the potential to make substantial contributions to addressing issues of production, resilience, hunger, bicultural restoration, and other issues in agriculture (Ebert, 2014). The potential benefits are highly dependent on both environmental (climate, soil) and social (cultural preferences, infrastructure) factors. For example, global trade and market demands for standardized crops have reduced the cultivation of diverse, locally adapted varieties in favor of a few high-yielding, exportable varieties (Fanzo, 2019). Exploring feasibility of alternative crops to broaden diversity and identifying and adopting biodiversity-friendly practices, markets, and conservation methods are critical steps for food security.

Insight 1.3 - Explore novel approaches to address climate-induced challenges in rangeland restoration and management.

Western rangelands constitute 30 percent of the U.S. land cover and play a crucial role in sustaining livestock and wildlife populations. Yet, these rangelands face multiple challenges, including climate-induced shifts in rainfall patterns and temperatures, intensified wildfires, and invasive non-native plants (Nouwakpo et al., 2019). These changes lead to erosion, soil degradation, and altered vegetation, necessitating adjustments in livestock grazing practices for sustainable use (Wilmer et al., 2018; Roche et al., 2015; Teague et al., 2013). These pressures underscore the urgency for adaptive strategies, including enhanced water management, adjusted grazing practices, and wildfire risk reduction, to bolster rangeland resilience. These innovations are vital for both food production and environmental conservation in livestock-dependent communities (NASM, 2023).

Insight 1.4 - Model biotic/abiotic stresses and crop growth to inform strategies for crop adaptation to climate challenges.

Climate change is set to reshape local crop choices in the long run. In the short term, farmers are likely to seek more resilient cultivars within existing crops (Acevedo et al., 2020; Rising et al., 2020; Sloat et al., 2020). Public breeders face challenges due to the lack of tools needed to meet the pace of climate change. For a breeder to focus on a trait, they need predictive models for guidance as to which trait(s) to develop, germplasm containing sufficient genetic variation, screening mechanisms for selecting traits, and the ability to characterize germplasm. Comprehensive threat typologies for crops in different regions and timeframes are necessary. These threats encompass biotic and abiotic stressors, varying across space and time. Local impacts of climate change on crop productivity can be assessed with crop models linked to climate projections. Combining pest and disease models with crop growth models is needed to evaluate risk profiles under different climate scenarios. Regional assessments can guide breeding efforts and other strategies for adaptation.

Insight 1.5 – Advance climate-resilient agriculture through comprehensive assessment of biotic and abiotic interaction dynamics and enhanced monitoring of climate-driven pathogen/pest migration.

Our knowledge of adapting plants to disease and pest pressures in a changing climate has significant gaps. We lack comprehensive insights into how climate variables, such as temperature shifts, altered precipitation, or increased CO_2 levels, affect the behavior of pathogens and pests and how their combined interactions affect plants (Desaint et al., 2021; Zandalinas et al., 2021; Cohen & Leach, 2020). This hinders our ability to predict how pathogens or pests will evolve. Although we have made progress in identifying genetic markers for resistance in some crops, we are far from understanding these traits in most plants and their response to climate variables, limiting our capacity to engineer crop resistance. Additionally, we lack information on the ecological consequences of deploying disease- or pest-resistant crops, whether developed through classical breeding or newer genome editing technologies. Addressing these gaps is crucial for sustainable agriculture and food security in a changing climate.

Plant pests and diseases are unpredictable in climate change, crossing borders and interacting with extreme weather events such as droughts, escalating the risk of global spread (Bebber, 2015). Dealing with new pathogens and pests is particularly challenging, and there is an opportunity for global collaboration in establishing a surveillance and monitoring system (Savary et al., 2023; Carvajal-Yepes et al., 2019). However, the development and sharing of data and models supporting coordinated strategies for pathogen and pest prediction and management are lacking (Garrett et al., 2022). Accurate predictions are vital for resistance breeding and improved pesticide use.

THEME 2. Participatory Research Processes

An important prerequisite for the development and adoption of sustainable agricultural practices and technologies over large geographic domains, as well as the sustainable utilization of certain resources (e.g., soil and water), is producer participation. Participatory approaches and a circular flow of information are recognized to provide social benefits as new technologies and practices are learned directly and then adapted to agroecological, social, and economic circumstances. Creating equitable (e.g., gender, race, socioeconomic) research, extension, and educational systems would be transformative and could lead to opportunities, commodities, relationships, and services that would ultimately change behavior. Through co-creation of knowledge, both constraints and opportunities for marginalized populations can be better understood, and more effective ways developed to address needs and enhance the contributions of these communities, which will ultimately improve agricultural productivity, food security, and poverty reduction (Sealey et al., 2020).

Producer and community participation is crucial at all stages for the co-creation, development, and adoption of sustainable agricultural practices and technologies, and allows for the customization of strategies that enhance agricultural resilience to climate change impacts. In addition, equitable agricultural research, extension, and educational systems are transformative and would lead to opportunities that change behavior, benefiting marginalized communities by alleviating constraints and creating opportunities for underrepresented groups.

Three exemplar insights were selected demonstrate the types of participatory research science needed to ensure development of innovative and practical solutions that are relevant and potentially adoptable.

Insight 2.1 – Develop holistic educational programs for agricultural and land management stakeholders to foster understanding of conservation program goals, challenges, and platforms.

While producers may not necessarily need an in-depth understanding of Corporate Green Practices (CGP), it is of paramount importance for their crop consultants and trusted advisors to possess a reasonable grasp of these and other sustainability strategies. This knowledge becomes invaluable when farmers engage in collaborations with companies for sustainability initiatives and participate in related programs. Such collaborations can bring about benefits ranging from cost-sharing arrangements and premium incentives to insurance adjustments and other value-added propositions. There is a pressing need for science that delves into the development and structuring of sustainability programs such as the CGP and the monitoring of their impact. Science areas should include effective direction and allocation of resources to encourage the widespread adoption of new and sustainable agricultural management practices by farmers (Markowski-Lindsay et al., 2019; Lipper et al., 2014). By comprehensively understanding the nuances of these programs, researchers, policymakers, and stakeholders can design initiatives that align with both the goals of the agricultural industry and the broader objectives of environmental sustainability.

Insight 2.2 - Prioritize agronomic and soil sciences research for socially acceptable climate change mitigation and reversal strategies.

Policymakers hold a significant stake in and are consumers of disciplinary research outcomes, alongside farmers, producers, and natural resource managers. Therefore, it is imperative to provide scientifically sound research that caters to their specific needs (Wolf and Lang, 2018). However, recent policies and incentives aimed at climate mitigation and adaptation lack adequate science-based guidance. Furthermore, farmers have been reluctant to participate in these initiatives due to several factors, including fundamental issues with science.

A key limitation overall within the scientific domain is that many existing studies that include experimental designs are inadequately powered to detect small effect sizes. Furthermore, there is a general dearth of synthesis science and the associated data infrastructure required to support it (Brouder et al., 2020). In this context, systematic reviews stand as the gold standard for synthesizing existing, primary science for the benefit of stakeholders and pinpointing knowledge gaps for future research. However, the time-consuming nature of synthesizing and publishing these reviews leads to them quickly becoming outdated. In this context, exploration of the potential of artificial intelligence (AI) and machine learning strategies should be explored, as they offer the prospect of "living systematic reviews." These dynamic reviews would have the capacity to automatically collect new scientific findings and update synthesis as fresh results are published (Marshall and Wallace, 2019; Thomas et al., 2017). In doing so, they would provide a means to keep policymaking and agricultural strategies in tune with the latest advancements and insights, ensuring that they remain relevant and effective in addressing the challenges posed by climate change and sustainable agriculture.

Insight 2.3 - Advance participatory research to address knowledge gaps in scaling productivity impact projections and improve communication of climate-smart agricultural benefits for small to midscale operations.

Empowering historically underserved and marginalized farmers for local food security is of paramount importance. Small and mid-sized farmers, particularly women and Black, indigenous, and people of color, play a vital role in contributing to local food security (Florick and Park, 2022). This recognition is gaining momentum within the agricultural community. Simultaneously, the farmer-led innovation approach underscores the critical importance of involving farmers directly in the research and design processes (Brouwer and Woodhill, 2016). Active farmer participation is pivotal for the successful integration of Climate-Smart Agricultural Practices into decision support frameworks. Any such farmer-centric approach should address the unique requirements and preferences of diverse communities, ensuring that Climate-Smart Agricultural Practices are not only technically sound but also culturally and socially appropriate (Florick and Park, 2022; Brouwer and Woodhill, 2016). Defining, scaling, and implanting such a multifaceted approach would significantly enhance the adoption and sustainable implementation of agricultural practices that are not only environmentally responsible – but would also potentially contribute to the well-being and resilience of historically underserved farming communities.

Small and mid-sized farmers, particularly women and historically underserved producers, play a vital role in contributing to local food security.

THEME 3. Mitigation and Adaptation Through Ecosystem Management

Land use change (for any purpose) is a major driver of global change (Tilman et al., 2001). Agricultural and food systems are estimated to account for one-third of global greenhouse gas (GHG) emissions, more than twice that of the transportation sector (IPCC, 2022). Thus, the future of the agricultural sector is no longer simply to maximize productivity, but to optimize it across far more diverse and complex geographical and sociological landscapes that include production practices, rural development, environmental issues, and social justice outcomes (Godfray et al., 2010). The conundrum is that agriculture contributes significantly to climate change while being significantly impacted by its consequences (Rosa and Gabrielli, 2022). As an example, livestock production is the world's largest user of land resources, encompassing 80 percent of all agricultural land (e.g., grazing systems, production of feed crops) and approximately 10 percent of global water use. The sustainability of livestock and other food production systems requires comprehensive and holistic solutions to meet the demand for food that is produced in environmentally sound and economically sustainable production systems.

Optimizing agricultural systems for climate mitigation and adaptation requires shifting focus from maximizing productivity to optimizing it across diverse landscapes and socioeconomic contexts to develop strategies that reduce GHG emissions while enhancing soil health, carbon sequestration, crop adaptation, biodiversity, and other ecosystem services.

Four exemplar insights were selected to demonstrate the types of ecosystem management-based science that are needed to inform mitigation and adaptation priorities.

Insight 3.1 – Address critical knowledge gaps in methane emissions from animal agriculture.

As noted above, livestock production is the world's largest user of land resources and a significant user of fresh water. Enteric methane from livestock contributes about 14.5 percent of global anthropogenic greenhouse gas emissions (Gerber et al., 2013). Because methane is short-lived in the atmosphere and very potent, mitigating methane emissions has significant near-term climate benefits (Cain et al., 2019). The adoption of emission reduction technologies (e.g., genetics, herd management, feed additives) is relatively limited in extensively managed U.S. rangeland and pasture grazing systems. Improved support for decision-making and implementation of emerging technologies could both reduce methane emissions (mitigation) and increase livestock performance on poor quality forage (adaptation). In addition, while advancements have been made in determining the potential of genetic selection, feed additives, and alternative manure management to mitigate methane emissions, still lacking are solutions that work across animal types, diets, climates, and management systems. Methodologies and supporting tools to evaluate and select individual animals with higher feed conversion efficiency and lower methane emissions are needed. While development of technical solutions is important, understanding socioeconomic trade-offs and producer incentives is critical for adoption of solutions that decrease enteric and manure methane sources (Beauchemin et al., 2022).

Insight 3.2 – Address soil organic carbon (SOC) storage for carbon mitigation, agricultural sustainability, and food security.

In recent years, interest in the potential of agriculture to mitigate greenhouse gas emissions, particularly carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH4), has grown. Rumpel et al. (2020) highlight the intriguing notion that the agricultural sector, often a source of these emissions, could, to some extent, counterbalance its environmental impact through the deliberate accumulation of soil organic matter and the enhancement of soil health. However, scholars have raised concerns about the credibility of carbon offset claims, particularly in forest projects (Badgley et al., 2022; Gifford, 2020; Marino et al., 2019). Establishing genuine carbon benefits requires addressing complex factors such as conditionality, additionality, leakage, and permanence (Nayak et al., 2019). Thus far, the simulation of soil organic carbon (SOC) does not provide a comprehensive tool for globally ensuring the effectiveness of SOC sequestration efforts or guaranteeing dependable carbon crediting (Garsia et al., 2023).

This science insight underscores the intricate and multifaceted nature of leveraging SOC accumulation in agriculture as a climate change mitigation strategy. While it offers promise, it also presents

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challenges related to measuring, verifying, and ensuring that the benefits are genuine and long-lasting, thus demanding further exploration and innovation in carbon offsetting strategies within the agricultural sector. Further, the social sciences have a key role in terms of better understanding incentives, technical assistance needs, and adoption, as well as ensuring equity in access and participation.

Insight 3.3 – Advance plant microbiome integration in crop breeding for enhanced stress resilience.

Plants are colonized by diverse groups of macro- and microorganisms that confer fitness advantages to the plant host, including growth promotion, nutrient uptake, stress tolerance, and resistance to pathogens (Trivedi et al., 2022; Trivedi et al., 2020; Compant et al., 2019; Hassani, Durán et al., 2018). The composition and abundance of crop microbiomes have shifted in modern crops compared to their wild ancestors, likely related to changes in crop plant disease resistance and root exudation (Gutierrez and Grillo, 2022). For example, wheat and barley mutants that provide broad resistance to powdery mildew also limit colonization by beneficial arbuscular mycorrhizal fungi (Jacott et al., 2020). A better understanding of how to select for beneficial plant-microbe interactions in agriculture has the potential for synergistic outcomes for plant stress tolerance. Knowledge of microbiome dynamics would foster strategies for deliberate cultivation of advantageous plant-microbe interactions in agriculture. Furthermore, knowledge of the role of the crop microbiome could improve mechanistic understanding of disease outbreaks, which may lead to more effective prediction, monitoring, and management of diseases. Thus, understanding how crop-microbiome interactions can deliver synergistic benefits, particularly in terms of bolstering plant stress tolerance (Friesen et al., 2011; Hawkes et al., 2021), is important to contributing to more resilient and sustainable agricultural systems.

Insight 3.4 - Harness the potential of AI-driven decision support tools to integrate emerging technologies to address both mitigation and adaptation strategies in agriculture.

In the realm of climate-smart agriculture, AI models are harnessed to analyze historical weather data and climate trends, providing invaluable insights for decision support tools that enable farmers to adapt proactively to shifting environmental conditions. A large and growing body of scientific research has demonstrated how Climate-Smart Agricultural Practices (CSAPs) can significantly improve the climate resilience of U.S. farmers. However,

the adoption of CSAPs remains slow, and results from controlled trials have been difficult to reproduce on working farms. Despite billions of dollars of investment over more than a decade, cover crops are used by a small minority of producers, use of no-till or conservation tillage has been stagnant, crop and livestock specialization is increasing, use of diverse crop rotations is less common, and utilization of agroforestry is relatively rare. A growing body of social science research on farmer decision-making and behavior points to three major categories of obstacles to the adoption of CSAPs: 1) economic constraints as farmers may face financial challenges related to the initial investment required for adopting CSAPs; 2) knowledge and information gaps as farmers may not be well-informed about the benefits of these practices; and 3) sociocultural norms such as peer pressure, social acceptance, and the perception of CSAPs as deviating from traditional farming practices (Epanchin-Neill et al., 2022; Burnett et al., 2018; Basch et al., 2017; Atwell et al., 2009; Carlisle, 2016; Carlson and Stockwell, 2013).

AI-driven decision support tools are instrumental in climate-smart agriculture by providing real-time data, predictions, and recommendations to help farmers adapt to changing climate conditions, reduce environmental impact, and enhance the sustainability and resilience of agricultural practices. Integrating AI technologies into the CSAPs through decision support tools using climate data and projections has the potential to enhance the climate resiliency of U.S. farmers by bridging the gap between research findings and practical implementation and promoting more sustainable and climate-resilient agricultural practices.

THEME 4. Climate-Informed Water Resource Management

Efficient utilization of water resources for agriculture necessitates coordinated actions at various levels, spanning from individual fields to community, watershed, catchment, and entire river basin scales. The primary aim is to optimize the beneficial utilization of both "green water," which refers to rainwater stored in the soil and used by plants, and "blue water," which denotes surface and groundwater sources. Recent assessments indicate that a significant portion of redirected water resources, estimated at approximately 90 percent, is currently allocated to agriculture, resulting in escalating competition with urban and industrial sectors for this precious resource. This allocation pertains to roughly 22 percent of cultivated land and plays a pivotal role in supplying about 40 percent of the world's food production.

Irrigation is predicted to expand over croplands as an adaptation strategy to climate change (Partridge et al., 2023). For this reason, the need for improved and integrated crop, livestock, soil, and water management practices is growing. In addition, continental U.S. rainfall distribution patterns are changing, with increasing intensity and frequency of extreme events becoming statistically detectable across the Midwest (Hess et al., 2020). Increased flooding and drought, especially late spring rains followed by late summer droughts and fall rains, disrupt planting and harvest.

Three exemplar insights were selected to demonstrate the types of collaborative science that are needed to advance climate-informed irrigation practices and water management strategies.

Insight 4.1 - Prioritize research on adaptive water management for climate-resilient agriculture.

Traditionally, farmers relied on ground-based methods for estimating crop water needs, but these methods struggle to provide localized data or adapt to specific field conditions (e.g., Ting et al., 2016). Satellite remote sensing has revolutionized this process by allowing us to map actual crop water usage and assess plant health across vast agricultural areas, greatly enhancing irrigation planning and water management. Recent advances in cloud computing, such as Google Earth Engine, and platforms such as OpenET (https://openetdata.org), have significantly improved the accessibility of satellite data for water managers and farmers. However, to ensure widespread adoption of these technologies, engaging stakeholders and establishing a unified framework for sharing information is crucial. Further, efforts to integrate satellite remote sensing and cloud computing are needed to provide accurate, real-time data that will support efficient irrigation planning and water management. Future science should prioritize the creation of a unified framework for disseminating satellite data to empower water managers and farmers, enabling adaptive and sustainable water resource management.

Insight 4.2 - Improve climate-resilient integrated watershed management through interdisciplinary approaches.

Understanding the impacts of climate change on surface hydrology, hydrologic modeling, bank stabilization, and water quality is an ongoing area of research (Fu et al., 2019). However, to achieve effective integrated water resource management at the watershed scale, a systems approach is needed. Such an approach should emphasize interdisciplinary collaboration and the comprehensive collection of data on various elements of water resource management, including water availability, assessment of water quality impairments, and determination of restoration requirements to ensure minimum flows and the preservation of water use designation. As the context of water resource management is increasingly shaped by the impacts of climate change, interdisciplinary collaboration and extensive data collection are vital not only to understand current conditions but also to adapt to the evolving challenges posed by climate change. Additionally, the advancement of nature-based solutions that enhance the sustainability of agricultural regions and ecosystem services is essential. Furthermore, exploring opportunities that bolster agricultural water security through practices such as soil health management, enhanced irrigation water-use efficiency, and improved surface water storage (Hatfield et al., 2019) is critical. These strategies are essential not only for safeguarding water resources but also for enhancing ecosystem and community resilience.

Insight 4.3 - Prioritize and foster collaborative research on Tribal water rights in the context of water demand, scarcity, and indigenous nation conflicts.

Assessing the implications of climate change on water resources and their impact on tribal water rights, with emphasis on the need for adaptive strategies, is essential. Developing equitable water allocation frameworks that respect indigenous rights, support sustainable water management, and improve communication regarding drought impacts will reduce conflicts and enhance resilient water systems. To achieve this, a comprehensive analysis of existing legal frameworks and historical agreements related to tribal water rights is necessary to provide a solid foundation for science and policy development (Young et al., 2019). Understanding the dynamics of increasing water demand, influenced by factors such as population growth, urbanization, and agricultural needs, is critical to assess how these pressures intersect with tribal water rights. Collaborative, well-resourced efforts involving researchers, policymakers, indigenous nations, and water authorities are central to crafting solutions at the complex intersection of tribal water rights, water demand, scarcity events, and conflict (Deol and Colby, 2018).

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THEME 5. Energy-Smart Agriculture and Technology Integration

Modern agriculture is an energy-intensive sector that accounts for approximately 10 percent of global energy consumption (IEA, 2020). Conventional agriculture utilizes fossil fuels for various purposes, such as producing fertilizers and pesticides and powering farming activities (e.g., plowing, harvesting, sowing, threshing, lighting, heating, cooling, and pumping water for irrigation). These practices that rely on fossil fuels are not sustainable in the long term. Non-fossil-fuel-based agriculture can be an important adaptation for meeting climate targets and increasing food system resilience. For example, new technologies allow electricity to be directly produced on farmlands. The integration of wind turbines on agricultural land has become common practice, with little effect on crop production and even offering a leasing income for the landowner.

Two exemplar insights were selected to demonstrate the types of energy-based science that are needed to make energy-smart technologies affordable and scalable and to understand their socioenvironmental impacts.

Insight 5.1 – Innovate toward wide-scale adoption of agrivoltaics as a means to provide farmer benefits and ecosystem services.

Agrivoltaics, the integration of photovoltaic (PV) panels with agricultural fields, offers a promising solution to address climate change challenges such as rising temperatures, extreme weather events (hail), water shortages, and greenhouse gas emissions (Barron-Gafford et al., 2019). This integrated approach contributes to sustainability by enhancing food production and energy generation simultaneously. However, its widespread adoption faces uncertainties related to compatibility with farming practices, acceptability among landowners and utilities, and long-term impacts on land productivity. Research is vital to understand the microclimatic effects of agrivoltaics on crops and to optimize agricultural productivity while generating clean energy. In water-limited agroecosystems, such as arid rangelands, well-designed PV arrays can reduce evapotranspiration, thereby conserving water (Kannenberg et al., 2023). Agrivoltaic science should prioritize scalable, holistic, and integrated design approaches that consider PV system layouts, crop selection, and livestock management practices (Sturchio and Knapp, 2023; Bardget, 2021; Ravi et al., 2016).

Insight 5.2 – Assess the co-benefits of biochar as a sustainable soil amendment for climate mitigation, soil health, and PFAS[1] mitigation.

Beyond its role in bioenergy, biochar, a byproduct of bioenergy production from forest and agricultural biomass, has gained significant attention due to its potential for remediating the impacts of climate change and environmental contamination (Lehmann et al., 2021, Joseph et al., 2021). Biochar can contribute to climate change mitigation by enhancing soil health, acting as a potent carbon sequestration tool, and remediating environmental pollution. Biochar application can enhance biodiversity by providing a conducive environment for various organisms, including earthworms and beneficial insects. Reforestation projects utilizing biochar-amended soils can aid in habitat restoration and contribute to overall ecosystem health. When thoughtfully integrated as a soil amendment within agricultural ecosystems, biochar not only improves soil quality but also sequesters carbon effectively, thereby mitigating the release of greenhouse gases into the atmosphere. Additionally, recent research highlights the ability of biochar to reduce the leaching of PFAS compounds, which are highly toxic and do not breakdown in the environment, from the soil. This emerging understanding underscores the potential of biochar not only as a climate change mitigation tool but also as a means of addressing environmental contaminants, further its potential (Lehmann et al., 2021; LePage et al., 2021; Chintala et al., 2020). The integration of biochar into agricultural and environmental management practices exemplifies a holistic approach to sustainability, addressing climate change, soil degradation, and pollution simultaneously. Continued research and practical implementation are essential to fully unlock the potential of biochar in mitigating climate change and fostering environmental resilience.

1 Per- and polyfluorinated substances

THEME 6. Strategic, Sustainable, and Regenerative Agricultural Practices

Current paradigms in production agriculture (e.g., conventional, organic, and regenerative production practices) tend to divide the agricultural science community and have only begun to receive the scientific attention they deserve. For example, a general lack of consensus exists on the coexistence of conventional and organic agricultural practices, as well as practices that include genetically modified crops and/or animals.

Regenerative sciences advocate a multifaceted approach, including diverse sustainable intensification methods such as agroforestry, perennialization, precision agriculture, and crop-livestock systems, tailored to specific agroecosystems and socioeconomic contexts. Integrating scientific knowledge with practical challenges, exploring a wide range of solutions (all the tools in the agricultural "toolbox"), and adopting holistic, agroecological approaches are fundamental steps toward achieving sustainable, regenerative agriculture.

Four exemplar insights were selected to demonstrate the types of multifaceted science that are needed to address the complexities of modern agriculture and foster the long-term health and vitality of agroecosystems.

Insight 6.1 - Identify and quantify the mechanisms and impacts of regenerative agricultural practices to inform evidence-based agricultural policies and practices that can support sustainable and resilient food systems.

The increasing need for sustainable land management strategies necessitates a thorough exploration of the intricate relationships among nature-based solutions, agronomic productivity, and resilience to environmental challenges (Pascual et al., 2017; Folke et al., 2016). Further, it is also critical to consider the socioeconomic and sociocultural implications, including access, equity, and justice. Understanding the potential synergies, trade-offs, and interactions among these elements is crucial for developing effective strategies that simultaneously address multiple environmental issues (Zabel et al., 2019; Díaz et al., 2015). Investigating the synergies and trade-offs among nature-based solutions, agronomic productivity, and resilience will contribute to sustainable land management strategies that address multiple environmental challenges simultaneously. Discoveries and creation of new cultural practices that improve one ecosystem service (e.g., carbon sequestration) should be studied in the context of being neutral, synergistic, or antagonistic with respect to other ecosystem services (e.g., biodiversity, water quality, nitrous oxide emissions).

Insight 6.2 - Advance nature-based solutions (NBS) that enhance sustainability in agricultural regions and ecosystem services toward mitigating the impacts of agriculture on water, soil, and climate.

Nature-based solutions (NBS) are strategies that utilize and mimic natural processes to address environmental challenges, build ecosystem resilience, and mitigate climate change (Bennett et al., 2019; Biggs et al., 2015). These solutions harness the inherent capacity of ecosystems to provide services (e.g., carbon sequestration, provisional services such as food production) and benefits for both human well-being and the environment (IPCC, 2020). NBS often involve local communities in their planning and implementation, fostering a sense of ownership and stewardship (Cohen-Shacham et al., 2016). NBS also offer economic benefits, such as sustainable livelihoods for communities, ecotourism opportunities, and enhanced agricultural productivity (Ives et al., 2018).

Science should focus on developing and implementing innovative practices that integrate agroecology and conservation approaches to promote soil health, water retention, and carbon sequestration (Lal, 2015; Kremen et al., 2012). NBS approaches generally limit the addition of fertilizers and chemicals that might lead to the increased emissions of greenhouse gases (e.g., nitrous oxide) (Gao and Cabrera-Serrenho, 2023). One partial solution is to develop more sustainable, closed-loop systems, where organic fertilizers (e.g., manure) from animal agriculture are applied to nearby crop fields (Kitamura et al., 2021). Investigation of the synergies between NBS, agronomic productivity, and resilience will contribute to sustainable land management strategies needed to address multiple environmental challenges simultaneously (Zabel et al., 2019; Díaz et al., 2015).

Insight 6.3 - Explore enhanced nutrient recovery from various wastewater sources.

Human waste contains valuable nitrogen (N) and phosphorus (P) resources that can support crop production (Dukes et al., 2020; Metson et al., 2016; Rose et al., 2015). While some of these nutrients can be captured in solid waste (Zhang and Lui, 2021; Robles et al., 2020; Harder et al., 2019), a significant portion remains unused in solution. If captured, these resources could boost plant growth and address food scarcity and climate resilience (Ryals et al., 2021). Yet regulatory and commercial motivations to pursue nutrient recovery from wastewater are currently lacking. Moreover, the absence of effective and efficient nutrient capture technologies from wastewater is a significant barrier that must be overcome to unlock the potential of wastewater nutrient recovery, offering solutions to both climate change and nutrient scarcity challenges.

Insight 6.4 - Promote equitable access to sustainable agricultural practices in the transition to regenerative farming.

Adapting agriculture to climate change holds significant implications for rural and nonfarm communities. Significant gaps persist in our understanding of the social and economic impacts of different agricultural pathways, such as conventional vs. agroecological production systems on farm households, workers, residents, and rural development. To ensure environmental justice, we must create strategies to ensure equitable distribution of the outcomes (Schlosberg and Collins, 2014), including fair access, participation, and prevention of harm to vulnerable populations. Additionally, policy development is essential to address the unique needs of agricultural and nonfarm communities (Dunlop and Rada, 2019), promoting resilience, sustainable livelihoods, and inclusive development. Centering research efforts on the people and communities that will be impacted is imperative to guide the creation of practical, user-friendly climate adaptation strategies tailored to local needs (Norman and Draper, 1986) and to foster innovation and local suitability.

Any approach to climate-adaptive agriculture must promote environmental justice and have policy relevance with a focus on potential impacts, risks, and vulnerabilities of people and communities. This multidisciplinary approach enhances rural community resilience while promoting equitable and sustainable agricultural systems.

THEME 7. Socioeconomic and Policy Research

Evidence-based policy is essential to overcome the lack of understanding between agricultural science and policy that is necessary to address impacts of climate change on food systems. In recent decades, domestic patterns of food production and consumption have become more interconnected with global markets for both food products and agricultural inputs. These new economics of food mean that small changes in production can lead to large fluctuations in price and access. Key factors related to global change drivers (one of them being climate change) are now understood to include regional declines in agricultural productivity, falling global stocks in grains, speculative trading, and establishment of trade barriers. In addition, increased purchasing power, shifting food preferences, access to global markets, and growing populations have led to significant shifts in consumption patterns in recent years that are anticipated to continue.

Three exemplar insights were selected to demonstrate the types of evidence-based science that are needed to address socioeconomic and policy issues in agriculture and natural resources management.

Insight 7.1 – Develop and evaluate models that integrate scientific insights into policy frameworks to enable informed decision-making for agricultural resilience, mitigation of negative impacts, and food security under changing climatic conditions.

Governments and companies are increasingly turning to improved land management in their portfolio of options to reduce carbon emissions and stem the impacts of climate change. Increased interest in these investments, however, is revealing significant challenges in quantifying their climate mitigation value. A primary challenge is the variable response of ecosystems to management interventions, which makes quantification highly uncertain. Current guidelines for carbon inventories also treat all carbon removals as equal, whereas carbon removals by natural ecosystems are inherently impermanent (Sierra et al., 2021). Codifying accurate GHG accounting protocols is crucial to ensure that climate mitigation and adaptation policies are based on reliable science and deliver durable outcomes.

Insight 7.2 – Integrate marginalized populations in the development of policies that address the barriers and drivers of the adoption of Climate-Smart Agricultural Practices among diverse communities.

Equity needs to be addressed in climate change policy and program development, considering the unequal impact of climate change in various communities. Williams (2021) stated that "there is no universal human experience of the climate emergency, but varying degrees of risk and responsibility." The impact of climate change (Williams, 2021), as well as the acceptance of global warming and the perceptions of the associated risks, is higher in communities of color (Ballew et al., 2021). Including communities of color in the decision-making process increases equitable representation to address the complexities, responsibilities, and vulnerabilities of climate change from their cultural and individual perspectives (Williams, 2021, Ballew et al., 2021). Climate change policies that are built with inclusive and equitable viewpoints will foster the new partnerships and science collaborations needed to explore the beliefs and risk perceptions of climate change on a greater and more inclusive scale.

Insight 7.3 – Engage indigenous peoples, with their deep experience as the original stewards of the land, to guide approaches to address climate change and ensure sustainable coexistence on a global scale.

As the original stewards of the land now called the United States, indigenous peoples have a rich history as custodians of local ecosystems rooted in Traditional Ecological Knowledge (TEK). In the face of pressing global challenges such as climate change, indigenous-led programs utilizing TEK have great value in creating ecological and community resilience. For example, indigenous researchers are increasingly leading programs in partnership with indigenous communities and non-indigenous researchers. Collaborations with indigenous researchers should involve jointly setting research goals and approaches and respecting data sovereignty, including the significance of oral traditions, ecological insights, and traditional practices in addressing climate challenges. By combining TEK with western scientific research, a more comprehensive understanding of climate impacts and adaptation can be gained (Whyte, 2018). This approach provides valuable insights, bolsters climate efforts, and helps foster trust among all involved. Integrating TEK into climate policies through partnerships with indigenous communities is essential to create more holistic and context-specific approaches. These partnerships must value the contributions of indigenous communities by ensuring the availability of adequate resources to carry-out joint research projects, including education and capacity building.

SUMMARY & CONCLUSION

This Horizon Scan for climate change science has identified and developed seven interconnected scientific themes that provide fresh insights for guiding future climate change research. By taking a comprehensive and inclusive approach that encompasses ecosystem and resource management, innovative technologies, and social justice, this Horizon Scan puts forward a compelling roadmap for how the research, extension, and education communities can contribute to mitigating the impacts of climate change while fostering productive working lands and sustainable food systems for all.

One of the significant themes focuses on regenerative agriculture, which enhances climate resilience through practices such as cover cropping, agroforestry, and soil carbon sequestration. These practices improve soil health and make agriculture more resilient to climate change, promoting sustainable food production. Additionally, the importance of nature-based climate solutions, which utilize natural ecosystems such as reforestation and wetland restoration to sequester carbon and combat climate change, is emphasized. Regenerative principles are integrated throughout, emphasizing the importance of resource efficiency in climate action. Science in this area also underscores the need to minimize waste, reuse resources, and transition to sustainable consumption patterns to reduce greenhouse gas emissions.

The Horizon Scan emphasizes the centrality of social justice and inclusion to finding solutions for climate resiliency. Historically marginalized communities possess valuable knowledge and experiences relevant to climate adaptation, and integrating their perspectives into science and policy design is essential to ensure equitable and innovative climate solutions.

The inclusion of technology as a theme underscores its role in achieving climate justice. Advancements in clean energy, climate modeling, and remote sensing provide essential tools for monitoring climate impacts and informing equitable policies.

The Horizon Scan also highlights the potential of community-led climate action, involving local communities in decision-making processes and empowering them to implement climate solutions. This approach fosters a sense of ownership, improves adoption, and enhances the effectiveness of climate initiatives. A crucial theme focused on climate adaptation tailored to vulnerable populations. Inclusive adaptation strategies that consider the unique needs and vulnerabilities of communities are essential for building resilience and ensuring climate justice.

In conclusion, just as life and diversity thrive at the edges of ecosystems, we must expand our intellectual ecosystems beyond disciplinary and campus boundaries. Higher education institutions need to engage with broader communities to bring about meaningful change. The challenge we face now is to translate the good intentions and ideas from this Horizon Scan into concrete actions. It is a pivotal moment for scientists, educators, practitioners, and all participants in this process. Future generations will judge us based on the actions we take to make a difference. We possess the ability to gain the knowledge and capability to drive change, so we must act expeditiously to address the pressing challenges of climate change.

The challenge we face now is to translate the good intentions and ideas from this Horizon Scan into concrete actions. It is a pivotal moment for scientists, educators, practitioners, and all participants in this process.

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GLOSSARY

ADAPTATION	Climate change adaptation is the process of adjusting to the actual or anticipated effects of climate change.
AGROFORESTRY	Agroforestry is a land management system in which trees and shrubs are intentionally integrated with crop and animal production to create environmental and social benefits.
BIOCHAR	The lightweight black residue, made of carbon and ashes, remaining after the pyrolysis of biomass that is a form of charcoal.
BIOPHYSICAL SYSTEMS	Environments that include biotic and abiotic components as well as physical, chemical, and biological factors. The characteristics and evolution of biophysical systems are influenced by processes or interactions between these different elements.
CLIMATE RESILIENCE	The capacity of social, economic, and ecosystems to maintain their function in the face of climate stresses and to adapt in anticipation of future hazardous events or trends imposed by climate change.
CLIMATE-SMART AGRICULTURAL PRACTICES	Climate-smart agricultural practices (CSAPs) are integrated approaches to managing land to help adapt agricultural methods, livestock, and crops to the effects of climate change while ensuring food security.
CLIMATE-SMART FORESTRY	Climate-Smart Forestry (CSF) is a collection of strategies and management actions that increase the carbon storage benefits from forests and the forest sector, support adaptation to climate change, and provide ecosystem services.
CROP MICROBIOMES	Crop microbiomes are the microbial ecosystems around crops that are composed of complex, multilateral interactions between microorganisms.
ECOSYSTEM SERVICES	Ecosystem services are the direct and indirect goods, services, processes, and conditions provided by nature that support human well-being.
ENVIRONMENTAL JUSTICE	Environmental justice is the fair treatment and involvement of all people involved in and impacted by environmental decision making. This includes equitable treatment and inclusion regardless of race, color, national origin, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies.
FOOD SECURITY	Food security is the physical and economic access to safe and nutritious food that meets dietary needs and supports a healthy lifestyle.

GREEN AND BLUE WATER	Blue water—freshwater bodies of water such as rivers, lakes, and reservoirs—comes from below surface aquifers and ice melts. Green water— freshwater found in plants and soil—is absorbed through plant roots and then released into the atmosphere.
INDIGENOUS TRADITIONAL ECOLOGICAL KNOWLEDGE (ITEK)	ITEK includes the observations, oral and written knowledge, practices, and beliefs about how to practice responsible stewardship of natural resources and ecosystems that are passed down generations. This knowledge draws from a long history of direct experiences with landscapes and continues to evolve as new insights are incorporated. ITEK is owned by Indigenous people.
MITIGATION	Climate change mitigation is the process of reducing sources that emit greenhouse gasses into the atmosphere or enhancing sinks that store greenhouse gasses.
NATURE-BASED SOLUTIONS	Nature-based Solutions integrate the management of natural processes and features to protect, manage, and restore ecosystems to promote biodiversity benefits, enhance climate resilience, and provide ecosystem services.
PRECISION AGRICULTURE	Precision agriculture is a management strategy that uses data and technology to support the efficiency, productivity, quality, profitability, and sustainability of agricultural production.
ROOT EXUDATION	Root exudation is the process by which plants release organic compounds into the soil around their roots to facilitate nutrient absorption, alter soil composition, and recruit beneficial microorganisms.
SYSTEMS-BASED/ SYSTEMS-THINKING	"Systems-based" or "systems-thinking" refers to a problem-solving approach or method of analysis that considers interactions and relationships between various components in a complex system. A systems-based approach bridges social and biophysical disciplines and facilitates a more holistic understanding of relevant challenges.
TRIBAL WATER RIGHTS	The legal and political rights of Tribes to access and use water and water resources. These rights acknowledge the historical, cultural, economic, and spiritual importance of water for Indigenous communities.
UNDERUTILIZED CROPS	Underutilized crops are wild, cultivated, or semi-domesticated crops that are not produced widely in mainstream agriculture and are under-studied in agricultural research. These neglected crops (e.g., quinoa, teff, and other Indigenous fruits or vegetables) possess valuable nutritional value, support soil health, and are resilient to harsh environmental conditions.
USER-CENTERED	User-centered describes strategies or design approaches that prioritize the needs and values of communities and relevant groups. A user-centered approach starts from a place of understanding the context and behaviors of the people involved and impacted.

APPENDIX A

Groups Formed to Support the Horizon Scan

Core Group Overview

The purpose of the Core Group was to support the planning and implementation of the Horizon Scan. The group included twenty (20) senior-level directors with expertise in climate change science related to agriculture and with deep knowledge and experience with cooperative extension programs. A list of Core Group members can be found in Appendix B. The objectives of the Core Group were to:

1. Confirm the Horizon Scan scope, goal, objectives, and plan of work.
2. Nominate approximately fifty (50) multi-disciplinary experts to form a National Climate Change Working Group (Working Group).
3. Provide advice to the Planning Group at key phases of the process.

The Core Group informed the planning process for the Horizon Scan by confirming objectives, timeline, and outcomes, as well as providing nominations and confirming participants to form the Working Group. Each member of the Core Group was asked to submit up to three nominations from their professional networks to populate the Working Group. They were encouraged to take into consideration diversity across gender, ethnicity, geographic location, area of expertise, seniority, and underrepresented groups and interests for their nominations. Nominations received were further mapped against their disciplines and expertise to form a representative Working Group.

During the implementation of the Horizon Scan, the Core Group was kept up to date with written status updates to stay informed of progress. In addition to advising the implementation of the Horizon Scan, the Core Group provided input and review during the drafting and finalization of the Horizon Scan Synthesis, the NCCR, and the Implementation Plan outline.

Working Group Overview

The Working Group actively participated in the Horizon Scan proceedings. Sixty-one (61) researchers from fifty-one (51) institutions—including academic institutions across the U.S., USDA Climate Hubs, and USDA Agricultural Research Service—were named to the Working Group. Working Group members represented a diversity of disciplines in the social and biophysical sciences, including but not limited soil science, hydrology, energy, land management, natural resources, forestry, economics, behavior change, and stakeholder engagement. A list of Working Group members can be found in Appendix C.

Nominated by the Core Group, members were evaluated based on their expertise and representation to produce a comprehensive body to inform the Horizon Scan. The Working Group participated iteratively in the Horizon Scan. Members produced initial insights, met in smaller discussion groups (called Expert Groups) to discuss the insights based on thematic areas, and provided feedback on the revised themes. A subset of the Working Group attended a workshop in Denver to distill the insights down further to identify the most important considerations to drive U.S. agriculture, forestry, and natural resources research into the coming decade.

APPENDIX B

Core Group Members

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APPENDIX C

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