WHITE PAPER: AN OVERVIEW OF CONCEPTUAL FRAMEWORKS, ANALYTICAL APPROACHES AND RESEARCH QUESTIONS IN THE FOOD-ENERGY-WATER NEXUS

SESYNC White Paper

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Executive Summary

The food-energy-water (FEW) nexus is increasingly emphasized and prioritized as a framework for research, technology, and policy to deal with complex socio-environmental problems. Producing food in sufficient quantity and of sufficient quality, ensuring enough but not too much water, and generating energy, all to meet human needs and desires, requires an understanding of how those goals complement or counteract one another in specific places and through specific processes. FEW nexus research focuses on understanding the interconnections among each system, in order to provide a more complete picture about the causes and consequences of changes within and across aspects of those systems. This paper synthesizes the current state of thinking and research in FEW nexus field. We first overview the systems underpinnings of the FEW nexus as a conceptual framework, and identify the assumptions, similarities and contrasts among the most cited models from current literature. Several analytical approaches – coupled systems, ecosystem services, flows and risk analysis – are emerging as key tools for conducting interdisciplinary FEW nexus research, and we identify their conceptual connections to systems thinking broadly as well as the specific assumptions that each make about the relationships among systems. Finally, based on expert consultations and assessment of current data availability, we highlight several topical areas of contemporary relevance for FEW nexus research at various scales. Characterizing the conceptual, analytical and empirical similarities and distinctions among approaches to FEW nexus research with a starting point for identifying innovative research questions and approaches.

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INTRODUCTION

As populations grow and migrate, and the climate becomes increasingly variable, there is an interest in and a mandate to focus research, policy, and citizen science efforts on understanding the dynamic relationships among food, energy, and water systems. Producing food in sufficient quantity and of sufficient quality, ensuring enough but not too much water, and generating energy, all to meet human needs and desires, increasingly demands an understanding of how those goals complement or counteract one another in specific places and at specific times. The food-energy-water (FEW) nexus has been increasingly emphasized and prioritized as a framework for research, technology, and policy to deal with complex socio-environmental problems that require improved scientific understandings of feedback loops and interactions across human and natural systems (Ringler et al., 2013; Hussey and Pittock, 2012). Recent interagency research programs led by the National Science Foundation and supported by other US government agencies have adopted the FEW nexus as a frame for integrated, interdisciplinary research to "improve system function and management, address system stress, increase resilience, and ensure sustainability" (NSF, 2016).

FEW nexus research focuses on understanding the interconnections among each system, in order to provide a more complete picture about the causes and consequences of changes within and across aspects of those systems. The purpose of this white paper is to summarize the current state of thinking and research in FEW nexus field. We first overview the dominant conceptual models of the FEW nexus, which draws on systems thinking, and then highlight several common and emerging analytical approaches used in contemporary FEW nexus research. Building on the conceptual and analytical review, we then identify in the literature several timely and high-impact research themes in FEW nexus research focused on the domestic United States. Finally, we describe a new effort at SESYNC to create a cyber platform and workshop process that supports the development of innovative data-driven research questions that address aspects of the FEW nexus. This white paper provides a foundation for individual researchers and research teams interested in taking a data-driven approach to FEW nexus issues in the domestic US context.

SYSTEMS THINKING AND THE FEW NEXUS

Systems thinking derives from a variety of disciplines, from engineering to population ecology to behavioral and communications sciences (Bahill and Gissing, 1998; Holling, 1973; Buckley, 1967). The term system refers to totality of the complex and interconnected elements that constitute a given domain. Systems thinking is an approach to investigating the world and can guide the identification and characterization of parts of systems in practice (Bawden, 1991; Checkland, 1985). Checkland (1999) notes, the notion of a system is as much a heuristic device as an empirically observable whole unit. For example, the idea of the social system as comprised of human actors and organizations that are distinct from those in the economic and political systems, generates conceptual boundaries that can then be used to describe real-world phenomena like cultural norms and individual decision-making (for discussion of boundary-creation in systems thinking, see Midgely, 1992). Systems thinking, then, is the process of applying the heuristic of systems to the investigation of the causes of and relationships among these real-world phenomena (for a thorough background on systems thinking in theory and practice, see Checkland, 1999).

In empirical science, the world is often separated at the most basic level into 'social systems' and 'natural systems' in order to identify the expected relationships between an action, its observation or measurement, and its expected effects. Increasingly, however, systems thinking is being applied to domains defined by what a system produces or generates. Health systems, education systems, information management systems – systems thinking is applied to identify the interrelated elements that comprise and shape the domain-specific outputs of health, education or information. Francis et al. (2003: 104) describe the food system, for example, as "an open system, interacting with nature and with society, and the development of a sustainable food system will require more attention to the efficiency of the entire process of converting natural resources to what reaches consumers' tables."

Though the notion of the FEW nexus has emerged over the past five years (Hussey and Pittock, 2012; Ringler et al., 2013; Mohtar and Lawford, 2016), the use of system thinking to frame each of the constituent systems has more history. In food systems, there has been a focus on the production side on integrated management through agroecological production, as well on conserving the natural resources that underpin food value chains (see Snapp and Pound, 2008; Francis et al., 2003; FAO, 2014). On the consumption side of the food system, global commodity chain and local food analyses both put an emphasis on the spatial and social relationships and networks that characterize the system (Gereffi et al., 2005; Busch and Bain, 2004; Hinrichs, 2000). Water systems have both a supply side, which can be conceptualized as a watershed or hydrological cycle, and a demand side, which includes both use and consumption (Molle and Molinga, 2003; Pimentel et al., 1997). A recent United States Geological Survey report describes the water available in a given system as being impacted by not only the "water volume within a hydrologic system and the rates of water movement through that system" but also "the quality of the water; the intended use of that water; laws and regulations that govern water ownership and use; the physical nature of the hydrologic system; the ecosystems, culture, lifestyles, and societal values of the region; and the economic aspects of water development" (Healy et al., 2015: 10). Energy systems are often conceptualized as both the totality of potential sources of energy, the uses and users of that energy, and the impacts and byproducts, both social and environmental, associated with energy generation and use (Jacobsson and Lauber, 2006; Afgan et al., 2000).

FEW nexus research, then, is concerned with the distinct systems that generate food, energy, and water. The nexus represents points of overlap or conflict among the elements of those systems necessary to generate those outputs, with the ultimate orientation toward "increasing efficiency, reducing trade-offs, building synergies and improving governance" across the systems (Hoff, 2011: 4). Characterizing and analyzing the relationships and tradeoffs inherent in decision-making and resource allocation in FEW systems requires a conceptual model that recognizes points of overlap and tension among the three systems. The simplest image is of a Venn diagram comprised of three circles. Nexus research considers topics that fall in the overlap of all three circles, as well as topics that fall in the overlap of any two of the circles. In other words, the issues and research areas that fall within the FEW nexus do not necessarily have direct or primary linkages to all three FEW systems. However, because nexus frameworks emphasize the interconnections among systems, FEW nexus research requires an acknowledgement of all of the relationships and feedbacks, direct and indirect, across the three systems that exist for any single issue or output.

CONCEPTUAL FRAMEWORKS OF THE FEW NEXUS

Conceptual frameworks are often used as a starting point and boundary object for studying complex empirical phenomena as a way to organize and define abstract concepts and theorized relationships among them (Shields and Rangarajan, 2013; Midgley, 1992). FEW nexus conceptual frameworks move beyond the systems thinking that underpins conceptual frameworks of relationships within individual systems, and instead focus on points of overlap, similarity, conflict, and tension across systems. As Bazilian et al. (2011) note, nexus frameworks avoid segmentation and embrace interconnection, which not only expands systems thinking but also reflects the material reality that systems are linked by global commonalities like impacts from climate change and global governance structures. These frameworks almost always involve feedback loops, multiple drivers of change, and complex, cross-scale interactions (Bizikova et al., 2013; Hoff, 2011). The following conceptual frameworks are taken from the growing literature on the FEW nexus from the past five years, and form the basis of much of the FEW nexus research and analysis happening today. They include frameworks from policy institutes in Europe (Figure 1) and Canada (Figure 4), an international economic organization (Figure 2), and academics from the Global North (Figure 3).

Figure 1. Original caption: *The water, energy and food security nexus (*Bonn2011 Nexus conference (from Hoff, 2011))

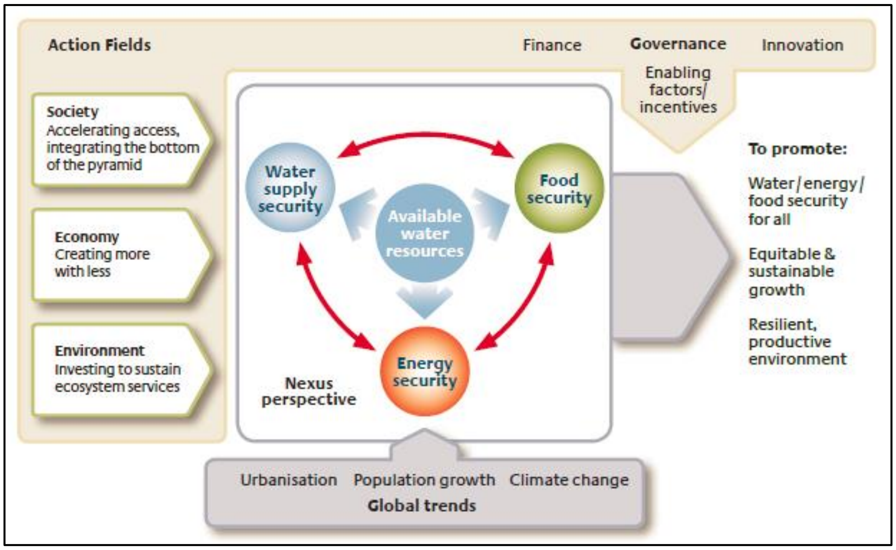


Figure 2. Original caption: *Nexus schematic with a security focus*
(World Economic Forum (from WEF, 2011, in Bazilian et al., 2011))

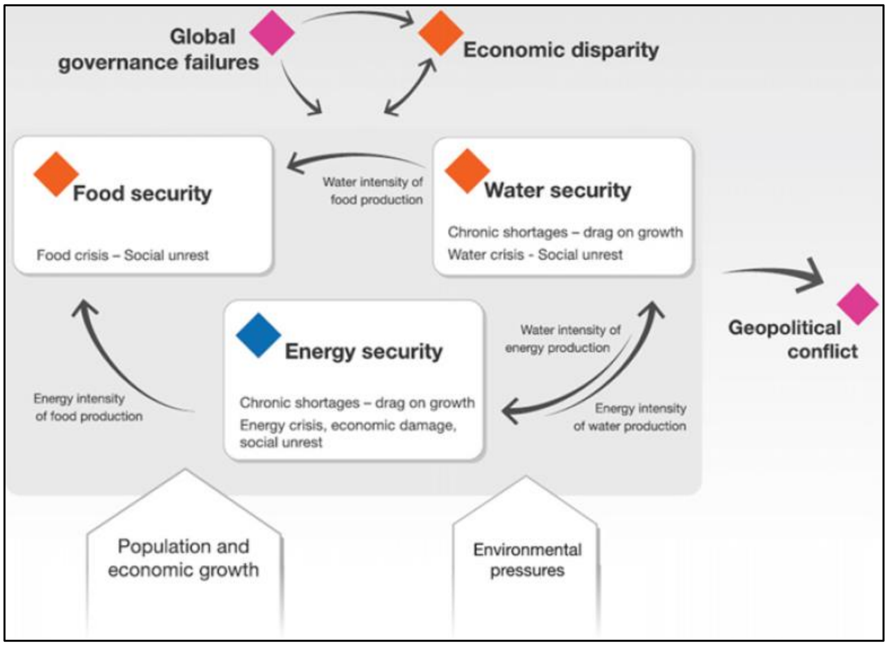


Figure 3. Original caption: *Schematic showing the water-energy-food nexus with effecting parameters*
(Mohtar and Daher, 2012)

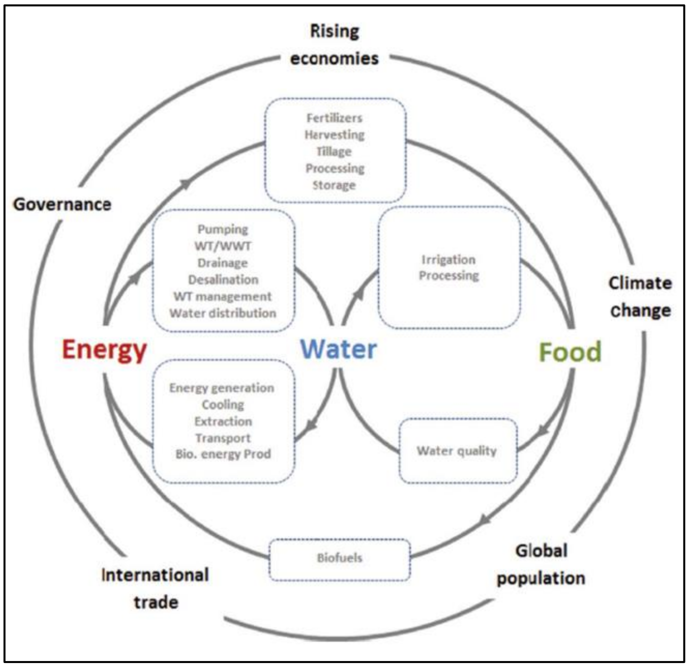
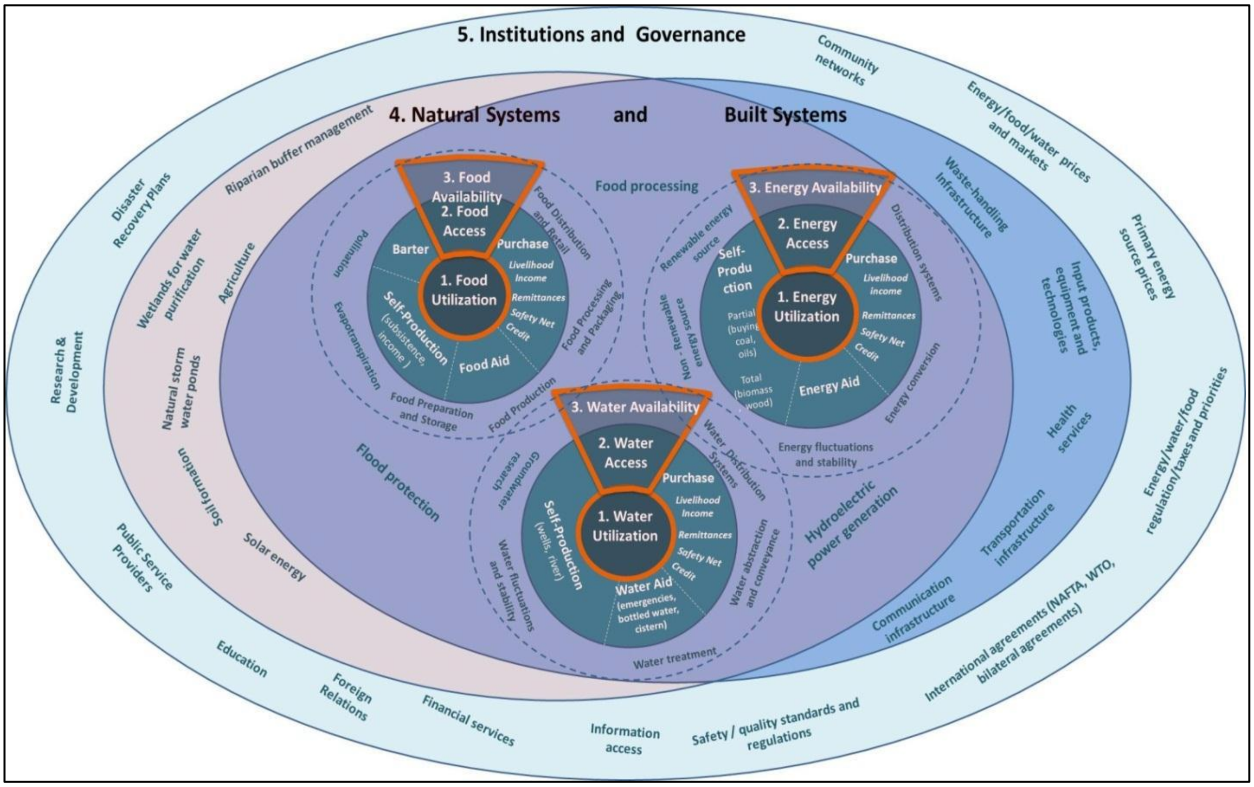


Figure 4. Original caption: *Overview of the framework linking water, food and energy security* (International Institute for Sustainable Development (from Bizikova et al., 2013)



As Bazilian et al. (2011) explain, the systems thinking necessary to understand FEW nexus issues often demands starting within one system and identifying the relationship among that system and the others. For example, when starting from the water system, the food system and the energy system are users of water and can impact the supply side; however, there are also demand-side actors whose decision-making that must be taken into account (Beck and Villaroel, 2013; Hoff, 2011; WEF, 2011). Within the energy system, water and agricultural products are inputs, but agriculture also vies with energy production for the use of water (Bazilian et al., 2011; IWMI, 2007). From the point of view of the food system, water and energy are both inputs and outputs, and food and energy systems compete for land as well as water (FAO, 2014; Harvey and Pilgrim, 2011).

All four of the FEW nexus conceptual frameworks above reflect a general systems approach to identifying the points of overlap and interconnection among the three systems, but there are differences among them in terms of what in fact constitutes the nexus. For a comprehensive summary of these frameworks, see Bizikova et al. (2013). Here we simply note some key commonalities and differences among them. All of the frameworks situate FEW systems and their nexus within broader geographic or substantive domains. For example, governance structures are conceptualized in each of the frameworks above as influencing all parts of the FEW systems and their nexus, as well as interacting with other, similarly broad systems like global population change. A second similarity among three of the four frameworks is a focus on food, energy and water security. Specific definitions of security vary, but all relate to human conceptions of quantity (availability), quality, and access to the resources generated by each system (for an overview of framings of security and risk, see Mooney and Hunt, 2009).

The main point of divergence among the FEW nexus conceptual frameworks above is the lens through which the nexus is defined. In Figure 1 (from Hoff, 2011), the core of the FEW nexus is available water resources, an empirical reality that ties the three systems together and defines the parameters of feedbacks, tradeoffs, and synergies. For the World Economic Forum in Figure 2 (WEF, 2011), physical availability and intensity of use of water and energy resources, and the tradeoffs between the use of each, ties together the FEW systems. In this conceptual framework, the nexus issue of energy-water availability is impacted at the broadest level by changes in the social and natural systems, and the nexus issue in turn generates impacts on the food system.

In contrast to the first FEW nexus conceptual framework, those articulated by Mohtar and Daher (2012) and Bizikova et al. (2013) identify a range of key empirical overlaps among the FEW systems that fall within the nexus, rather than orienting around a single issue or physical dimension of the FEW systems. Mohtar and Daher's (2012) model, in Figure 3, identifies a range of human activities and decisions that reflect interactions and tradeoffs between two of the three systems. Each of these is a nexus issue that primarily reflects the overlap of two of the three systems, and can then be analyzed with an eye toward the indirect linkages to the third system as well. Hellegers et al. (2010) offer some examples of these types of nexus issues, like the relationship between energy generation and water use, and the implications of these tradeoffs for groundwater availability and rural livelihoods.

The final FEW nexus conceptual framework presented above in Figure 4 was created from a literature review and synthesis of many existing FEW nexus conceptual models, including the others overviewed here. This final model (Bizikova et al., 2013) represents a systems thinking approach that is anthropocentric, in that the broadest system is one of human institutions and governance structures. Nested within this model are natural and human systems, and within the overlap of those two systems are nested systems that create food, energy, and water security for people. Bizikova et al. (2013) further break down the security frame into availability, accessibility, and utilization, to further specify the impacts of the relationships and feedback among the constituent systems at different levels. Conceptually, the FEW nexus framework in Figure 4 situates any aspect of any single of the FEW systems in a model that demands attention to the interactions and/or feedbacks with both of the other two systems, as well as to the broader human and natural systems within which the FEW systems function.

FEW NEXUS ANALYTICAL APPROACHES

All of the FEW nexus frameworks presented and discussed above use systems thinking to conceptualize the relationships among different types of systems, at different scales. In this sense, then, the frameworks can act as boundary objects that set out the broad concepts and relationships that fall within and around FEW nexus research. Operationalizing these conceptual frameworks in order to analyze and characterize the concepts and relationships, however, can and does occur using a variety of analytical approaches that reflect more general trends in studying human-environment interactions from a systems perspective. Each of these analytical approaches have theories and methodologies associated with them, hence making them primarily analytical rather than conceptual. In this section, we overview the four analytical approaches most often used in FEW nexus research: coupled systems, ecosystem services, flows, and risk.

COUPLED SYSTEMS

The coupled systems (also called socio-ecological systems and coupled human-natural systems) approach sees contemporary human–environment interactions and issues as representative of complex systems, which require integrated and interdisciplinary approaches to characterize and manage (Antle et al., 2014; Binder et al., 2013; Holling, 2004; Gallopín et al., 2001). Gallopín et al. (2001: 222) explain the orientation of coupled systems theory: "fundamental uncertainty is introduced both by our limited understanding of human ecological processes, by the intrinsic indeterminism of complex dynamic systems, and by myriad human goals." Nested within coupled systems theory broadly are many articulations of how to understand and analyze relationships and changes in coupled systems. Examples include coupled human-natural systems (CHANS; Liu et al., 2007), resilience theory (Folke, 2006; Holling, 1973), adaptive capacity and management (Carpenter and Brock, 2008; Gallopín, 2006; Lebel et al., 2006), and theories of governance for collective decision-making (Ostrom, 2009; Avelino and Rotmans, 2009).

The analytical approaches of coupled system theories reflect a foundational assumption about uncertainty and complexity (see Binder et al., 2013, for a comprehensive overview of analytical approaches in socio-ecological systems). Analytical approaches include identifying the key variables that are constitutive of the coupled system in question (Holling, 1973), determining the hierarchy of these variables in terms of their potential to alter the system state (Ostrom, 2009), and building scenarios and simulation models to characterize possible and probable trajectories of change for the whole system (Antle et al., 2014; Folke, 2006). One key feature of the coupled systems analytical approach is the need to incorporate spatial and temporal heterogeneity. Analyses therefore often use population-based simulation approaches to modeling change, which derive from both ecology (Holling, 1973) and theoretical economics (Antle et al., 2014). One limitation of the probabilistic or simulation analytical approach in the coupled systems approach is that capturing the complexity and recursive nature of future change does not address normative questions about the change process and outcomes for specific coupled systems (Smith and Stirling, 2008; Lebel et al., 2006). Ostrom's (2009) and other's (Antle, 2015) contributions to the coupled systems analytical approach have been to push for a multi-level approach to identifying common patterns in relationships and leverage points, and then fitting a generic model to a specific context.

There are many examples of FEW nexus research in the coupled systems approach, with a large body of work emerging from the Stockholm Resilience Centre that focuses on characterizing adaptive management of FEW resources and their tradeoffs (for a few examples, see Sendzimir et al., 2011; Evans, 2008; Allison and Hobbs, 2004). In the field of international agricultural research for development, integrated approaches to water, soil, and pest management reflect the coupled systems approach by identifying opportunities and constraints within the socio-ecological agricultural system, and development of system-specific management approaches (for examples of integrated soil and water management, see Haggblade and Hazell, 2010; IWMI, 2007). In the domestic US context, there are coupled system modeling efforts underway to generate simulations of the impacts of changes in both the ecological and social systems on crop production in common agricultural production systems like maize and soybean (Antle, 2015). Finally, a report released by the US government Institute of Medicine and National Research Council (IOM and NRC, 2015) uses a coupled systems approach to analyze agricultural production in the United States as a part of the bioeconomy.

ECOSYSTEM SERVICES

The ecosystem services approach takes a similar starting point to the coupled systems approach, positing that “people are integral parts of ecosystems and that a dynamic interaction exists between them and other parts of ecosystems, with the changing human condition driving, both directly and indirectly, changes in ecosystems and thereby causing changes in human well-being” (Millennium Ecosystem Assessment, 2005: v). Rather than theorizing about complexity associated with these relationships, however, in the ecosystems services approach there are discrete linkages between the ecosystem and human systems: the service provided by the ecosystem to human well-being (for a foundational articulation of the approach, see Daily, 1997). In this sense, the ecosystem services approach is anthropocentric, as it characterizes dimensions of the ecosystem as they pertain to human categories of need, use, and meaning (Binder et al., 2013; Boyd and Banzhf, 2007; Gitay et al., 2001). Within the overall approach, the payment for ecosystem services approach further situates ecosystem services in the human context by assigning value through monetary and financial accounting mechanisms (Mauerhofer et al., 2013). As the payments for ecosystem services theories have matured into mainstream articulations for conservation and sustainability practice, the notion of natural capital has become an increasingly applied heuristic for explaining how economic valuation relates to the natural world (Daily et al., 2009). At the same time, there has emerged related critical analysis of the challenges and dangers associated with the ‘commodification of nature’ (Castree, 2008; McCarthy, 2005) and the replacement of ecological restoration with the restoration of human-focused services (Suding et al. 2015, Palmer et al. 2014, Palmer et al. 2015).

The ecosystem services approach categorizes the services that ecosystems provide as provisioning, regulating, cultural, and supporting services (Millennium Ecosystem Assessment, 2005). Each of these analytical categories reflects both the empirical or ‘natural’ characteristic of the ecosystem service in question, as well as the way that humans relate to that service. For example, provisioning services are those that generate physical goods like food or water that are consumed by people. Supporting services, in contrast, are processes like photosynthesis that are necessary foundations for generating provisioning services. The incorporation of both natural and human dimensions of each service into its definition and characterization makes explicit the linkages across human-defined systems (Bizikova et al., 2013). At the same time, the ecosystem services analytical approach has been critiqued for not providing a clear enough methodological articulation of common metrics and measurements that can be used in accounting schemes (Boyd and Bazhaf, 2007). The use of contingent valuation and monetary value as a common unit of measure is one response to this analytical challenge, as a way to make calculated decisions about tradeoffs associated with complex issues like those in the FEW nexus (Hoogeveen, 2014).

Valuing ecosystem services in the context of food systems is a particularly complicated calculation, since agricultural production systems are both a user of ecosystem services and a part of specific ecosystems that generate other services (Poppy et al., 2014). Powlson et al. (2011) offers the example of soils, noting that soil functioning provides a supporting service to humans by providing the nutrients needed for food production, and that management of those soils for agricultural production can provide regulating services to the human system. Other economic concepts and principles, like marginal value and marginal rate of return, are also being used to capture the temporal and spatial heterogeneity associated with the economic valuation of natural resources (see Jaeger et al., 2013, for an example using water resources). There has been a more recent move to incorporate some element of coupled systems theories into ecosystem services analyses by bundling ecosystem services and modeling the tradeoffs within and across bundles as another way to capture heterogeneity and feedback mechanisms (Poppy et al., 2014; Remme et al., 2014). The natural capital approach also combines elements of the coupled systems approach with a more classic ecosystem services approach, by using a multi-level approach to identifying contextual drivers of change and balance sheets for trade-off analyses that use both human measures of value but also ecologically relevant measures like tons of carbon (Daily et al., 2009).

Ecosystem services analyses are increasingly common in domestic and international FEW nexus analyses. Within the US, the idea of ecosystem services as they relate to environmental protection have been a part of federal policy dialogues since the late 1990s, with more recent incorporation into Farm Bill and land management guidelines for forest and grazing land (see Bear, 2014 for history)[1]. Examples include the application of payments for ecosystem services accounting schemes and markets existing at local and regional levels in the US; a classic case is protection of the New York City drinking water supply in the Catskills (Appleton, 2002). In the international context, the modeling approaches to ecosystem services bundling described by Poppy et al. (2014) are being applied to specific cases of food security in sub-Saharan Africa. The authors note that increasing the complexity of analytical relationships in the ecosystem services analysis allows for disaggregation across the population of the impacts of changes in the ecosystem. This differentiation is especially helpful in contexts where interactions in the FEW nexus disproportionately impact vulnerable or marginalized human populations for whom access to food, water and energy are often tightly coupled. There are also well-established, international-scale payment for ecosystem services analyses and implementation in contexts where national-level regulatory structures are weak (Mauerhofer et al., 2013). The United Nations Reducing Emissions from Deforestation and Forest Degradation (REDD) program is one high-profile example.

FLOWS

Whereas coupled systems and ecosystems services approachs are somewhat hierarchical in orientation, the approach of flows reflects a more horizontal orientation toward relationships and connections among systems' components. The flows approach has been conceptualized using the biological notion of metabolism to describe how inputs move through a system process and produce outputs, which in turn become inputs in some other system process. Metabolic theory is used literally, to describe the flow of natural resources through organisms in biotic systems (Schramski et al., 2015; Brown et al., 2004), and has also been used to describe flows of resources through built systems like cities (Wolman's (1965) 'urban metabolism'; see also Villarroel Walker et al., 2014). Industrial ecology also builds on the idea of flows as inputs and outputs, and emphasizes the notion of carrying capacity of a system, that demands for outputs cannot exceed available inputs (Lowe and Evans, 1995). From a critical theory perspective, a strand of Marxian social science theory has long used the metabolism heuristic to analyze the rift generated by the extractive nature of capitalist production, which disrupts flows by separating the use of inputs from the consumption or use of outputs (Foster, 1999). A more general social science approach for flows emerges from this critique: flows reflect a "new type of time-space organization of social practices" that reflects the globalization and distanciation of production, consumption and finance (Mol, 2007: 301; see also Castells, 2010; Harvey, 2006). The flows approach is elegant in its conceptual simplicity, but has been

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[1] The National Ecosystem Services Partnership (nespguidebook.com) provides extensive documentation for the use of ecosystem services by federal agencies, with many case studies that fall within the FEW nexus.

critiqued by methodologists on the basis of oversimplifying complex processes as well as of having complex data needs (Hoff, 2011; Ayres, 1995).

The flows approach is operationalized with analytical concepts like cycles, balance sheets, and footprints, many of which are commonly used in FEW nexus research (Sobal et al. 1998). Life cycle analysis (LCA), for example, is an analytical method stemming from systems engineering (Blanchard and Fabrycky, 2013) that accounts for all inputs into and outputs from a product over the course of its use-life, from 'cradle to grave' (Ayres, 1995: 199). Analysis of cycles is also often used to characterize flows of elemental nutrients, greenhouse gases, and energy (Tilman and Clark, 2014; Elser and Bennett, 2011; Khan and Hanjra, 2009). Balance sheets are sometimes used in the context of LCA as an associated analytical tool that depicts the relative level of inputs and outputs, and can also be used to depict supply and demand dynamics that drive or are embedded within the movement of resources and goods. The virtual water approach, for example, uses a balance sheet approach to characterize areas of water surplus and deficit, amount of water embodied in traded goods and materials, and associated water use efficiencies of trade (Mekonnen and Hoekstra, 2011; Allouche, 2011). The flows approach and the analytical accounting for resource use that comes from it also underlay the notion of measuring the total resource use – the 'footprint' – of a product or process (Chavez and Ramaswami, 2013).

Although the flows approach might be less familiar to some researchers than coupled systems or ecosystem services, the analytical concepts with the flows approach are often used in FEW nexus research. Schramski et al. (2015), for example, use an LCA approach to compare greenhouse gas emissions of different types of animal protein production, while Nijdam et al. (2012) calculates the carbon and land footprints of animal food products using a similar approach. Analyses of nutrient cycling are also common in FEW nexus studies that link flows of nitrogen and phosphorus to yield gaps, fertilizer use and energy consumption (Pradhan et al., 2015; Khan and Hanjra, 2009). Virtual water and virtual land balance sheets have been used to model current and future trade relationship needs among countries (Fader et al., 2013; Allouche, 2011). Critical social science analyses often link natural resource use to geopolitical and economic networks to identify drivers of food insecurity and imbalances (Salerno, 2014; Chavez and Ramaswami, 2013; Mol, 2007). Jorgenson and Givens (2015) extend these analyses to assess the carbon footprint of individual well-being, which shifts the analysis away from the input/output model of the classic flow approach and toward an analytical frame that identifies differentiation and vulnerability across places and within populations.

RISK

The risk approach is less integrated at a theoretical level than the other three approaches overviewed here, and at the same time, the analytical approaches used in the risk approach cut across the other approaches applied to FEW nexus questions. The risk approach can start from the sources of risk or the impacts of risk on human decision-making and well-being, and in the social sciences often moves to discussion of how risk is defined and who gets to define it (Mooney and Hunt, 2009) In general, the risk approach distinguishes between natural hazards and human-generated risks (Beck, 1992). The former, hazards, can come from scarcity or abundance of a natural resource, which constitute a physical risk to individuals and communities (Molle and Molinga, 2003). The latter, human-generated risks, generally refer to either technological impacts (as in Beck's (1992) articulation of the 'risk society') or to political and economic power relationships, and the potential for human conflict that they generate. From either source of risk, impacts are most often conceptualized at either the individual level, with a focus on human security – literally the viability of human life – or the security of some material component of individual existence – food security, water security (Bizikova, 2013; Allouche, 2011). The risk approach also identifies impacts at higher, systems-levels – for example, impacts on economic and political systems are often discussed in the context of climate change (Molle and Mollinga, 2003).

The multi-scale and discursive nature of the risk approach means that analytical approaches are often oriented around measuring variability and uncertainty, and on analyzing scenarios rather than empirical measurements of change. Though less clearly defined from a methodological perspective than some of the other analytical approaches discussed in this section, risk analysis cuts across these other approaches. By engaging with uncertainty and complexity, the risk approach aligns with both coupled-systems and ecosystem services analyses that stress the need to understand relationships among system components and changes in those components over time. At the same time, the scenarios used in risk analyses (for a recent example, see Lloyd's, 2015) reflect an analytical approach that captures tradeoffs and calculates future impacts much like analyses in the flows approach. The results of risk analyses often combine pieces of each of the other approaches in outputs like assessment tools, rapid response and contingency plans, and policy recommendations (IRENA, 2015; WEF, 2011).

The risk approach has long been used in food systems to discuss the impacts of impending population growth, pest pressures and, more recently, climate variability. Actual analyses are often simulation and statistical models that predict the likelihood of a specific risk or hazard and its impacts in a given place or on a given system. Devineni et al. (2015), for example, analyzes water risk in the United State in light of climate models and the current drought. Pradhan et al. (2015) assess global risk for yield gaps in the context of decreasing soil nutrient availability. System-level impacts of risks in the FEW nexus often focus on political units, like cities or nations, or economic systems (see for example, Beck and Villarroel Walker, 2013). Two recent reports emphasize the relationship between business practices, water risk and economic viability. Roberts and Barton (2015) analyze the water risk of 37 agri-food companies, and characterize their risk-mitigation practices. Lloyd's of London (2015) uses actuarial approaches to assess scenarios of shocks to the global food system and their potential impacts on the insurance industry.

RELEVANT AREAS OF FOOD-ENERGY-WATER NEXUS RESEARCH IN THE US CONTEXT

NUTRIENT CYCLING AND AVAILABILITY

The flow of nutrients, largely nitrogen and phosphorus, from agricultural production to water bodies has been a long-standing concern in the domestic US context, and there are ongoing efforts to identify the sources, sinks, and flow paths of nutrients across and through the landscape (Metson et al., 2015; King et al., 2015; for historical context, see Smil, 2000). Increasingly, there is also concern about how climate variability will impact nutrient flows, as saltwater incursion, changes in precipitation, and other changes in the biophysical environment could change the speed at which current and historic sources release nutrients (Ardón et al., 2013; Staver and Brinsfield, 2001; Leatherman, 2000). More study of how nutrient flows and cycles are affected by climate variability is needed to make models more precise and to set standards that are reflective of actual biophysical conditions. Managing nutrient flows through human systems and built infrastructure requires energy to run wastewater treatment plants, compost food waste, and otherwise gather sources of nutrients for sequestration and potential reuse (Decker et al., 2000; Lundin et al., 2000). Use of biosolids as fertilizers in agricultural production is one often-cited way to close the nutrient cycle (to return nutrients taken from the ground by plants to the location of cultivation), and this is an area of increasing research interest and focus (Dawson and Hilton, 2011).

While overabundance of nutrients in water bodies and other specific environments is a concern, lack of nutrients and changes in nutrient balances are also important challenges situated in the FEW nexus (Elser and Bennett, 2011; Van Vuuren et al., 2010). Long-term studies suggest that soils across the globe are being depleted of both nitrogen and phosphorus, because of intensification of agricultural production and an emphasis on synthetic fertilizers rather than integrated soil management activities (Bouwman et al., 2009; Liu et al., 2008). Fertilizer production is highly energy intensive, and there is increasing emphasis in the US context on precision agriculture, to increase efficient use of nutrient inputs to produce environmental benefits in the form of fewer nutrients flowing out of fields and less energy used, as well as efficient use of capital inputs by farmers to improve livelihoods (Lowenberg-DeBoer, 2015; Foley et al., 2011, Galloway et al., 2008; Tilman et al., 2002). While nitrogen is an atmospheric element that is not limited in terms of quantity, phosphorus is not, and the finite nature of known rock phosphorus reserves has led to concerns about ‘peak phosphorus’ (Childers et al., 2011; Elser and Bennett, 2011; Cordell et al. 2009). Phosphorus reclamation and recycling could contribute to both increased water quality and more efficient cycling of nutrients from farms to food and back (Chowdhury et al., 2014). However, the scale of use, management,and recycling decisions for both nitrogen and phosphorus are often unaligned, making regulatory efforts difficult to implement (for parallels to carbon and energy management, see Socolow, 1999).

PEST MANAGEMENT

Pest management in agricultural production systems includes mitigating the impacts on production quantity and quality from weeds, insects, and pathogens. Pimentel et al. (2000) estimate that about a quarter of all crop losses (in terms of potential yield) in the US are due to weeds or insects, and the annual value of crop losses to weeds, insects, and pathogens totals close to $100 billion. Estimates of the monetary costs of pest management in the US further increase when the costs of pest control, including the use of synthetic and organic herbicide and insecticide, the use of pest-resistant seeds, and changing land use demands are included (Pimentel et al., 2001; Phipps and Park, 2000). In addition, there are also indirect and non-monetary costs associated with pest pressures and pest management. Synthetic pesticides require energy inputs to create and to ship, although energy budgets for agricultural production consistently show that pesticides contribute a relatively small percentage of the overall energy use in agriculture (Pimentel et al., 2005; Pervanchon et al., 2002). The use of both synthetic and organic pesticides often requires water for spraying or spreading, which can limit the use of some management approaches in areas where water is scarce (Phipps and Park, 2000). Integrated and organic approaches to pest management, like biopesticides, microbial inoculants, and the use of crop rotations and companion planting, are often noted as both decreasing the monetary and energetic costs of pest management and contributing to ecosystem function and services by improving soil health and providing pollinator habitat (Power, 2010; Berg, 2009; Pimentel et al., 2000). However, many of these alternative pest management approaches require increased labor inputs. In the domestic US context, where farm labor must be employed, producers often make a calculation between intensifying their pest management approaches by increasing labor or chemical input costs, or extensifying production by simply planting a larger area and accepting greater per unit losses (Conforti and Giampietro, 1997).

The trade-offs faced by agricultural producers in making decisions about pest management strategies are exacerbated by the uncertainty that comes with climate variability. With changing weather and temperature patterns, pest populations are responding in ways that are not necessarily built into the informal assumptions and formal models used by farmers to make decisions about pest management (Garrett et al., 2006; Harvell et al., 2002). Estimates about the range and spread of pest populations, for example, are based on past experience and uncertain climate assumptions, and they often do not account for human management decisions (Tilman et al., 2002; Mack et al., 2000). Of particular concern is the impact of the standardization of agriculture on pest populations. As Tilman et al. (2002) note, ecological and epidemiological assumptions suggest that as the area planted under just a few key commodity crops increases, the incidence of pests associated with these crops should increase as well. At the same time, changes in the abiotic environment affect the potential ranges of both crop and pest populations in ways that are not necessarily reflective of the broader ecosystem's ability to support either population (Chakraborty et al., 2000). All of these changes have increased concern about the need for water inputs in the form of increased irrigation to bolster plant resilience to pest pressures, as well as the potential need for increased use of chemicals if pest populations respond favorably to climatic change (Huberty and Denno, 2004; Chakraborty et al., 2000; Coakley et al., 1999). In the context of US agriculture, which varies widely in the diversity and extent of specific cropping systems, modeling efforts on the impacts of climate change on agricultural pest pressures must include estimates about not only changing pest populations but also the unintended consequences of any pest management approach (Garret et al., 2006; Mack et al., 2000).

WATER AVAILABILITY AND WATER USE

The quality, quantity, and availability of water resources both influence and are affected by food and energy systems. Projected impacts of climate change on water resources vary across the US. Earlier snowmelt in areas where irrigation water comes from mountain snowpack-derived runoff could result in increases in water delivery curtailments if the water cannot be contained for use throughout the year (Vano et al., 2010). In the Southwest, future electricity mixes will have a disproportionate impact on other water uses as hydroelectricity increases (Yates et al., 2013). Simulation models suggest that at a national scale the largest impacts from climate change will be on both non-consumptive uses, like recreation and species habitat, and on lower-value consumptive uses such as agriculture, as water is reallocated to uses with higher monetary value like energy production (Henderson et al., 2015). Sixty percent of irrigation in the US relies on groundwater, and aquifer overexploitation could significantly impact crop production (Scanlon et al., 2012). Engineered systems that divert surface water for artificial recharge of aquifers could contribute to sustainable groundwater management (Scanlon et al., 2012). However, sustaining non-consumptive uses such as hydropower and recreation during drought is typically more complex because management facilities and institutions are less effective in protecting non-consumptive use during drought (Lord et al., 1995; Booker, 1995). Rule changes could offer solutions for this vulnerability. However, such changes are extremely difficult to make, because decision-making institutions were designed to resolve conflicts over consumptive uses by private actors, not necessarily to facilitate action in the common interest (Miller et al., 1997). Several bills introduced in Congress in recent years have proposed to integrate energy and water planning and decision-making but have failed to pass, even though coordinating these planning efforts has been cited as critically important to both energy and water security by multiple government organizations (Sanders et al., 2014).

Water productivity, or the value of goods and services produced per unit of water used, has improved in the US since the mid-1970s. Water withdrawals in the US are projected to continue to decline as once-through cooling system thermoelectric plants retire, but there are large uncertainties about the water-use intensity of future energy production scenarios based on changes in fuel preferences, cooling practices for electricity generating units, environmental regulations, climate, and the electric power grid (Sanders et al., 2015). Total US water withdrawals have decreased by 17% from 1980 to 2010. The decrease in water-use intensity is mainly driven by changes in intensity from irrigation on farms and recirculating cooling technology used by thermoelectric power plants (Wang et al., 2015). In the Northeast region, reducing the impact of upstream thermal pollution can result in efficient regional scenarios and alleviate vulnerabilities to climate impacts on river water available for cooling, if water and energy service planning are coordinated (Miara et al., 2013). Projected changes to 2030 suggest that total aggregate water withdrawals will increase by approximately 3%, mostly occurring in the southern US associated with new municipal and domestic withdrawals in California, Texas, Arizona, Florida, and Georgia (Chen et al., 2013). Brown et al. (2013) similarly project that water withdrawals in the US will stay within 3% of 2005 levels even with an expected 51% increase in population over 50 years. However, climate impacts that result in higher amounts of agricultural and landscape irrigation substantially raise this projection. Key obstacles to improving water productivity include: uncertainty regarding the longevity and maintenance costs of infrastructure, upfront costs for land and infrastructure, quantification of unpriced benefits, and overcoming water underpricing (Grant et al., 2012).

NON-TRADITIONAL IRRIGATION WATER AND INFRASTRUCTURE

The increasing pressures put on consumptive water use because of climate variability and population growth have pushed many localities to consider the use of non-traditional water for a variety of purposes, including irrigation. To date, human health considerations have dominated regulatory strategies surrounding greywater (water that has not come in contact with human waste), while environmental risks are ignored or underrepresented (Maimon et al., 2010). However, harnessing water sources previously considered marginal, such as saline, treated effluent, and desalinated waters, also requires careful consideration of long-term impacts to soil conditions due to new types and levels of compounds introduced to agroecosystems, as well as assessment of the energy intensity of treatment and transport (Assouline et al., 2015; Plapally and Lienhard, 2012). Primary concerns associated with wastewater reuse include buildup of contaminants and salts in soils in the case of irrigation, and the possibility that incomplete removal of chemical or microbiological hazards during treatment may expose people to disease through food contamination. Although prevalent internationally, the use of treated wastewater in the US is currently limited, at less than 5% of municipal supply (Grant et al., 2012). Direct potable reuse is not practiced in the US except in a few small-scale operations, but several indirect potable reuse facilities are operational (Sato et al., 2013). For example, California and Arizona have recognized the benefits of onsite reuse of greywater and have created highly detailed frameworks for regulation. California's current water storage, conveyance, and treatment infrastructure allows for adapting to severe prolonged drought without desalinization but remains underdeveloped, despite severe economic and water supply effects to many regions that would disrupt agriculture and environmental uses (Harou et al., 2010). Even regions with well-established and well-funded water resource infrastructure such as the Pacific Northwest will face substantial obstacles when it comes to climate change adaptation without significant investments in technical capacity (Hamlet, 2011).

The main obstacles to wastewater reuse at the household level are public acceptance (“yuck factor”), perceptions of risk from reclaimed wastewater, and cost (Duong and Saphores, 2015). Concerns about health risks center on microbiological pathogens, and pharmaceuticals and personal care products (PPCPs), because they can accumulate in the tissues of plants irrigated with wastewater. Low concentrations of PPCPs typically do not present acute risks to human health, but they may drastically affect other living organisms. Although most literature to date suggests that levels of residues of PPCPs in plant tissue due to wastewater irrigation represent a *de minimis* risk to human health, some scholars argue that many studies omit necessary information to accurately quantify exposure to plants, such as the frequency and duration of irrigation (Prosser and Sibley, 2015; Malchi et al., 2015). There is an urgent need to collect more wastewater treatment and re-use data to understand health risk associated with reclaimed and recycled wastewater. Simultaneously, produce-related illnesses have been increasing in the US from 1% of foodborne diseases in the 1970s to 12% in the 1990s (Lynch et al., 2009), and it now may be the leading cause of foodborne illness in the US. This increase could be due to the growth in the operation of confined animal feedlots since the 1980s, shifting US diets towards more produce, and/or field and processing technologies that make plants more vulnerable to contamination and increase the likelihood of pathogen spread.

FOOD WASTE AND FOOD SAFETY

Food waste and food safety are food system issues that have complex social and ecological components. Food waste is an inefficiency in the food system in which not all food supplied is consumed and water and energy used in its production are wasted. Energy embedded in wasted food represents approximately 2% of the annual energy consumption in the US (Cuéllar and Webber, 2010). Most of the greenhouse gas emissions associated with food waste are from embedded emissions associated with production, processing, transport, and retailing of wasted food, whereas a small component comes from the decomposition of wasted food deposited in landfills (Venkat, 2011). The high emissions intensity of beef makes it the single largest contributor to emissions from wasted food (Venkat 2011). The production of lost and wasted food in the US is also associated with over 25% of total freshwater used in the US (Hall et al., 2009). Production, processing, and disposal of avoidable food waste is responsible for approximately 113 million metric tons of carbon dioxide equivalent per year (Venkat, 2011). Concern for foodborne illness is the most common reason for discarding food by American consumers (Neff et al., 2015). Other drivers of food waste in the US include the relative cost of food, demographic trends, behavioral aspects, and retailer practices and store sizes (Thyberg and Tonjes, 2015; Thyberg et al., 2015). Although the most energy intensive food category for production is meat, poultry, and fish; the dairy and vegetable categories have the greatest embedded energy in their waste due to their higher proportional waste compared to meat (Cuéllar and Webber, 2010).

Food safety regulations and outcomes are closely linked to water quality and energy-intensive treatment technologies. Food safety in the US relies heavily on legal liability and the court system in addition to regulations (Brewster and Goldsmith, 2007). Lengthy food system supply chains, legal decisions, limited federal agency budgets, fragmented authority, and the rights given to businesses in the US result in the current mosaic of food safety practices. New regulations under the Food Safety and Modernization Act (FSMA) cover approximately 80% of food consumed within the US; meat poultry and dairy are regulated separately by the USDA rather than the FDA (Nakuja et al., 2015). The FSMA focuses on preventing food-related problems rather than mitigating them. However, the FDA has been slow in developing and implementing the new regulations as it is consistently under-resourced (Nakuja et al., 2015). Government regulation is also co-evolving with the growing predominance of private and third-party standards by entities such as transnational supermarket chains as supply chains in global agri-food system are structured by vertically integrated transnational supermarkets (Henson and Reardon, 2005). The shift toward managing food safety through private standards can result in both improvements in food safety and quality as well as reproducing and deepening existing social and ecological inequalities as smaller producers are excluded from larger markets due to high costs of food safety technology and compliance (Henson and Reardon, 2005; Konefal et al., 2005). There is evidence that standards impede trade flows through the prohibitive costs of compliance, particularly for poorer countries (Anders and Caswell, 2009). The size of processing plants and market incentives will influence the choice of food safety technology used to meet food safety regulations (Ollinger et al., 2004).

BIOFUELS

Biofuels are a quintessential FEW nexus issue. The production of biofuels requires land, energy, and water as inputs to production, and can compete with food crops for inputs and arable land. In addition, biofuels will have non-trivial impacts on the transport energy sector and its GHG emissions. As pressure increases to find alternative energy source to fossil fuels, biofuels will play an increasing important role in domestic and international economic and energy portfolios. For example, it is expected that biofuels will fulfill roughly 20-30% of global transportation energy mix over the next 40 years (Murphy et al., 2011). Following the definitions provided by Lee and Lavoie (2014), biofuels can be classified as follows: first-generation biofuels are directly related to a biomass that is generally edible by humans; second-generation biofuels are defined as fuels produced from a wide array of different feedstock, ranging from lignocellulosic feedstocks to municipal solid wastes; and third-generation biofuels are, at this point, related to algal biomass or more broadly the potential utilization of CO2 as feedstock. Future demand for biofuels will likely be met from a transition from first generation food crops for biofuels (e.g., maize) to second and third generation biofuels based on lignocellulosic feedstocks (Murphy et al., 2011).

Policies aimed at bolstering biofuels as alternatives to fossil fuels in national energy portfolios have often been designed and implemented without consideration of the full costs and benefits for other social, economic, and natural systems impacted by biofuel production (Bazilian et al., 2011). Biofuel production has the potential to compete directly with food crop production and global food supplies. Biofuel production demand on agricultural lands will vary significantly between countries and regions depending on a variety of factors, including agricultural commodity prices, global supply chain configurations (Godar et al., 2015; Garrett et al., 2013), biophysical conditions, and national agricultural policies (Murphy et al., 2011). For example, policy changes and increased global demands for biofuels in the mid-2000s prompted many farmers to convert existing croplands to biofuels (Searchinger et al., 2008). The diversion of croplands from food crops to biofuels triggered higher crop prices, and farmers around the world responded by clearing more forest and grassland to produce more feed and food. Subsequent studies have confirmed that higher soybean prices accelerated clearing of Brazilian rainforest (Morton et al., 2006). Further, if increased demand for biofuels results in conversion of land to agriculture, the GHG emissions from such conversion will likely overwhelm GHG savings from replacing fossil fuel sources (Harvey and Pilgrim, 2011). Consequently, any increased demand for land to produce biofuels to meet energy needs must be considered in light of potential climate impacts and GHG emissions over the feedstock's entire lifecycle (for reviews of the systemic impacts, see Smith et al., 2010; Woods et al., 2010).

ENERGY EXTRACTION

Energy production consumes freshwater along the entire supply chain from extraction and conversion of raw energy sources to generation of power (Fthenakis and Kim, 2010; Gleick, 1994; Holland et al., 2015). Given the reliance on water of current energy production technologies, impacts to water access due to physical scarcity to regulatory limitations can have significant consequences for energy security (IEA, 2012). Despite this, natural resource management and climate adaptation policies typically do not integrate energy and water objectives (Pittcock, 2011; Scott et al., 2011), and emerging climate-energy strategies have the potential to negatively affect freshwater resources (Fulton and Cooley, 2015). Such shortcomings have led many to call for improved accounting of water resources through the life cycle of energy production and consumption in international trade policies and sustainability assessments (see Holland et al., 2015 for discussion).

Water consumption from energy production varies by energy sector and location. Recent work by Holland et al. (2015) analyzed global freshwater consumption for the gas, electricity, and petroleum energy sectors. For some energy sectors, particularly petroleum, large geographic disconnects are possible through global commodity trade between locations of energy production and consumption (Holland et al., 2015). Often, petroleum products that are produced for the global commodity market are extracted and refined in developing countries and locations of water scarcity, which concentrates social, environmental, and economic impacts and potentially exacerbates existing problems (IEA, 2012). This is in contrast to gas and electricity production for which production and consumption are typically contained within the same geographic area, and thus are more directly connected with freshwater consumption. However, hydraulic fracturing (i.e., 'fracking') is an emerging gas and oil extraction technology that is increasingly popular in the U.S. and can be extremely water-intensive, as it involves “injection of fluids into a well under pressures high enough to fracture the host rock, thereby increasing the permeability of the rock and facilitating the extraction of the hydrocarbon resource" (Healy et al., 2015: 12). Hydraulic fracturing has been praised by some for increasing US energy security, while also being condemned by others as harmful to the environment and freshwater resources (Healy et al., 2015). Given the extensive interconnections at the water-energy nexus, future management strategies will need to understand such trade-offs in order to develop balanced policies.

CLIMATE CHANGE

Variations in the frequency and/or intensity of precipitation attributed to climate change has recently been implicated as main driver of food crises and/or social unrest (Lagi et al., 2015; Puma et al., 2015; Suweiss et al., 2013; Hanjra and Qureshi, 2010). The effects of drought, delayed monsoons, or excessive rain can lead to spikes in food prices and social unrest, such as the ‘onion demonstrations’ in India (Ghosh, 2013), ‘pasta protests’ in Italy (Associated Press, 2007), and ‘tortilla riots’ in Mexico (Watts, 2007). Stress on groundwater resources, which are crucial for food production in many arid areas, has recently intensified due to changing precipitation patterns. In Syria, for example, demands for allowing drilling of wells to unprecedented depths has potentially exacerbated an already unstable political situation (Gleick, 2014). In the US, alternative energy policies that expand corn production for ethanol as a climate adaptation strategy may have unintended consequences in distant agricultural production regions, such as expansion of soy production in Brazil in response to decreased US soy production at the cost of deforestation in the Amazon (Naylor et al., 2007).

Increased reliance on global commodity trade to meet food supplies in the context of climate change introduces potential vulnerabilities to climate disruptions in the global food system. Weather-related shocks like drought are particularly important to consider because of crop sensitivity to weather extremes and the expectation that such extremes will become more frequent in the future (Gornall et al., 2010; Puma et al., 2015). A recent and promising analytical approach to identifying potential points of vulnerability involves coupling trade network analysis with climate model simulations to explore the impacts of weather-related shocks on food production, food prices, and reactive behavior (including large-scale governmental intervention, export bans, and panic buying) that feeds back into the trade network (Puma et al., 2015). Puma et al. (2015) found that drought impacts created the greatest disruption of the trade network and losses of global food supply when European wheat and Asian rice production were effected with average food supply losses on the order of 11 and 14 percent, respectively. Similar network-based analyses have been used to quantify the embodied, or 'virtual', water used to produce agricultural commodities that are consumed elsewhere (Carr et al., 2013; Feng et al., 2012). The interaction of climate change, agricultural commodity production and global trade, and displaced water and energy use associated with such production is a global FEW issue amenable to modeling approaches that can characterize the sustainability of globally interconnected production and consumption patterns.

DATA TO MOTIVATE SYNTHESIS PROJECT

Addressing FEW nexus research questions, regardless of the chosen analytical approach and topical area, requires combining multiple types of data that reflect the components of FEW systems and the relationships among components across systems. The socio-environmental synthesis process articulated at SESYNC can contribute to and support FEW nexus research that uses a variety of analytical approaches within the broad context of systems approaches. The synthesis process requires iteration between conceptual framework, research questions, and data identification, in order to consistently refine realistic and empirically testable research questions and analyses to answer them. For individual scholars and teams of collaborators, socio-environmental synthesis that focuses on FEW nexus questions requires engagement with data about not only the social and environmental dimensions of one large, complex system (food, energy, or water) but knowledge of the content and characteristics of data across multiple complex systems. In addition to content area expertise, FEW nexus research, like all synthesis research, requires the use and combination of data in conceptually innovative ways. However, it can often be difficult to identify data can allow a researcher to ask questions that reflect the FEW nexus conceptual framework and to apply common analytical approaches to investigate FEW nexus questions.

To address the challenges associated with moving from questions to data, SESYNC initiated the Data to Motivate Synthesis (DTMS) project. Currently being developed in conjunction with partners at the USDA and USGS, DTMS is building an integrated platform of cybertools as well as a workshop process to facilitate data discovery that catalyzes new research questions in the FEW nexus. All of the data catalogued in the DTMS integrated platform is publically available, and was identified primarily through the Climate Data Initiative's Food Resilience, Water, and Energy themes[2], as well as from other federal and state agency sources. The integrated platform consists of three tools: a catalog of data and concepts related to the FEW nexus, an ontology that characterizes the relationships between data and concepts from various analytical

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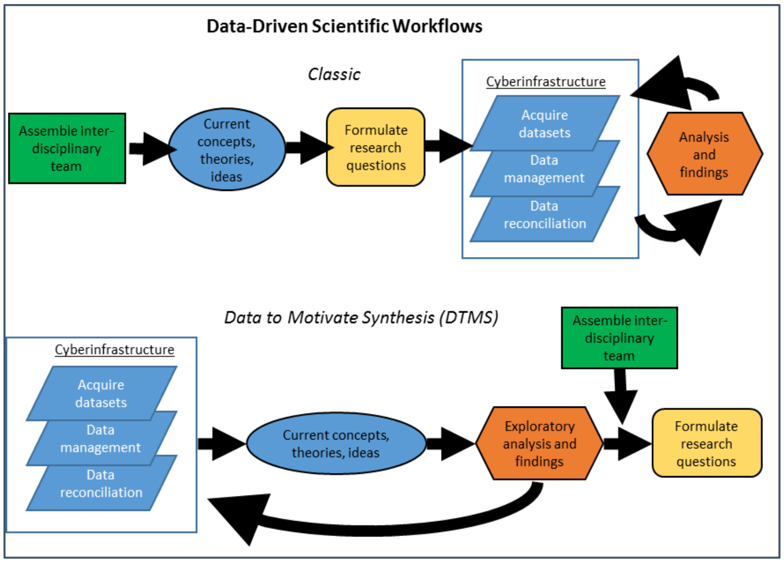
[2] https://www.data.gov/climate/

approaches, and a set of workbench spaces for users to further explore metadata and relationships among data. The integrated platform is accessed through a single user interface that allows the user to search for data and concepts using keywords, explore the conceptual relationships among data in the ontology, and to compare characteristics of the data to identify integration opportunities and challenges. At shown in Figure 5, DTMS workshops for early-career scholars will leverage the integrated platform cybertools to flip the conventional synthesis process, which moves from theory to question to data, to a new workflow that begins with facilitated data exploration and discovery to catalyze data-driven research questions. Data identified through a collaborative data discovery process acts as a boundary object for bridging disciplinary and epistemological divides, as well as fostering communication between researchers.

Figure 5: Flipping the synthesis process: from questions-to-data to data-to-questions



CONCLUSION

The complex challenges currently facing food, energy and water systems separately and in specific locations around the world are increasingly recognized as not only internally challenging but made further complicated by myriad linkages across systems, as well as over time and space. The articulation of the FEW nexus is a new framing of an old problem, one that identifies the dynamic nature of the components and the relationships within and across complex systems. The conceptual frameworks describing the FEW nexus draw on the long history of systems thinking to provide a starting point for applying broad-based systems approaches to specific research questions that span food, energy, and water as inputs and outputs foundational to human well-being. Several analytical approaches - coupled systems, ecosystem services, flows, and risk – each focus on different dynamics and characterizations of complex FEW systems, and specific approaches will be better suited to specific FEW nexus research questions. Regardless of the analytical approach used, FEW nexus synthesis research will require diverse and heterogeneous data sources and types, and these data must be combined in ways that are analytically and conceptually consistent. To support and encourage research in the FEW nexus, SESYNC has developed the DTMS project to test the hypothesis that innovative questions that span multiple complex systems can be generated by a data discovery to question and framework formulation process.

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