NSF FEW Workshop White Paper- Addressing the Food-Energy-Water System Trilemma: Balancing Reliance on Technological and Institutional Solutions

Padowski, J.C.[1,2]; Adam, J.C.[2,3]; Hampton, S.E.[1,4]; Kruger, C.[5]; Yoder, J.[2,6]; Bandaragoda, C.[7]; Barber, M.[8]; Beveridge, C.F.[7]; Boll, J.[3]; Boyd[9], A.; Cai, X.M.[10]; Cameron, T.[11]; Carrera, L.[12]; Carpenter-Boggs, L.[13]; Chowdhury, I.[3]; Cristea, N.C.[7]; Dickerson-Lange, S.E.[7]; Dinicola, R.[14]; Elmer, V.[15]; Flores, A.N.[16]; Horner-Devine, A.R.[7]; Huggins, D[17].; Hurd, B.H.[18]; Istanbulluoglu, E.[7]; Katz, S[4].; Kraucunas, I.[19]; Mao, X.[7]; Mieno, T.[20]; Milman, A.[21]; Perrone, D.[22,23]; Rajagopalan, K.[3,5]; Richey, A.S.[3]; Roberts, M.[24]; Smith, D.R.[25]; Wu. J.[26]

Introduction

Population growth, human development, climate change, and global economic interdependence have all played a significant role in altering the form and function of modern food, energy and water systems (Khan and Hanjra, 2009; Steffen *et al.*, 2015). In changing how resources are acquired and used, all three sectors have become tightly coupled and interdependent for continued productivity (Perrone and Hornberger, 2014). For instance, in many areas management for agricultural priorities through large-scale, mechanized farming has significantly increased agricultural yields but requires substantially higher water and energy inputs to grow, harvest, process and distribute food (Hoff, 2011). In other regions, increasing water demands have intensified competition between sectors needing water for hydropower, irrigation and in-stream flow requirements for maintaining healthy fish and shellfish populations (Feldman, 2008; Kareiva *et al*., 2000).

Author Affiliations

[1] *Center for Environmental Research, Education and Outreach, Washington State University, Pullman, WA, 99164, USA*
[2] *State of Washington Water Research Center, Washington State University, Pullman, WA, 99164, USA*
[3] *Department of Civil and Environmental Engineering, Washington State University, Pullman, WA, 99164, USA*
[4] *School of the Environment, Washington State University, Pullman, WA, 99164, USA*
[5] *Center for Sustaining Agriculture and Natural Resources, Washington State University, Mount Vernon, WA, 98273, USA*
[6] *School of Economic Sciences, Washington State University, Pullman, WA, 99164, USA*
[7] *Department of Civil and Environmental Engineering, University of Washington, Seattle, WA 98195, USA*
[8] *Civil and Environmental Engineering, University of Utah, Salt Lake City, UT 84112*
[9] *The Edward R. Murrow College of Communication, Washington State University, Pullman, WA, 99164,*
[10] *Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA*
[11] *Department of Economics, University of Oregon, Eugene, OR 97403, USA*
[12] *Fondazione Eni Enrico Mattei, Isola di S. Giorgio Maggiore 8, 30124 Venice, Italy*
[13] *Crop and Soil Sciences, Washington State University, Pullman, WA 99164, USA*
[14] *Washington Water Science Center, United States Geological Survey, Tacoma, WA 98402, USA*
[15] *Department of Planning, Public Policy and Management, University of Oregon, Eugene, OR 97403, USA*
[16] *Department of Geosciences, Boise State University, Boise, ID 83725, USA*
[17] *USDA Agricultural Research Service, Pullman, WA 99164, USA*
[18] *Department of Agricultural Economics, New Mexico State University, Las Cruces, New Mexico, 88003, USA*
[19] *Pacific Northwest National Laboratory, Richland, WA 99352, USA*
[20] *Agricultural Economics, University of Nebraska Lincoln, Lincoln, NE, 68588, USA*
[21] *Department of Environmental Conservation, University of Massachusetts, Amherst, MA 01003, USA*
[22] *Civil and Environmental Engineering, Stanford University, Stanford, CA, 94305, USA*
[23] *Water in the West, Stanford University, Stanford, CA, 94305, USA*
[24] *Department of Economics, University of Hawaii at Manoa, Honolulu, HI 98622, USA*
[25] *USDA-ARS, Grassland, Soil and Water Research Unit, Temple, TX 76502, USA*
[26] *Department of Applied Economics, Oregon State University, Corvallis, OR 97331, USA*

As concerns over food, energy and water security grow, it has become increasingly apparent that the complex biophysical, economic, and social interactions that shape food-energy-water (FEW) systems will require coordinated and integrated management if future human and environmental demands for resources are to be met. Currently, a poor understanding of the biophysical feedbacks (Bazilian *et al.*, 2011; Lawford *et al.*, 2013; Villarroel Walker *et al.*, 2012) and institutional disconnects between and within FEW sectors (Lele *et al.*, 2013; Stein, 2013) means there is no clear strategy for dealing with the emerging externalities or increasing complexity of the integrated FEW nexus (Hoff, 2011; Liu *et al.*, 2015). Effectively addressing these profound and problematic transformations at the FEW nexus remains a major challenge (Adnan, 2013; Hoff, 2011). Therefore, as research on FEW nexus issues expands, it is crucial that the role and impact of human management be thoroughly understood in relation to the cultural, economic, political and environmental security of the whole FEW system.

Looking Ahead- FEW Nexus Challenges and Opportunities

In addressing the FEW nexus challenge it is imperative that future research and development no longer focus only on solitary sectors, but explicitly confront the broad array of problematic nexus interdependencies across the multiple sectors and scales of the FEW system. Implicit within this challenge is determining an appropriate balance between technological (e.g. products or processes) and institutional (e.g. legal or policy-based) approaches for improving the efficiency and productivity of food, energy and water systems. Recognizing how these two approaches complement, substitute for, or conflict with each other within and between sectors will play a key role in determining appropriate strategies to manage trade-offs and resolve resource conflicts. Until then, resource managers, policy makers, consumers and researchers will continue to struggle to keep up with the changing conditions and availability of resources while navigating the various technologies and institutional structures controlling resource access and use across multiple user and management groups (Lele *et al.*, 2013; Liu *et al.*, 2015; Stein, 2013).

Given the breadth of the FEW nexus challenge, it is expected that scientific opportunities to advance and support sustainable FEW management will be ample and varied. However, central to all future FEW research will be the need for a greater understanding of those factors driving both technological and institutional innovations and their adoption within and across FEW sectors. To accomplish this, more information must be generated in the form of increased monitoring and sampling, improved scientific models, and through better methods for interdisciplinary data analysis. In turn, this information could support the development of a new roadmap for successful collaborations between researchers, managers and stakeholders within the cultural, socio-economic and biophysical domains of the FEW nexus so that this scientific evidence can be used to advance productive technological developments and support clearly articulated laws and policies that institutionalize fair and sustainable use of resources.

Given these FEW system challenges and opportunities, the following cross-cutting areas have been identified as fundamental for framing productive, integrative and insightful FEW solutions: 1) defining the FEW nexus; 2) coordinating across sectors and scales; 3) facilitating data intensive research, and 4) understanding resilience in FEW systems.

1) Defining the FEW Nexus

A poor or narrow understanding of the critical linkages between the FEW sectors can lead to inaccurate and imprecise science and modeling outcomes, counter-productive technological developments and ineffective policies. Therefore, new research on the FEW nexus will require a better overall understanding of FEW interdependencies, both in terms of the way nexus research is pursued, and in the vocabulary, metrics and indicators used to describe, assess and discuss these critical links between science, technology and governance in FEW systems.

FEW research should focus on the interdependencies between FEW sectors. Historically, both management and research have focused on dynamics and solutions within a sector. Given the tightly coupled nature of the FEW system, it is clear that improved efficiencies and processes within one sector inevitably alter the productivity of one or more other sectors. For example, improved water efficiency in a crop is an important innovation in itself, but it does not necessarily result in more water availability for other water users, depending on both the relevant hydrology and the water governance structure (Simons *et al.*, 2015). It is therefore important that research explicitly consider how new scientific information can be produced and used to inform technological or institutional solutions that span nexus interdependencies and improve the overall sustainability of FEW systems. To facilitate this change, funding agencies will need to provide clear guidance on how to address nexus issues by framing calls for new research proposals around issues of FEW system interdependencies and externalities, rather than sectoral issues, and research institutions will need to smooth the path so collaborative, interdisciplinary research is easier to execute.

An interdisciplinary conceptual framework of the FEW nexus is needed to provide a common language and facilitate communication between systems. A refined conceptual model is needed to better reflect how environmental needs and human decisions impact the availability, flow and quality of FEW resources. Key to this conceptual framework will be clearly identifying and mapping both the important biophysical processes and the way in which information and signals are being transmitted, detected, translated, and responded to by actors within the FEW system. Such a conceptual model will require thoroughly integrating information across multiple science disciplines- including those not traditionally included in FEW research (e.g. political ecology, anthropology)- to create a standard, interdisciplinary vocabulary for describing and discussing different technology and policy solutions for meeting common goals and objectives within an integrated FEW system. Such a model will also provide a strategic roadmap into the nexus for many researchers whose training lies primarily within one sector.

Specific indicators and metrics need to be defined to describe the interconnections between FEW sectors*.* To analyze the FEW system, knowledge gaps and data needs must be addressed at the boundaries of water-energy, water-food, and energy-food. Standardized, quantifiable indicators, such as those listed below, could serve as useful tools for describing sectoral inter-relationships.

- Whole FEW System: Relative prices among FEW goods and services are important to characterize the economic tradeoffs for the production and consumption of FEW resources, and are critical links between each sector through markets.

- Water for Food: Water productivity and water accounting methods to measure the efficiency of water use, either as nutrients or profit per unit of water use (Molden, 2007).
- Food for Water: Virtual water flow via food trade for assessing and mitigating regional water stress (Chapagain and Hoekstra, 2008)
- Water for Energy: Water withdrawals or consumption per unit of energy for describing water intensity for energy production (e.g., a thermal or nuclear power plant, a hydropower plant, or from biofuel and natural gas sources).
- Energy for Water: Energy required per unit of water used (e.g. desalination, water delivery, treatment, and withdrawal) to represent energy efficiency in the water sector (Hoff, 2011).
- Energy for Food: Energy use accounting for direct (e.g. food production, storage, shipment and cooking) and indirect requirements of food production (e.g. producing and delivering agricultural materials/facilities such as fertilizer, pesticides or machinery.
- Food for Energy: Indicated by bioenergy feedstock, especially the so-called "1st generation" of bioenergy crops such as corn, soybean and sugar cane, which are also food crops.

2) Coordinating Across Sectors and Scales

The FEW nexus is multi-dimensional, integrating a wide array of actors, institutions, geographies, scales, timeframes and disciplines. In a world where technologies and institutions can present both conduits and barriers for transformation and improved system governance, clear strategies for integrating science across bottom-up and top-down management are needed to bridge existing gaps between scales and sectors to ensure that technological innovation occurs in concert with institutional and social change.

Better coordination and integration of scientific knowledge and data at the boundaries of overlapping FEW sectors is needed. Improved knowledge and models of how information is processed, shared and used across FEW systems will be needed to identify the key players within and across systems, where and how information is being exchanged, and who the important boundary-spanning agents are. Such models would be powerful instruments for identifying "friction spots" along these boundaries where opportunities for improved, coupled, technological and institutional development can occur, and where facilitating enhanced coordination and cooperation among institutions and the scientific community may be valuable. Shared communication strategies that facilitate public engagement and education about the "friction spots" are critical to deescalate emerging conflicts and build consensus.

Efforts to better incorporate adaptive strategies into FEW management are needed. Current FEW management frameworks would benefit from integrating key concepts of adaptive management- ongoing monitoring, modeling, experimentation and assessment- into existing strategies and policies. To facilitate such integration, FEW research should produce and share data and models that clearly capture changes in the state of the system at timescales aligned with regulation, impact assessment, and planning. Information collected on these system changes should incorporate and reflect not only an updated, collective scientific understanding of FEW systems but those technological advances, institutional mandates and social expectations generated by those embedded within the FEW system.

Research must aim to empower individuals and institutions to engage as full partners in managing FEW resources and play an active role in addressing FEW challenges. Leadership plays a key role in helping to remove barriers to new technological and institutional solutions in the FEW system. Markets emerge and adapt to changes in resource availability and technology, but operate within institutional contexts. Markets are usually imperfect, especially in relation to many environmental goods and services, but information, technology, and innovative institutional design can improve market effectiveness and facilitate effective resource allocation among competing uses. Other incentives and creative metrics that support decision-making, increase community learning and facilitate collective impact will also be needed to ensure that early and continued engagement in management occurs at the individual, regional and national level. Information and decisions tools that democratize and crowd-source innovation would help build researcher-stakeholder trust, and ensure solutions are relevant to the area in which they're being applied.

3) Facilitating Data-Intensive Research

Recent improvements in technological and computing capabilities have allowed researchers to collect or generate massive volumes of data that could be used to help better understand and manage FEW connections. However, significant and fundamental institutional and technological advances are needed to productively harness these data to advance fundamental understanding of FEW systems and improve decision-making.

Technological advances in data management are needed to support the rapid and efficient collection, organization and analysis of information. These advances may require new infrastructure for storing, curating and managing large-volume and/or confidential data, improved approaches for maintaining metadata standards across disparate types of data, or simply identifying appropriate existing solutions. Most scientific fields have evolved using much smaller data sets than will become available, so advances are needed in educating disciplinary students and scientists in the use of big, multi-disciplinary data. Students and scientists must be taught computational techniques for analyzing big data sets, and new analysis techniques must be identified and developed that are more appropriate for - and make better use of - big data.

More social science research is needed to understand how people use information, especially as new types and greater volumes of data become available. Appropriate and effective visualization is a rich field for research and involves many disciplines (e.g. computer science, communication, ethics researchers, statisticians, domain sciences). FEW research would greatly benefit from understanding how different disciplinary researchers confront problems with large data, and how trainees can be best taught to effectively work with and use these big data. These new opportunities to re-evaluate the robustness of current methods, and to develop new techniques, will play a key role in advancing scientific knowledge of the FEW system.

Strategies for collecting, utilizing and sharing within a data-rich environment will require early and robust engagement with key stakeholders to ensure data are used and managed in ethically and responsible ways. There is both fertile territory and great need for ethics scholars to engage in FEW research. New science must be informed by best practices in evaluating and responsibly addressing ethical dilemmas that arise at all stages of the research process such that confidentiality and other issues of human welfare are dealt with rapidly and transparently. New innovations in data collection technologies are needed to address potential privacy violations, while FEW collaborative outputs and products will need to ensure they do not compromise the welfare of the individuals embedded within the FEW system.

4) Understanding Resilience in FEW Systems

Management actions and resource user choices greatly influence the ability of a FEW system to sustainably persist into the future. Further research should aim to more clearly identify how well sectors are able to absorb- or transform in response to- major system shocks and whether these changes will perpetuate or shift the system towards a more or less desirable state.

Understanding the adaptive capacity and transformability of a FEW system will be essential where and when impacts from climate change and resource limitations become more acute. FEW researchers and managers need better knowledge of how sectors and systems respond to biophysical, technological and institutional perturbations. Identifying the key drivers of system change, their tipping points (both positive and negative) and how systems transform in response to these changes will be crucial for determining how to manage and optimize socio-ecological welfare within these complex systems. The costs of system transformability or resilience should also be considered to reduce the implementation of undesirable trade-offs and increase the capacity of the system to manage uncertainty and reduce risk.

Optimizing resource allocation could play a key role in addressing system inefficiencies and building resilience within and between FEW sectors. Greater diversification of FEW inputs, processes and outputs could help buffer systems from uncertainty and increase their resilience to biophysical or institutional shocks. To accomplish this, research needs to consider where and why strong FEW system interdependencies occur, what social (political, economic, cultural) and technological processes have led to existing practices, and how current sectoral inefficiencies could be managed to enhance system redundancy without creating additional negative externalities. Optimizing and capitalizing waste in one sector or point of time to buffer another will require the development and use of technological, policy, and market instruments and infrastructure that can identify and incorporate information about the costs, benefits, barriers, uncertainty, and impacts of resource allocation decisions.

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