White Paper

Human Adaptations to Climate Change: Impacts on the Resilience of Regional Food, Energy and Water Systems

prepared for

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Contents

1. Introduction 1
2. Summary of Workshop Results 2
4. Conclusions 7

Appendix 1: Workshop Participants
Appendix 2: Multidisciplinary Perspectives
1. Introduction

Context. The nexus among regional-scale food, energy, and water systems (FEWS) has gained increasing attention from both academics and policy-makers, especially in light of recent natural disasters that reveal hidden vulnerabilities in the infrastructures and resources supporting basic community needs. This white paper is based on a NSF-sponsored workshop held at The Ohio State University on November 4 and 5, 2015, involving over 50 prominent researchers from universities and government agencies. The workshop focused on the basic science and theory needed to further our understanding of regional FEWS, with an emphasis on the dynamic coupling among biophysical, economic, and social systems.

Problem Statement. The direct effects of climate change, including increased climate variability, extreme storm events, sea level rise in coastal areas, and increased drought in arid regions, will induce a range of indirect effects due to human adaptations, including potential migration from severely impacted areas (e.g., coastal and arid regions such as the Southwestern US) to less vulnerable areas (e.g., non-coastal and relatively water abundant areas such as the Midwestern US). These prospects suggest a range of stresses on regional FEWS and raise a number of unanswered questions. For example:

- How will population increase in receiving regions influence urbanization, lifestyles, and demand on FEWS?
- Efforts to mitigate greenhouse gas emissions will likely accelerate development of renewable energy sources, many of which are land intensive, although new technologies and resource conservation efforts may reduce land intensity. How will changing land use patterns alter regional allocations of land for energy and food production, and how will this alter the demand for and supply of water?
- Green infrastructure (GI) may be affordable and beneficial as a response to extreme weather events that increase storm runoff and threaten water quality. What is the optimal placement of GI across urban-rural landscapes and how does this impact food and energy production at different geographic scales?
- Threats to food security will likely drive increased emphasis on regional food systems, including both self-sufficiency and greater capacity for trade among regions. How will new scales of production and distribution change demands for energy, and preserve water supply?
- How will competition for land and other resources impact the vulnerability and adaptive capacity of communities, not just to climate change, but also to other environmental, economic and social shocks?

The goals of the workshop were to (i) consider the science that informs questions of climate change impacts, human adaptations, and implications for FEWS at regional scales, and on this basis, (ii) identify the current knowledge gaps, and (iii) develop a research agenda to be synthesized in this white paper.

The above problem statement is well aligned with the needs of numerous federal agencies that have identified both sustainability and resilience as crucial to the continued prosperity of the U.S. and its allies. The White House has issued a series of Executive Orders instructing federal agencies to address these issues, and ongoing research is being conducted by DHS, DOD, DOE, USDA, NOAA, NIST, and EPA.

Main Insight. The main insight that emerged from a series of intensive workshop discussions is that human adaptations to climate change both respond to and influence spatial and temporal mismatches in the demand and supply of food, energy and water resources across a range of scales, but particularly at regional scales. Thus, incorporating adaptive behavior at the individual and community levels into coupled human-natural system models is a critical research gap for understanding the resilience of regional FEWS.
and designing innovative FEWS solutions.\textsuperscript{1} The following sections highlight the research questions and gaps that emerged in three key areas of human adaptations—human migration, land use, and community adaptation—as well as the scientific and data challenges for integrated modeling and innovation.

2. Summary of Workshop Results

Human Migration. Migration is the ultimate human adaptation to changing environmental conditions, including climate change and natural disasters. Much attention has been paid to preparatory measures and technological improvements intended to mitigate the consequences of stresses and shocks and to improve community resilience for vulnerable regions, such as developing countries afflicted by poverty and resource scarcity, as well as coastal or drought-prone areas. However, there remain many open questions on the relationship between climate-induced migration and FEWS. Changes in climate-related variables, such as temperature, precipitation and sea level, will have both direct and indirect effects on migration patterns. Direct effects include, for example, the relocation of the population along gradients of human habitat quality, such as from flooded coastal or drought-stricken regions to non-coastal ones.\textsuperscript{2} Indirect effects relate to possible changes in individual preferences and risk perceptions, such as increased concern about regional climate vulnerability. Whether directly or indirectly induced, climate-related migration typically results in changes in the socio-economic distribution of residents and the industrial mix of businesses, coupled with increased competition for land due to continued urbanization and economic development. Besides climate effects, another potential migration factor in the U.S. is the influx of political refugees.

These human-induced changes will increase the stressors on regional FEWS, e.g., by increasing the competition for land to support food, fiber and energy production and exacerbating impacts on water availability and quality, all of which increase vulnerability to other environmental, economic and social shocks and impact the adaptive capacity of these regions. In extreme cases, migration could lead to unsustainable population growth, which in turn might lead to land and waterway mismanagement and food shortage crises. The uncertain effects of climate-induced migration are accentuated by the openness of regional economies, in which people, goods and services flow freely from one region to another; the complexity of these regions, which are subject to multiple levels and types of governance and other interactions across local, regional and global scales; and the importance of spatial heterogeneity, including spatial variations in intra-regional location choices, land use changes and ecological functioning. These aspects of regional FEWS and their potential impact on system structure, function and feedbacks have not been addressed sufficiently to develop strategies for managing risks and enhancing the resilience and adaptive capacity of regions that may be less directly vulnerable to climate change, but may experience indirect effects due to increased climate-induced in-migration. Some key questions and challenges related to these themes that emerged from the workshop are:

- What are the potential nonlinear dynamics and tipping points that may arise due to climate change and its impacts on migration?
- What types of migration patterns can we anticipate due to climate change (especially toward non-vulnerable regions such as the Midwestern U.S.)? How do these migration patterns differ among different groups of individuals (e.g. skilled vs. non-skilled, rich vs. poor, young vs. old)?

\textsuperscript{1} In fact, some participants suggested the acronym FEWSS to denote the nexus of food-energy-water-social systems
\textsuperscript{2} Ironically, over the last few decades, some vulnerable coastal areas in the U.S. have experienced population growth.
• How do we account for the long-run vs. short-run effects of climate change? No prediction or scenario for human migration can be developed without realistic forecasts of future changes in climate variables?

• How would the anticipated migration patterns affect the sustainability of FEWS in the receiving regions? What role can local institutions play in improving FEWS sustainability? Is there any lesson to be learned from experiences in international contexts? (e.g., the Netherlands response to coastal vulnerability?).

Currently there are several critical research gaps that arise in addressing these questions. First, currently available migration models are based on long-run equilibrium assumptions that can consider marginal changes, but ignore the potential for nonlinear dynamics and tipping points, and therefore are unable to consider how migration patterns may respond to abrupt climate-induced changes. Second, improved modeling of long-run migration patterns requires a better dialogue between different disciplines to study human migration in response to climate change. Collaborations between social scientists studying regional migration and climate change modelers are limited, in part due to disciplinary norms and a lack of publishing outlets for this type of interdisciplinary work.

Land Use and Natural Capital. Increased human migration to less vulnerable, e.g., non-coastal and water abundant, regions is likely to increase competition for land in these receiving regions. Coupled with greater variation in climatic conditions, especially rainfall, these effects have wide-ranging implications for efficient and resilient land use patterns. Rising urbanization pressures coupled with increased demands for renewable (e.g., bio-based) fuels, may impact regional food production and security and reduce ecosystem services, thus creating tradeoffs among water availability, food production, and renewable energy supply. Changes such as these will induce human adaptations in land practices and policies, which in turn will influence additional changes in land use and FEWS. Key research questions that emerge from consideration of these linkages include:

• What types and patterns of land uses and natural capital stocks may increase the resilience and adaptability of regional FEWS? For example, how do the spatial distribution, density, and capacity of a specific land use (e.g., agriculture or housing) influence the resilience of the land use system? Does spatial diversification increase or decrease the resilience of regional FEWS? How might land use changes impact the resilience of a household, community, or regional economy? Are there capacity constraints on changes in a specific land use system—crop, forest, wetland or urban—that can be absorbed while still providing critical services, including productivity, profitability, ecosystem integrity, and quality of life?

• What are the implications of sustainable agroecosystem management as a foundation to enhance the resilience and adaptive capacity of FEWS? Transformational waste management approaches will be needed to better couple systems and eliminate leaks in FEWS. How can we develop landscape level, system-wide tests of alternative agricultural systems that re-couple animal-plant nutrient cycling, preserve keystone species and establish biological communities that are adapted to climate variation, increase reliance on perennial plant systems, and match food production with nutrient requirements of local populations while creating surplus to meet needs elsewhere?

• What are the inter- and intra-regional spatial interactions of shifting human populations relative to food production and food sheds, water availability and watersheds, energy portfolios and energy sheds? Spatial heterogeneity in natural capital stocks and land uses imply spatial variations in the optimal provisioning of food, energy and water services both across and within regions. What factors influence the optimal mix and pattern of land uses and how does human migration influence this? How can well-established methods, such as life cycle analysis and ecosystem service valuation, be applied and adapted to account for the spatial and temporal dynamics at a systems level?
How can we integrate natural and urban landscapes in ways that maximize the benefits of capital investments and best complement their respective functions? Investing in natural capital, including land dedicated to providing ecosystem services through agroecological practices, renewable energy, and green infrastructure, may improve the resilience of regional FEWS to some aspects of climate change, e.g., increased precipitation. However, such investments may have unintended effects, such as increased competition for urban land and potential economic inequalities. What are the interdependencies and trade-offs of investing in natural capital across the urban-rural gradient?

How do changes in economic or environmental conditions influence regional FEWS? For example, how will global changes in water availability and intensity of water use (e.g., conservation) influence regional FEW demands? What are the spillovers across regions and from regional to global scales? What are the linkages among spatial distributions and use intensities of energy supply, water supply, and industrial activity? How are industry and population locations co-determined?

These questions imply several research gaps. First, downscaling in climate models from continental to regional scales is needed to provide better insight into the range of potential patterns of temperature and precipitation to which regional FEWS will have to adapt. Similarly, upscaling from local to regional and continental levels will be needed. Second, data are needed on land use, land cover, land ownership, and land management that are both nationally comprehensive and locally detailed. Currently data are limited to selected states or metro regions with incompatible time series and limited possibilities for integration across different data sources. Third, multiple innovations in modeling are needed, including cross temporal- and spatial-scale modeling of FEWS with empirically-based, holistic ecosystem models of multiple ecosystem services, interdependencies, human decision-making and feedbacks for thorough valuation of ecosystem inputs and services. These modeling challenges are addressed further in Section 3.

Community Adaptation. A number of factors influence the adaptive capacity and resilience of heterogeneous communities and have important implications for FEWS management. These include the adaptive capacity of existing governance systems, the diversity and flexibility of available FEWS infrastructures, and the carrying capacity of existing built and natural infrastructures. However, gauging community responses and adaptions to climate change will require a deeper understanding and investigation of the relationship between humans and institutions. More specifically, we need to understand the dimensionalities of humans and human groups as they affect capacities to respond, drive, and impact how institutions respond. The following key research questions were identified based on consideration of these community adaptations and feedback responses:

- What factors lead to institutional inertia (e.g., political, academic) and how do social organizations modify different forms of inertia?
- Under what conditions do large-scale social transformations occur, such as changes in household patterns of landscaping and irrigation? How can we integrate communities with experience in responding to environmental and climate perturbations into the research community?
- How does adaptive capacity vary across social groups (e.g., stratified by demographic characteristics such as income, age, ethnicity and race)? How do institutional support and responsiveness vary across these groups, including the influence of place and geographic history on social conditions? Does the degree of engagement by these groups in the institutional processes influence their adaptive capacity?
- What type of an analytical framework will be needed to capture system-wide unintended consequences of adaptation, including maladaptation? Under what conditions does adaptation yield positive or negative effects over time?
• What are the tipping points in both natural and human systems that could influence or trigger communities in gradual or abrupt ways, e.g., ecological changes that gradually alter access to natural capital or abrupt exceedance of carrying capacity due to displaced migrants? Can we measure how much change FEWS can absorb and retain their core functions of productivity, profitability and ecosystem integrity?

• How do local impacts of global processes influence the willingness of individuals and communities to take communal action? Both climate change and food systems have place-based manifestations and global influences. As people become aware of place, how willing are they to engage in collective action, create new commons, or act in ways that benefit the overall community?

• What is the role of cultural-value oriented markets in organizing individuals? One commonly-cited example is a “local foods system,” which offers a means of organizing individuals with various political affiliations to consider market alternatives in a non-confrontational manner. How do such cultural-value markets alter consumer behavior and create new voluntary and involuntary associations, as well as new attitudes? Do they shift individuals towards a more cooperative mindset, leading to increased consensus-building and creation of new economic opportunities?

Addressing these questions will be helpful in informing community preparedness, increasing sensitivity to potential tipping points, and advocating for integrated consideration of FEWS with public health and equitable job opportunities. A number of key research gaps need to be addressed in order to realize this research agenda. First and foremost is the need for data integration and harmonization based on forward-thinking, standardized protocols (akin to the Library of Congress). Second, changes in the competitive structures within academia are essential to overcome time and logistical barriers as well as disciplinary fragmentation. Win-win incentives are needed, and researchers should be encouraged to engage in similar or compatible research to enable integration across disciplines, data sharing, and standardization. NSF has an opportunity to invest in data integration systems and to support meta-analysis of database construction, oversight and accessibility. This will enable pursuit of long-term, integrated research among social scientists, yielding better data products to inform policy decisions. Finally, a critical research gap is the lack of modeling capabilities to integrate across disciplines, address scalar diversity and interactions (i.e., micro-, meso-, and macro-level scale), account for place-based considerations, and incorporate key dimensions of uncertainty, yet not be restricted by conventional modeling assumptions and simplifications. Research needs related to modeling are discussed further in the next section.

3. Research Needs for Integrated Modeling and Innovation

Integrated Assessment. Flexible FEWS technologies (e.g., reserve storage capacity) are needed so that society can adapt to challenges and take advantage of opportunities in the future. However, there are few existing tools available to guide and test adaptable infrastructure technologies in terms of their environmental, social, and economic impacts. Historical data analysis is necessary, but is increasingly inadequate for assessing the potential impacts of new technologies and projecting future impacts. Advancements in integrated modeling and simulation will address this challenge; for example, by anticipating the transition of power generation assets from natural gas to renewable energy, capital planners can optimize current designs to facilitate future retrofits in an affordable and sustainable manner.

To enable this type of integrated assessment, models are needed of coupled human and natural systems with endogenously determined technology choices. Such models typically involve coupling economic, engineering, biophysical, biogeochemical, and hydrological models. The workshop identified a number of specific research challenges that are commonly recognized in the modeling community, including:
• **Model integration.** Transitioning from a patchwork of models to a seamless linkage among multiple models that ensures consistency of underlying assumptions, incorporates feedback effects, and integrates across temporal and spatial scales to resolve questions of inter- and intra-regional dynamics.

• **Human behavior.** Incorporating social and behavioral dynamics (e.g., beliefs, values, learning at an individual level and barriers, enablers, and inertia at a community level) into coupled human-natural system models. A specific need is to develop empirically-based, holistic models of multiple ecosystem services, with inclusion of human decision-making and feedbacks, for thorough valuation of ecosystem inputs and services that contribute to FEWS.

• **Uncertainty and Variability.** Incorporating information about both the centers and tails of probability distributions around uncertain or variable parameters and functional relationships that are utilized in scenario modeling.

• **Nonlinearity.** Better understanding of the drivers and implications of potential nonlinear dynamics, including tipping points and large transformative changes in both environmental systems (e.g., climate, land cover) and human systems (e.g., migration, community responses), and the ability to anticipate and distinguish these from incremental changes or averages based on historical patterns. This is an important requisite for adaptive management.

• **Feedbacks.** Recognition of fast and slow interactions within and across natural and human systems of FEWS, including strong or weak feedbacks coupled with inertia. These feedbacks may be dampened due to the unresponsiveness of individuals or governments to environmental changes.

• **New equilibria.** Modeling the outcomes associated with new and evolving FEWS stresses and changing conditions. More structural and simulation-based models are needed to extend empirically-based models estimated with historical data.

• **Community participatory modeling.** Educated citizens and workers who can contribute their insights and values to plan, monitor, and adapt management practices and policies that balance many tradeoffs and seek social justice and equity.

• **Scenario development and forecasting.** Scenarios of plausible futures, e.g., increased extreme weather events, greater land competition, and accelerated human migration, to guide the development of comprehensive models that can project potential future changes. This requires participatory modeling to develop scenarios and careful empirical analysis to develop robust forecasts and quantification of the uncertainty of such forecasts. In particular, it is important to develop statistical and modeling approaches that can address non-perturbative (i.e., gradual) change, enabling incorporation of the projected impacts of climate change upon the resilience of FEWS infrastructures.

Critical data gaps will need to be addressed in order to meet these modeling challenges. As emphasized in previous sections, to enable integrated modeling of FEWS it is essential to have better integration across datasets. Additional data-related challenges include ensuring the privacy and security of shared datasets, determining which data collection activities are most cost-effective for FEWS research, and reducing the economic burdens of data collection.

**Technological innovation.** Enhancing the resilience of regional FEWS to the direct and indirect impacts of climate change requires technologies that are inherently flexible, adaptive, resilient, and sustainable over the long term. A clear consensus emerged during the workshop that the increasing capabilities of information science and sensing technologies are impacting food, energy, and water systems, and enabling new management, monitoring, and forecasting paradigms that were previously impossible. It is important to “bridge the gap” between researchers focused on technology development and those focused on applying these technologies in FEWS research. Given the dynamic nature of FEWS evolution, it is important that technology and sensor innovations be integrated rapidly into these systems.
Finally, the workshop discussions considered technological innovations and their distinct impacts on the food, energy, and water areas. The growing importance of precision agriculture for enhanced production and environmental sustainability was discussed, along with the need for continued management of biotechnologies and their implementation. New irrigation technologies and better systems for re-use of wastewater were highlighted, along with alternative cooling methods and continued improvements in solar energy technologies. Educational technologies were also discussed as cross-cutting to all FEWS themes. A significant challenge is communicating complex FEWS issues in ways that resonate with such varied audiences as K-12 students, other researchers, and the general public.

4. Conclusions

There is broad scientific consensus that climate change is occurring, and will have environmental, social, and economic impacts that vary across regions, resulting in both opportunities and challenges. Actions that we take now and in the future can both mitigate climate change by reducing GHG concentrations in the atmosphere and prepare FEWS to adapt to impacts that are already evident. Synergistic systems can be developed that will minimize or avoid troublesome tradeoffs such as those between agriculture and water use or between food and energy production. But at community and regional levels, the many tradeoffs inherent in maintaining equitable and consistent supplies defies an optimal solution for all for all people and interests, and the continuous process of adaptive management may be more likely to lead to resilient FEWS. This will require a better understanding of the dynamic linkages among food, energy and water systems and the critical role that human adaptations play in the dynamics and interdependences of these systems across temporal, spatial and institutional scales.

**Intellectual merit.** The Ohio State workshop has contributed to a growing body of knowledge about the types of human adaptations that are critical to understanding how coupled human-natural systems are likely to respond to climate change and the implications for regional FEWS—and in particular, those in less vulnerable regions that may experience greater in-migration and land competition. Due to the interdependence among food, water, energy, land, and ecosystem services, an interdisciplinary approach is essential for understanding the dynamic coupling among biophysical systems, economic systems, and social and behavioral systems. Key research areas to be explored include inter- and intraregional household and firm migration decisions in the face of climate change; the role of built and natural capital in preserving and harnessing ecosystem services; the roles for technology and innovation as well as social and cultural aspects in influencing community responsiveness and resilience; and modeling challenges for regional FEWS sustainability and resilience assessment.

**Broader impacts.** The research priorities identified in this white paper will address the needs of society in the face of unprecedented changes in regional climatic conditions, as well as rapid technological and social change. In particular, the development of improved scientific knowledge will help all levels of government to anticipate, prepare for, and respond to the direct and indirect consequences of climate change, including both gradually increasing stresses, sudden shocks and new system structure and function. The suggested research initiatives will support decision makers in gathering high-value information, exploring potential future scenarios, developing capital investment plans, ensuring adaptive capacity, planning for disruptions, and practicing adaptive management of regional FEWS. In addition, these research priorities provide guidance for educational priorities in the development of a 21st-century workforce with the requisite disciplinary knowledge and the capacity to work effectively in interdisciplinary teams on the design and management of FEWS. Finally, credible research results will facilitate knowledge transfer and dialogue about effective governance of FEWS among public and private sector stakeholder groups.
Acknowledgments: The primary writing team for this white paper consisted of Elena Irwin, Casey Hoy, Alessandra Faggian, Jay Martin, Joseph Fiksel, Joe Campbell, Richard Moore, and Joel Johnson. Helpful feedback and suggested edits were provided by Jeff Bielicki, Hans Herren, Andy Miller, and Rae Zimmerman.
Appendix 1: Workshop Participants

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<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
<th>Areas of Research</th>
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<td>Arizona State</td>
<td>Coupled human-natural systems and resilience modeling</td>
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<tr>
<td>Amy Ando</td>
<td>U. of Illinois</td>
<td>Natural resource and environmental economics</td>
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<tr>
<td>Bhavik Bakshi</td>
<td>Ohio State</td>
<td>Ecosystem services modeling, life cycle assessment</td>
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<td>Ed Barbier</td>
<td>U. of Wyoming</td>
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<td>Budhendra Bhaduri</td>
<td>Oak Ridge</td>
<td>Geographic information science and technology</td>
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<td>Jeffrey Bielicki</td>
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<td>Energy and environmental systems and policy</td>
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<td>Michael Bowers</td>
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<td>Jill Clark</td>
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<td>Food systems and community adaptations</td>
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<td>Maria Conroy</td>
<td>Ohio State</td>
<td>Urban planning and sustainability</td>
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<td>Peter Craigmile</td>
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<td>Statistical models for complex environmental processes</td>
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<td>Cornelia Flora</td>
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<td>Community capitals, climate change adaptation</td>
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<tr>
<td>Alessandra Faggian*</td>
<td>Ohio State</td>
<td>Regional migration</td>
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<td>Amenities and regional migration</td>
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<td>Dynamic ecological-economic modeling</td>
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<td>Hans Herren+</td>
<td>Millennium Institute</td>
<td>International food security</td>
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<td>Clare Hinrichs</td>
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<td>Sociology of alternative food and energy systems</td>
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<td>Casey Hoy*</td>
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<td>Agroecosystem management and food security</td>
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<td>Elena Irwin (P.I.)*</td>
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<td>Doug Jackson-Smith</td>
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<td>Sociology of water sustainability</td>
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<td>Joel Johnson</td>
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<td>Remote sensing technologies</td>
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<td>Jasmeet Judge</td>
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<td>Madhu Khanna</td>
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<td>Doug Lipton</td>
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<td>Adaptation to climate change</td>
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<td>Sidharth Misra</td>
<td>NASA JPL</td>
<td>Sensor technologies for earth science observations</td>
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<td>Erwan Monier</td>
<td>MIT</td>
<td>Sources of uncertainty in regional climate projections</td>
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<td>Richard Moore</td>
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<td>Rural anthropology and environmental science</td>
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<td>Rae Zimmerman+</td>
<td>New York University</td>
<td>Resilience of urban infrastructure services</td>
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**Lead Facilitator:** Andy Burnett, Knowinnovation

**Facilitation team:** Donnalyn Roxey, Joseph Campbell, Amanda Davey

*Principal Investigator team members.*

+Invited speakers who sparked discussion.
Appendix 2: Multidisciplinary Perspectives

The following summarizes the suggested research topics that emerged from intensive breakout session discussions over the course of the two-day workshop.

FEWS data management

- Gather data on extreme conditions (rather than average) due to variability and impacts on human behavior (e.g., effect of extreme temperatures or storms on location choice/migration)
- Obtain primary data on local government policy responses to environmental issues
- Obtain privately owned datasets for public use (e.g., from farmers and corporations)
- Integrate and cross-calibrate data from multiple sources (sensors, satellites, surveys, census)
- Develop integrated data systems to support cross-disciplinary research; e.g., national land use database (with metadata) including detailed parcel level land use and land/property values
- Develop measurable indicators for key characteristics, e.g., social justice, food security, water quality, adaptive capacity, behavior change
- Develop pervasive and scalable data collection methods to validate physical and social models, and to provide real-time FEWS monitoring.
- Facilitate and encourage data utilization and sharing; address challenges of privacy, security, differing scales, cross-calibration, regulation
- Determine appropriate data quality and resolution needed for investigation of different types of FEWS strategies.
- Inventory, reorganization, and harmonization of previously connected data, with techniques for downscaling (global to local)
- Mine historical data to discern patterns that indicate potential tipping points.

FEWS modeling and analytics

- Integrated assessment of implications of climate-induced migration patterns on receiving regions, e.g., infrastructure pressures, economic output, and increased resilience
- Improved statistical modeling techniques to account for extremes (i.e., “tails”) in future climate disruption scenarios, rather than focusing on means of the distribution.
- Improved structural modelling of long-term behavioral and economic patterns to identify causal implications of climate change.
- Calculation of “true cost” of food, energy, and water resources as climate and economic conditions change.
- Estimation of time frames over which resources will become scarce and resulting impacts on human adaptation/mitigation efforts.
- Investigate appropriate scale and complexity of Integrated Assessment Models for analyzing climate adaptation strategies, accounting for cultural and place-based factors.
- Interaction of mobility with FEWS infrastructures (e.g., electric vehicles require centralized energy systems; biofuels are more spatially diffuse but have stronger coupling with food systems).
- Investigate role of ecosystem services within an agricultural framework, including interactions between soil and water, to help correct nutrient imbalance.
- Incorporate human values and ecosystem benefits into valuation of ecosystem services, and connect these to ecosystem functions that may not be evident (e.g., soil formation).
- Extend ecosystem models to include agent-based models of human decision-making and corresponding feedback loops.
- Analyze value of system resilience, including potential gain or loss in value when the system shifts to a different equilibrium.
- Combine generalized equilibrium modeling, biophysical life cycle modeling, and agent-based behavioral modeling at a regional scale.
• Develop integrated models for coupled human-natural systems that incorporate feedback across different spatial and temporal scales.
• Improve modeling to effectively characterize and include uncertainty, including tails of distributions and “informative missingness” (e.g., known unknowns)
• Extend decision science to account for social and cultural factors.
• Identify leading indicators that signal proximity to a tipping point; extend existing models to capture tipping points.
• Develop comprehensive models of economic, sociological, environmental factors; create stylized models that incorporate important factors.
• Enable community participatory modeling.

Case studies of human adaptation to climate change
• Hurricane Katrina (sudden major disaster and economic shock) as an example of differential effects on different income groups
• Interregional differences (e.g., Midwest vs. South) in adaptive response to changing agricultural patterns and decline in agricultural labor.
• Persistence of land development in coastal areas (e.g., Florida) or drought areas (e.g., Arizona) despite increased risks of extreme weather (effects of local policies and insurance markets).
• International analogues to U.S. in terms of adaptation strategies (e.g., Netherlands investments in coping with rising sea level)
• Adaptation of wealthy nations to refugee migration in Africa/Middle East in response to cumulative changes—climate disruptions combined with sociopolitical factors.
• Drivers and impacts of seasonal or cyclical migration (e.g., winter in Florida) and responses of communities and infrastructure

Economic and behavioral research
• Improved projection of population and demographic trends at a regional level
• Factors that influence human adaptation and migration patterns in response to climate change (e.g., income inequality, age, income, diet, government incentives)
• Factors that influence businesses relocation in response to climate change (e.g., population trends, workforce availability, future technologies, government policies)
• Investigation of thresholds for changes in human migration patterns under alternative climate scenarios
• Analysis of changes in risk perception following dramatic climate events.
• Adaptation of food production, transport and storage methods to climate change, energy conservation, and increased global demand (e.g., local vs. centralized production)
• Anticipated changes in agricultural practices, including water management, pest management, nutrient management, crop varieties and schedules, intensification vs. extensification of land.
• Relationships between land use, water use, and energy, e.g., increased bioenergy production implies competition for land with other uses, increased nutrient pollution, increased water withdrawals for irrigation, etc.
• Effects of inertia on ability of FEWS to adapt—local political systems, special interests, planning processes, land regulation, infrastructure management
• Patterns of community investment after catastrophic events—short-term responses vs. consideration of longer-term vulnerabilities
• Defining, measuring, evaluating resilience at individual household, neighborhood and community scales; connecting FEWS resilience with household, community, economy resilience, e.g., how does a loss of resilience in food, energy or water impact resilience of household, community, economy?
• Human adaptations in terms of agricultural and urban land use changes in response to the direst effects of climate change (e.g., changes in physical geography) and indirect effects (e.g., human migration)
• Intensified land and water competition as a result of adaptations to climate change, e.g., greater demand for land for green infrastructure to manage flooding and storm water runoff;
• Agricultural and industrial shifts as key drivers and responses to changes in FEWS at inter-regional (multi-state) level, e.g., impacts of changes in water availability and energy production on the spatial distribution of agricultural production and industry mix.
• Integration of models of household location choice with models of agricultural land demand; models of coupled geo-physical/infrastructure systems (i.e. storm-water management)

Ecological systems research
• Spatial analysis of shifting human populations, food production and food sheds, water availability and watersheds, energy portfolios and energy sheds (spatially varying system level lifecycle analysis).
• From farm to fork: Integrated lifecycle and ecosystem modeling approach to consider implications of changing climate for soil-water-vegetation-market-social interactions.
• Transition to sustainable agroecosystem management with a natural capital foundation to enhance resilience and adaptive capacity.
• Sustainable agriculture and adaptive capacity of regions: How much change can specific cropping systems absorb and still retain core functions: productivity, profitability, ecosystem integrity.
• Ecosystem services, agroecology, renewable energy, and green infrastructure as organizing principles for FEWS.
• Transformational waste management systems to better couple food, water, energy systems.
• Increased prevalence of perennial plants in agricultural landscapes.
• Landscape level system-wide tests of alternative agricultural systems that re-couple animal-plant nutrient cycling, support biological communities that are adapted to climate variation, and match nutritional components of production with nutrient requirements of the human population on the landscape and create surplus where feasible to meet needs elsewhere.
• Implications of changes in resilience at different scales for land use change and vice versa, implications of changes in land for resilience, e.g., impacts of spatial diversification of food production (i.e., growing food in more places) or specific patterns of urbanization on resilience of a neighborhood, community, or economy.

Educational & academic research
• Development of trained integrators, rather than specialists, to take macroscopic perspective on FEWS issues and practice team science
• Mechanisms to develop academic incentives for cross-disciplinary research collaboration, standardized protocols, and data sharing.
• Support local capacity building and transformation of community planning practices toward acceptance of uncertainty, systems thinking, integrated planning, and recognition of long-term implications for human health and well-being.
• Promotion of more holistic systems thinking in primary education, including understanding of the role of ecosystems in human sustainability and resilience.
• Education of scientific community about constraints and needs of policy makers, farmers, businesses, utility operators, etc.
• Support communication and improved risk perception for future vulnerabilities (where probabilities are hard to quantify)

Policy & institutional research
• Changes in local and national policy development (e.g., decentralized authority, longer planning horizons) in response to repeated shocks.
• Projection of future policy changes under alternative climate scenarios, e.g., cap and trade, full-cost pricing of water resources
• Emerging adaptive government policies, e.g., anti-immigration laws, investment in sea walls, subsidies, support of private substitution for public goods, tolerance of social inequities.
• Implications of migration on infrastructure, housing, and land use policies (e.g., increased urbanization vs. increased sprawl or re-ruralization)

• Investigation of causal links between environmental changes, policy changes, and adaptive behavior, including interaction of land use, food, and energy policies.

• Implications of climate policy for land-use (settlement patterns) at intra-regional scales; changes in policies as adaptations to climate change, e.g., greater regulation of development in flood zones, building code changes; unintended consequences of policies that may make communities less resilience, e.g., insurance makes it more likely that people will rebuild in flood zone.

• Approaches for integration of regulatory structures and policies (drinking water, stormwater, zoning, waste management, etc.)

• Harmonize land-use policy and agricultural policy with ecological constraints and goals, while balancing human and FEWS needs at multiple scales.

• Investigate forces that cause institutional change mediated by social organization, collective action, institutional culture, leading to typology of community adaptation.

• Investigate psychological motivations and cognitive biases that influence financial and policy decisions in local communities.

• Agile, adaptive governance models for managing FEWS in response to climate change (e.g., hard vs. soft policies).

• Support government decision-making processes that consider long term implications due to climate change (e.g., design bridges to accommodate increased water flow).

• Potential for social transformations toward inclusive/integrated governance systems, and impact on decision-making capacity and FEWS outcomes.

Technological innovation

• Reduce energy intensity and fossil fuel consumption in agricultural supply chains.

• Develop alternative sources of fertilizer to reduce fossil fuel dependency and water pollution.

• Improve renewable energy technologies to broaden geographic range of effective utilization.

• Implement principle of “circular economy” to utilize wastes as resources.

• Modify water distribution systems to enable grey water reuse.

• Develop distributed technologies that increase resilience/robustness of FEWS.

• Design flexible, adaptive FEWS infrastructures to preserve range of future options and enable dynamic balancing between rural and urban requirements.

• Develop methods for purposeful management and protection of ecosystem services in the face of climate and other stressors.

• Alternatives to human migration—movement of resources and means of production to community locations

• Investigation of appropriate scale and conditions for implementation of Green Infrastructure as a complement to grey infrastructure, including assessment of resilience improvement.

• Social costs and practical implications of large-scale transition to renewable energy sources, including supply chain issues and placement of facilities.

• Communication and coordination technologies and participatory structures that reduce the need for centralized governance.

• Develop FEWS technologies that embrace ecosystem compatibility, sustainability, and resilience, and can be adapted for local and natural design.

• Robust, low-cost sensing technologies for rapid monitoring of dynamics and extreme conditions.