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PERSPECTIVE

The U.S. food–energy–water system: A blueprint to fill the mesoscale gap for science and decision-making

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Abstract Food, energy, and water (FEW) are interdependent and must be examined as a coupled natural–human system. This perspective essay defines FEW systems and outlines key findings about them as a blueprint for future models to satisfy six key objectives. The first three focus on linking the FEW production and consumption to impacts on Earth cycles in a spatially specific manner in order to diagnose problems and identify potential solutions. The second three focus on describing the evolution of FEW systems to identify risks, thus empowering the FEW actors to better achieve the goals of resilience and sustainability. Four key findings about the FEW systems that guide future model development are (1) that they engage ecological, carbon, water, and nutrient cycles most powerfully among all human systems; (2) that they operate primarily at a mesoscale best captured by counties, districts, and cities; (3) that cities are hubs within the FEW system; and (4) that the FEW system forms a complex network.

Keywords Environmental footprints ·
Food–energy–water nexus · Network analysis ·
Urban ecology

INTRODUCTION: WHY SHOULD WE STUDY FOOD–ENERGY–WATER SYSTEMS?

The basis of the argument that Earth has now entered the "Anthropocene" (Steffen et al. 2007) is that human activities, most of them occurring within the confines of the economy, are an instrumental component of carbon, water, nitrogen, phosphorus, and other critical Earth cycles. While services produce the majority of jobs and gross domestic product, it is through the essential activities of food, fiber, and energy production and consumption, with their copious use of water, that the agroindustrial metabolism of our economies (see, for example, Fischer-Kowalski 1998) most powerfully engages the planet's material and energetic metabolism. Thus, there is a powerful, but complex, relationship between the food–energy–water (FEW) systems and their impact on Earth cycles, such as climate change, eutrophication, water-resource depletion, and land use and land cover change. These can exceed planetary limits as concieved by some (Rockstrom et al. 2009).

FEW systems are modern humanity's lifeline. They supply the daily necessities for human survival, making their security and sustainability critical to humanity. In an interdependent world of ever-increasing connectivity, ensuring resiliency during extreme conditions requires understanding spatially and temporally dislocated production and consumption patterns and supply chains. Since the OPEC oil embargo of 1973, Westerners have understood systemic energy vulnerability, as exemplified by dependency upon crude oil imports from the Persian Gulf. When news of the September 11, 2001 terrorist attacks hit the airwaves and the internet, many Americans' first response was to rush to the gas station. Unlike the oil shocks of the late twentieth century, emerging twenty-first century FEW system vulnerabilities are not always readily apparent based on a global market for a single commodity. Rather, as exemplified by the contribution of the 2007–2010 drought to the ongoing Syrian conflict (Kelley et al. 2015), vulnerabilities lie within subtle interdependencies among resources and hotspots. Fresh water in particular has emerged as a—some would assert *the*—worldwide resource-security issue of coming decades (e.g., Vörösmarty et al. 2010). Yet the availability of piped water from municipal water utilities is only the tip of the water-security iceberg. More than 80 percent of the U.S. annual

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consumptive water footprint of over 800 km^3 (7.6 m^3 cap-ita^{-1} day^{-1}) is derived from the production of food, fiber, and other agricultural products (Mekonnen and Hoekstra 2011) that are often shipped across the continent or even the globe. Bailey and Wellesley (2017) have identified fourteen global food-shipping chokepoints, including the U.S. Gulf Coast ports and the U.S. inland waterways and rail networks that, if temporarily rendered inoperable, would lead to food distribution crises with dramatic impacts on human welfare.

Appreciation for the interdependencies among and tradeoffs between food, energy, and water has sparked the desire to examine them jointly, as evidenced by the U.S. National Science Foundation Innovations in Food, Energy, Water System (INFEWS) program initiated in 2016. For instance, most of our water footprint—blue (derived from withdrawals) and even more so green (transpiration from rainfed crops)—is embedded in food. Most of the rest is embedded in energy (e.g., thermoelectric cooling), with water requirements per MWh of electricity varying from almost none for wind power and photovoltaics to about 2 m^3 for coal, oil, and nuclear power to as high as 180 m^3 for biofuels (Hoff 2011). Modern food production is not only water intensive, but nutrient- and energy intensive, with fossil-fuel consumption by large machines and for nitrogen fixation eclipsing the caloric content of agricultural outputs (Haberl et al. 2016). Pumping water consumes sizeable proportions of electricity, as do water and wastewater treatment. Desalinated water has been referred to as "bottled electricity." These examples illustrate that analyzing FEW systems jointly can reveal substantial efficiencies that are missed when food, energy, and water

systems are optimized individually (Smajgl et al. 2016). Here, we focus on outcomes of the FEW system interdependencies, rather than intersectoral tradeoffs.

DEFINING A FOOD–ENERGY–WATER SYSTEM

A food–energy–water (FEW) system is difficult to define, even if its core components are clear. As illustrated in Fig. 1 with the example of livestock-based food, these are: inputs (water, energy, nutrients), and emissions (water, carbon, nutrients) at key links in the supply chain. Material throughput and energy transformation in the production of provisioning ecosystem services (as defined by Millennium Ecosystem Assessment 2005)—food, fiber, and biofuels from agriculture—is a core component of the FEW system. The concept of human appropriation of net primary productivity (see, for example, Haberl et al. 2007), where humans harvest ecological productivity while also diminishing it through land use change, helps clarify this rural heart of the FEW production system. Nonagricultural water withdrawals, energy infrastructure such as power plants, fossil fuel extraction, and resource-related manufacturing industries (e.g., food processing, mineral refining, lumber milling) are also core FEW production or supply components.

Cities also lie at the core of the FEW system, where demand for and consumption of food, energy, and water, is increasingly concentrated. For the first time in human history, the majority of people now live in cities, and this is anticipated to increase further to 70 percent by 2050 (Hoff 2011). What connects supply and demand is trade, while
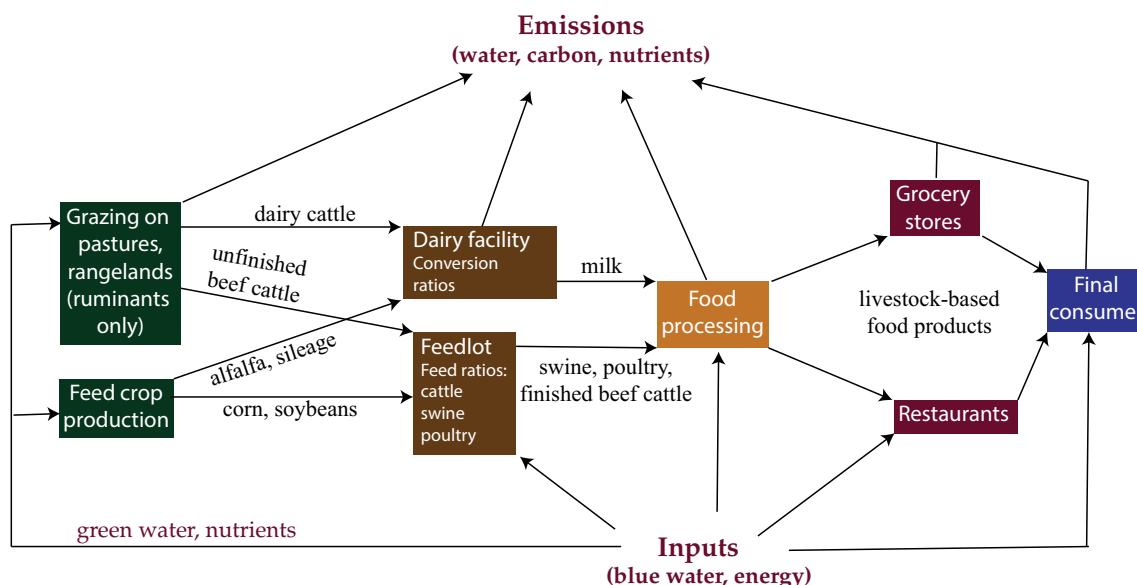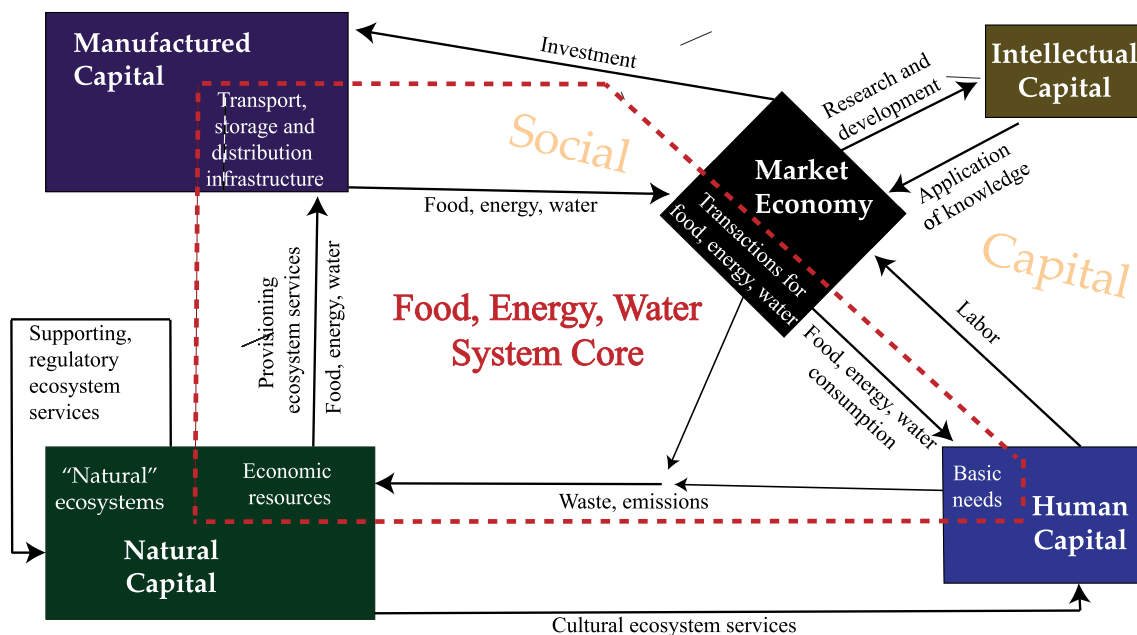

Fig. 1 Diagram of core food–energy–water (FEW) system elements. This example is for a livestock-based food production system. Note that footprint analysis is integrated along the full supply chain

freight transport connects production with consumption. This places oil, gas, and water pipelines, electrical grids, barge corridors, railroads, and interstate highways at the core of the FEW system, as well as essential storage facilities like reservoirs and warehouses. Markets for these basic goods, with their essential control mechanism of prices, are also core components of the FEW system, as are the subsidies that promote and regulations that constrain these markets.

Defining the outer boundary of FEW systems, however, is another matter because they are inextricably embedded in a broadly defined ecological–economic system, where their core is clear, but their boundary is fuzzy. Beyond the red dashed line (Fig. 2) lies the "FEW-everything system" (FEWe). Rather than a sharp boundary, FEW systems are deeply interlinked with, and heavily controlled by, the larger economic system, with all of its governing policies. In developed economies, FEW systems comprise a minority of gross domestic product. Yet, they are the footprint-heavy foundation of the entire socioeconomic superstructure, while also its main point of contact with natural ecosystems; this is why food, energy and water provision are referred to as "primary" economic activities. Components of the FEW system exist at all spatial scales from individuals to farms and firms, but the entirety of the FEW system only emerges at larger spatial scales that we can define as the "mesoscale" of counties, regions, or metropolitan areas. Temporally, integrated FEW systems operate hour-to-hour and are transformed over a period of decades.

Every linkage within the core of a FEW system requires not only natural capital, but financial, manufactured, human, and social capital, both formal (e.g., environmental, labor, and financial regulations) and informal (e.g., relationships among individuals in social networks). These essential resources are sometimes referred to as "infrastructure" rather than "capital." In the realm of natural capital, economic resources such as proven reserves of fossil fuels, board-feet of harvestable timber, and soils that support crops or livestock grazing are a core part of the FEW system. They emerge from and integrate seamlessly with natural ecosystems, which are, however, maintained and reproduced through supporting and regulatory ecosystem services. In the realm of manufactured capital, transport and storage infrastructures, including the electrical grid and oil, gas, and water pipelines, are the core FEW system components. The physical cities for which these form a circulatory system lie in its periphery. In the realm of human capital, the consumption of food, energy, and water—the basic, essential needs—lies at the core of the FEW system. Other human-support mechanisms, including cultural ecosystem services, lie at its periphery. In the realm of the market economy, money exchanged for food, water, and energy is a core part of the FEW system. The financial system that controls the economy as a whole lies in its periphery. This makes the scientific enterprise of understanding and building models of FEW systems a matter of closely describing their essential core components, marshaling the ever-expanding reservoir of available data, and identifying their critical interactions and

Fig. 2 Diagram of how food–energy–water (FEW) systems are embedded within the broader ecological-economy. Note that FEW systems are important for ecosystem services

interdependencies. Then, as it becomes necessary and possible, models should be incrementally expanded to include the most essential peripheral elements.

Objectives of a model of the whole FEW system

The purpose of this perspective essay is to coalesce what we know and do not yet know about FEW systems, and to outline a blueprint for a feasible and useful model of the complete FEW system, using the United States as the template. A model of the FEW system for a nation should be able to achieve the following six objectives:

1. To develop an accurate system-level knowledge based on how the provision and consumption of FEW are linked to impacts on Earth cycles, especially through land-use change, ecological impacts, water resource depletion and degradation, eutrophication, and greenhouse gas emissions;
2. To pinpoint when and where these impacts or footprints occur and to trace them forward through the supply chain, from resource extraction, to manufacturing, distribution, to the time and location where food or energy are consumed—and backward so that consumption can be linked with distant footprints;
3. To enable diagnosis of specific disturbances to Earth cycles and thereby to better identify effective solutions (e.g., modified consumption behavior or supply-chain linkages) that can bolster ecosystem service delivery in a manner that improves human welfare;
4. To describe how FEW systems have evolved over decades, observe how they have responded to major shocks and stresses in the past, and understand how they may respond to natural and human shocks and stresses in coming decades, so that measures to bolster systemwide resilience can be identified;
5. To identify security risks, dependencies, vulnerabilities, and/or solutions that emerge at the FEW system level, but are invisible from the perspective of any single component, jurisdiction, or sector of the system; and
6. To identify the institutional actors in the FEW system that have the power to mitigate or intensify security and sustainability problems, whether directly or indirectly, and to identify the spatial and sectoral scopes of power of each actor over the components of the FEW system.

Our scientific knowledge can and should be organized into a framework that meets these six objectives. If we can achieve this goal, the resulting modeling capability will enable scientific investigation of the FEW system's properties of sustainability, efficiency, vulnerability, and resilience, while empowering actors to modify their network linkages, consumption patterns, or production processes in light of the complete network of FEW system interconnections.

HOW WELL CAN OUR CURRENT KNOWLEDGE OF FOOD–ENERGY–WATER SYSTEMS MEET THESE OBJECTIVES?

We have learned a great deal in the twenty first century about the anatomy, response mechanisms, patterns, and trajectories of FEW systems. Yet, as we will see, this knowledge currently falls well short of satisfying the objectives listed above. In particular, it lacks the empirical spatial precision and temporal responsiveness needed to guide decision-making on natural resource-use and environmental management. Most of what we know is based on national, or at best state-scale snapshots of single layers of a system that is inherently multilayered, dynamic, and geographically detailed. In the most well-studied and data-rich regions such as the United States, the basic data resources available about water, food, energy, and their interactions do exist (at least at a moderate level of detail), but they have not been appropriately synthesized to enable system-level understanding. A data fusion approach is therefore essential to improving our understanding. Existing findings about FEW systems reveal the utility of our existing data, but also its limitations.

Finding 1: FEW systems powerfully engage carbon, water, and nutrient cycles

Because they embed substantial volumes of water (e.g., Mubako and Lant 2008), nitrogen (e.g., Leach et al. 2012), phosphorus (e.g., Xue and Landis 2010), and carbon (e.g., Fargione et al. 2008), FEW systems are as much a part of Earth system cycles as water running downhill in a watershed or atmospheric carbon captured by plants through photosynthesis. Measurement of blue and green water footprints has been refined to a global methodological standard (Hoekstra et al. 2011) and estimated for every nation on Earth (Mekonnen and Hoekstra 2011). Carbon footprints have been mapped for the U.S. at a fine-scale resolution (Gurney et al. 2009). Though less well developed, nitrogen footprints can now also be derived (Leach et al. 2012).

Human appropriation of net primary productivity (HANPP), first measured by Vitousek et al. (1986), has been refined to 10 km-resolution global maps by authors from the Vienna-based Institute of Social Ecology (Haberl et al. 2007) and linked to land use changes, to land use-based impacts on carbon emissions (Erb et al. 2017) and to supply chains to generate a very useful measure of

embodied HANPP (Erb et al. 2009), analogous to virtual water. Embodied HANPP thus represents our best approach to identifying the spatially specific ecological footprint of goods and places.

All of these footprints can be assessed (generally unfavorably) against the criterion of sustainability (Hoekstra and Wiedmann 2014). These observations represent only the highlights of an increasingly abundant scientific literature that has been able to generate more and more refined estimates of the resource consumption (water, HANPP) or emissions to overutilized environmental sinks (carbon, nutrients), popularly known as footprints, that are committed when specific food, fiber, and energy products are produced, transported, transformed, and consumed. In addition to mapping footprints, impacts of the FEW system on ecosystem services and, through them, on quality of life can also be mapped. What is needed, however, is more systematic information on how the goods that generate these footprints move through supply chains, as this is the key to linking consumption to geographically and sometimes temporally distant production-based footprints.

Finding 2: The complete FEW system operates primarily at the spatial mesoscale

There is a dialectical tension between globalization (as thesis) and local self-sufficiency (as antithesis). Globalization interconnects points of demand to distant sources of supply and utilizes comparative advantage to promise improvements in total systemic resource use efficiency and productivity, such as for water through virtual water trade (e.g., Konar et al. 2013). Local self-sufficiency promises independence from foreign control, reduced transportation costs, sustainable environmental impacts, and embedded social relationships beyond the commercial (Carolan 2011). Yet, the empirical reality of FEW systems transcends this dichotomy. While both global and local scales are evident, the majority of the twenty first century FEW system operates between these extremes at the mesoscale: teleconnected watersheds, ecoregions, and air masses in the natural realm, crop belts, industry clusters, wholesale transportation and storage infrastructures, and political districts in the human realm.

Recent research bridging geoscience and social science has revealed a rapidly growing global scale interconnectivity of resources through trade with emerging teleconnections, such as the soybean trade between southern Brazil-northern Argentina and eastern China (Dalin et al. 2012). Emerging in the last few decades, this massive virtual water exchange is driven by stress on north China's water supplies so severe that it is building and repurposing canals (e.g., the ancient Grand Canal) to divert Yangtze River basin waters north to the depleted Yellow basin.

More recently, it has become apparent that these international virtual water flows are the tip of the iceberg; a much larger interconnectivity is evident at mesoscales defined by river basins, metropolitan areas (Chini et al. 2017), U.S. counties (Ruddell 2017) and U.S. states (Mubako and Lant 2013; Dang et al. 2014).

Mesoscale connectivity also dominates in energy. In 2015, 91 percent of the U.S. energy consumption was supplied by domestic sources, with water-intensive hydraulic fracturing enabling increasing production from an evolving archipelago of oil and gas shale plays. Much of the remaining 9 percent were petroleum imports sourced from Canada and Mexico (U.S. Energy Information Administration 2017) making North America a largely self-sufficient energy-supply system. Yet nearly every location within North America is either a massive exporter or importer of energy, lacking local capacity in key components of the energy system. Connecting the local and the continental scales, we find the critical mesoscale of the FEW system featuring a vast network of pipelines and transmission lines. The grid, which in 2010 required 161 billion gallons per day, 45 percent of U.S. water withdrawals, for its operation (not including requirements for hydropower or biofuels,) is a quintessential mesoscale distribution network fraught with security risks and sustainability dilemmas.

Using the National Water Economy Dataset (NWED v1.1; Rushforth and Ruddell 2018), we find here that, at a national scale, internal transfers of blue virtual water (352 019 Mm^3) exceed the sum of imports and exports (10 671 Mm^3 and 7263 Mm^3, respectively) by a factor of twenty. At a state scale, virtual water exports and imports are nearly an order of magnitude greater than at the national scale (77 343 Mm^3), but are still exceeded by internal transfers (292 610 Mm^3) by a factor of nearly four. Yet at the county scale, exports and imports (332 695 Mm^3) quadruple those at the state scale to exceed internal transfers (19 324 Mm^3) by a factor of seventeen. A finer scale would thus capture few additional transfers. The percentage of blue water footprints that cross county borders is 98 percent, but this decreases to 50 percent for metro area borders and 19 percent for state borders (Fig. 3a). Only 2 percent crosses the U.S. border. These patterns demonstrate that virtual water trade is primarily a mesoscale phenomenon that, while not inherently operative at the county scale, is best and most simply captured at that scale.

This finding is reinforced when the distribution of net virtual water flows is examined. U.S. States clearly show functional specialization with the two largest net importers and the two largest net exporters generating positive and negative blue virtual water trade balances, respectively, of about 5000 Mm^3 (Fig. 3b). At the county scale, however,
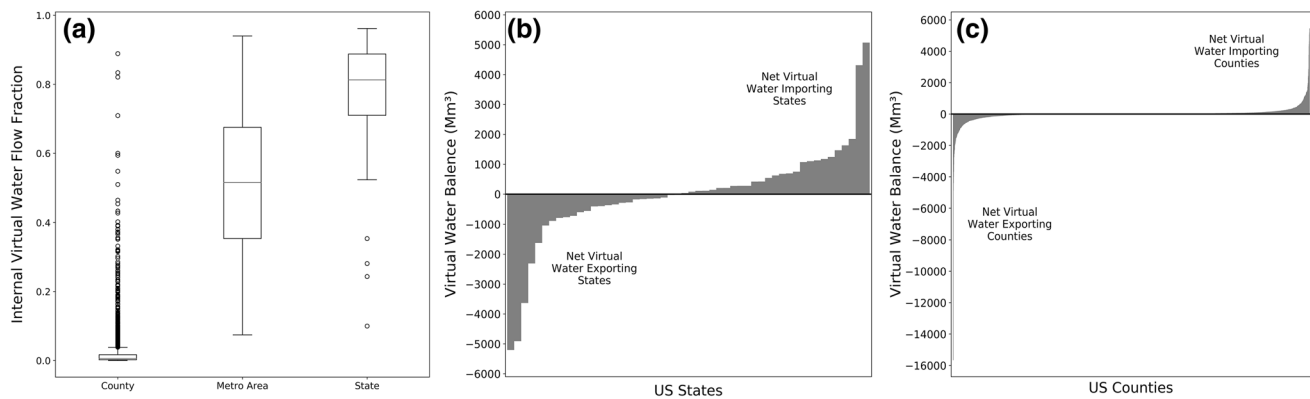
Fig. 3 a Comparison of internal versus external blue virtual water transfers at the county, metro area, and the state scale. Distribution of net blue virtual water balances for **b** the U.S. states, and **c** counties

we observe an equally high level of maximum net imports in some large urban counties, and maximum net exports reaching a level three times greater than for any state in key irrigated rural counties (Fig. 3c). Functional differentiation in the network of blue virtual water trade is thus captured even more effectively at the county than at the state scale of analysis. This is the coarsest scale that identifies major geographic and economic distinctions, and the finest scale that preserves coherent and complete FEW system networks, while also preserving individual- and establishment-level data-privacy requirements.

Because it is such a volumetrically large and essential factor of production of both food and energy, virtual water trade patterns provide important insights into FEW systems as a whole. It is thus evident from these results that the role of a geographic "place" in the FEW system is determined by its urban (net FEW consumer) versus rural (net FEW producer) functionality, its role in the agroindustrial system, and whether it commands an important position along FEW trade routes. These functional roles as virtual water importers, exporters, or transporters largely emerge at the spatial scale of counties, with states simply serving as an aggregation of counties and the U.S. as an aggregation of states. Each county's unique place in the FEW system is dependent upon population, urbanization, natural resource endowment, economic structure, transportation connectivity, water, and energy conveyance infrastructure, and regulatory environment. Yet the relative contribution of these factors and their interactions at specific locations and times within the U.S. remains unknown.

Finding 3: Cities are hubs within the FEW system

Classical geography defines a "hinterland" on which all cities have always been dependent for their food, water, and energy supplies. In the twenty first century, hundreds of mesoscale city hinterlands overlap, while bearing no correspondence to watershed, state, or other political boundaries. As manufacturing and service centers that generate an ever-increasing share of gross domestic product, cities are key mesoscale hubs in the FEW system, especially medium-size cities situated within clusters of agricultural or energy-producing counties (Rushforth and Ruddell 2018). Each city's geographic pattern of direct piped water supply, of food and energy supply, and of indirect virtual water supply is unique. Each city's FEW supply chain, therefore, embeds a unique set of vulnerabilities (e.g., Berardy and Chester 2017)—and a unique set of opportunities for cities to deploy their political and financial powers to strengthen their resilience and sustainability. By importing resource-intensive goods, wealthy metropolitan regions with advanced service sectors provide markets for rural agricultural and resource-based industries, while simultaneously externalizing environmental impacts and exposing themselves to vulnerabilities beyond their direct control (Rushforth and Ruddell 2016).

A new chapter in urban ecology and biogeochemistry (Kaye et al. 2006) is being written by examining the sustainability of FEW imports to cities (Kennedy et al. 2015). Importantly, urban lifestyles capture efficiencies that make them less directly resource-consumptive than suburban, small town, or rural lifestyles on a per capita basis (Bettencourt 2013). This, however, only mitigates security-of-supply problems. For example, Fig. 4 maps virtual water flows to Flagstaff, AZ, a growing city whose fairly secure municipal water supplies (by U.S. southwestern standards) mask the increasing insecurity of its water supply chain via its food and energy sources (Rushforth and Ruddell 2016). Largely derived from the Colorado River basin, Flagstaff's already oversubscribed virtual water supplies are further threatened by rapid regional population growth and urbanization of key irrigated croplands in the face of increasing aridity borne of climate change (Seager et al. 2007). Marston et al. (2015) found annual virtual water
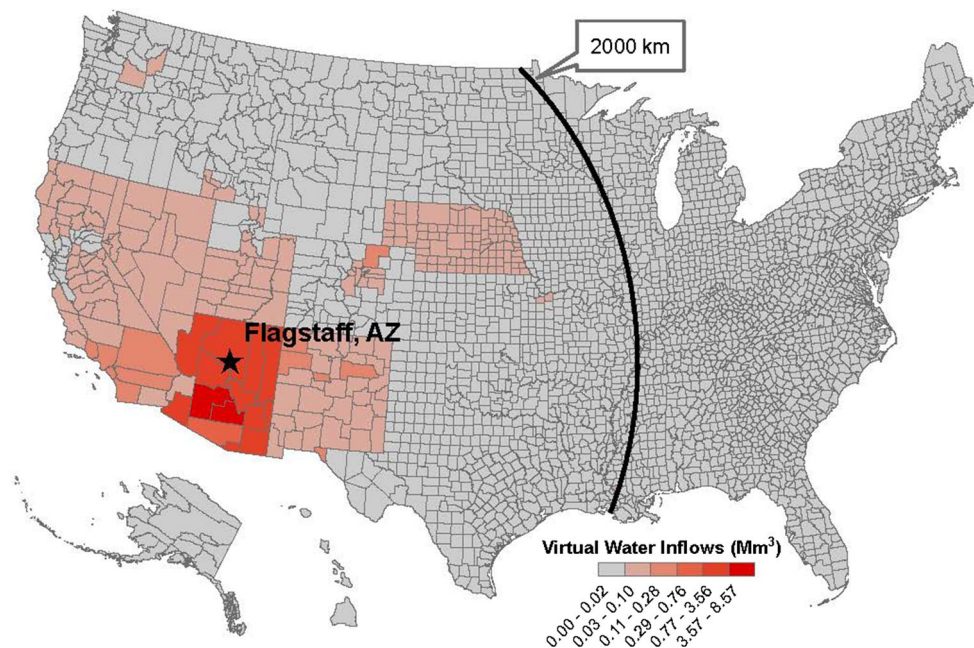
Fig. 4 Virtual water flows into Flagstaff, AZ Reproduced with permission from Rushforth and Ruddell (2016)

transfers from the depleting High Plains, Mississippi Embayment, and Central Valley (CA) aquifers of 18, 9, and 7 km³, respectively, with each groundwater resource primarily serving an individualized set of seven U.S. metropolitan areas. Other U.S. cities currently rely for essential food supplies upon increasingly drought-prone climates (Averyt et al. 2013). Others depend upon electricity made possible by unsustainable supplies of water for thermoelectric cooling. Once these supply chains are rendered visible, cities can manage them to drive sustainability while increasing resilience (Seto et al. 2012; McManamay et al. 2017).

Finding 4: Food–energy–water systems form a complex network

Figure 5 displays (a) the patterns of food trade among U.S. states (Lin et al. 2014) and (b) the resulting patterns of virtual water trade (Dang et al. 2014). Following rules of economic geography, states bordering the Mississippi River and its navigable tributaries export crops globally via Louisiana, but also serve as the hub of a domestic network in the prime raw materials of livestock feed and food processing—corn, soybeans, wheat—that support food-dependent Atlantic and Gulf Coast states. These crops are primarily rainfed and weather dependent so events like the 2012 drought can have a major impact on supply chains throughout the nation and beyond. California, and its neighbors in Mexico and Arizona, are also a hub of a network of food interdependency, supplying specialty crops to regional cities, especially in winter, while

depending equally upon the corn–soybean–wheat surplus from the less river-accessible Great Plains. These food trade patterns re-emerge as a network of virtual water interdependency where Midwestern exports of green water and Southwestern exports of blue water are prominent water–food system interdependencies.

As this important example demonstrates, even if constrained by state-level data, network theory provides the fundamental tools we need to describe the FEW system (Konar et al. 2011). One normative objective for this network includes ensuring the reliability of the FEW lifeline to all people—at all times. Another is to minimize the natural resources it consumes, and the environmental sinks it places demands upon, as measured by carbon, water, nutrient, HANPP, and other footprints. In order to empower agents within the FEW system to pursue these objectives, we need to develop both an empirically reliable description and the quantitative theories relating how the network responds to systemic stresses and shocks to reduce vulnerability and bolster resilience, sustainability, and efficiency.

Prices, of course, are the regulators of supply and demand in FEW supply chains, at least on the margin and under routine conditions. If the system is behaving in an economically rational manner, the loss of a supply-chain connection due to resource depletion, infrastructure failures, regulatory blunders, or other political or environmental disturbances should result in supplies being replaced by the next least-expensive option in the network, with an overall rise in prices for the commodity suffering a reduction in supply. For an individual city, resilience lies in
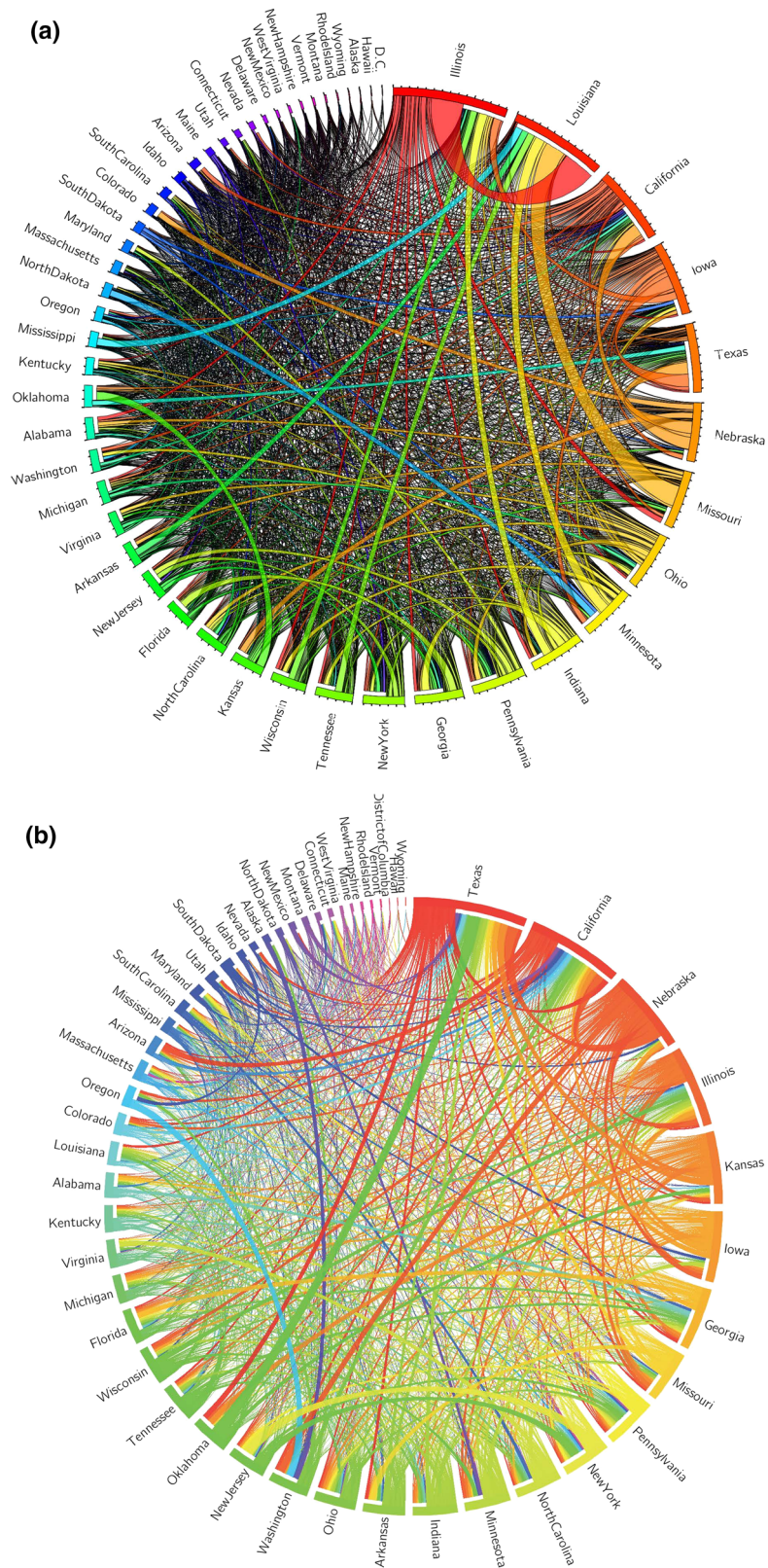
Fig. 5 Network representation of **a** food flows and **b** virtual water flows within the 50 U.S. states. The states are ranked according to the total trade volume and plotted clockwise in descending order. The size of the outer bar indicates the total trade volume of each state. Export volume is indicated with links emanating from the outer bar of the same color. Import volume is indicated with a white area separating the outer bar from links of a different color. Reproduced with permission from **a** Lin et al. (2014), **b** Dang et al. (2014)

minimizing the increase in supply costs that would occur in the event of a supply-chain disruption, whatever be its cause. The loss of a city's key supplier only leads to an immediate shortage if sufficient storage and alternative suppliers are both lacking. In this case, where prices and markets fail, true shocks must be addressed using the toolkits of emergency management. In a FEW system, shocks can impact human welfare powerfully and immediately. For this reason, the analysis of complex FEW networks moves beyond the scope of economics to consider conditions of rapid and potentially catastrophic change.

Boundaries are an essential feature of complex networks, and therefore of FEW models. Crossing boundaries is inherent in networks, yet geographic boundaries are real and have major consequences. Cascading power failures can stop at state borders, for example, with the Texas power grid (ERCOT). Through surface flows, river networks connect locations within the same watershed, but not outside it. Regulations apply only to the part of a FEW network's nodes that lie inside the geographic border of the authority that enforces them. Some actors may not care about footprints beyond their political boundary (Ruddell et al. 2014).

Exogenous (coming from beyond the system boundary) shocks to the FEW system include extreme weather and climatic events (e.g., the Dust Bowl of the 1930s and 1988 Midwestern drought, Hurricanes Katrina and Rita in 2005 and Harvey and Irma in 2017, the 1993 and 2011 Mississippi River floods), terrorist threats such as 9–11, or infrastructure and international trade disruptions (e.g., the effect of Middle East conflicts in 1973, 1979, 1990–1991, and 2003 on oil supplies). Security-of-demand (not only of supply) can also be examined through FEW network analysis (Ruddell et al. 2014); "happiness lies in multiple pipelines" is a practical expression of resilience among oil exporters (Yergin 2011). The built infrastructure of transportation and trade—roads, ports, railways, pipelines, and power lines—is essential to our understanding of how the FEW system can adapt to exogenous stresses and shocks.

Endogenous (from within the system boundary) trends and key political decisions might have an even greater impact on FEW system performance. Consider the approval or denial of permits to build pipelines (e.g., Dakota Access, Keystone) and other critical infrastructure (e.g., nuclear power plants). Does the rapid emergence of wind and solar power increase electrical system resilience through decentralization or undermine it through intermittency? Consider past, current, and possible future environmental regulations such as Clean Water Act Total Maximum Daily Load (TMDL) restrictions on sediment and nutrient loads in watersheds, or Clean Air Act limitations on sulfur, methane, and carbon dioxide emissions, or

deregulation under the Energy Policy Act of 1992, which contributed to the 2000–2001 electricity crisis in California. Seldom do localities calculate their internal FEW system resilience or vulnerability to their own or their neighbors' regulatory decisions.

How responsive has the U.S. FEW network been to these shocks over the last half-century? We need to know whether a more fully integrated trading network improves resilience by providing more sources of supply (and demand), or whether it ensures that a disturbance anywhere ripples through the entire system, like the Northeast blackouts of 1965 and 2003. Does too much local self-sufficiency, in contrast, limit a locality's options when a local drought intensifies or critical infrastructure fails? Some evidence indicates that maximum resilience lies at a yet-to-be determined optimum between these extremes (D'Odorico et al. 2010). Network analysis can identify the range of system interconnectivity that is "just right"—that is, the best balance between efficiency and resilience to exogenous and endogenous shocks.

While the complex interdependencies within FEW systems do not lend themselves to standard network analysis, multiplex networks allow for the representation of the complex interlinkages between trade flows of different commodities (see, for example, Baggio et al. 2016) and are essential to furthering our knowledge of the linkages between independently managed, but physically interdependent, food, energy, and water systems, the economy, and human well-being. Further, multiplex, interdependent networks are key to diagnose mismatches between political and social decision-making boundaries and the interdependent FEW system (see, for example, Sayles and Baggio 2017).

DISCUSSION

A blueprint for development of few system models: Dynamic networks at the mesoscale

Modeling FEW as a system facilitates analysis of multiple objectives of performance in order to address critical knowledge gaps, especially understanding the tradeoffs and complementarities among system-level objectives of resilience and sustainability. For example, does reducing vulnerability to supply shortages reduce or exacerbate water, carbon, nutrient, HANPP and other footprints? Filling these knowledge gaps requires place-based and localized FEW systems research, with results fed into a mesoscale empirical database and, from there, to mesoscale models of the FEW system. Such a systems model, in turn, can be subjected to a barrage of potential risks in scenario form to determine critical points of vulnerability and thus identify measures to improve the FEW system at multiple spatial
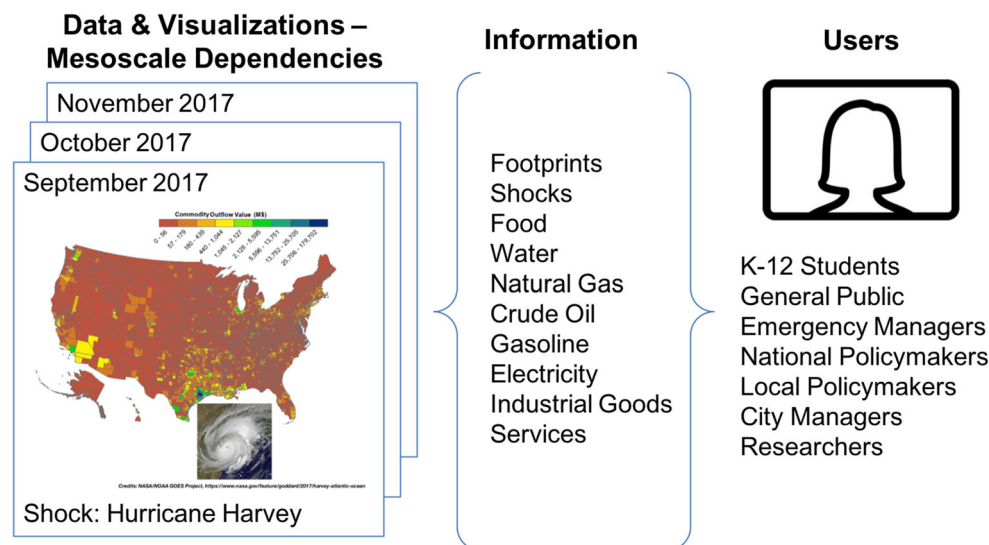
Fig. 6 Example of a data visualization framework that can be used to convey monthly information on FEW system elements at the county scale to a broad section of decision makers and the general public

and temporal scales. Such a dataset and model could be simple and theoretically consistent, complex and empirically realistic, or both. Once constructed, the general methodology could be adapted to build a similar model of the FEW system for the European Union, China, or the entire planet.

Through the National Science Foundation's Innovations in Food–Energy–Water Systems (INFEWS) program, researchers from around the U.S. have proposed to develop a sufficiently complete empirical description of the U.S. FEW system, disaggregated to the spatial mesoscale of individual counties, cities, and small watersheds (see, for example, FEWSION 2016). The analytical strategy entails integrating (1) footprint analysis with (2) production, consumption, trade, storage, and transit-mode data, to (3) construct a network model of the U.S. FEW system and its dynamics based on the observed history of recent decades. This enables a data fusion across economic sectors to assess sustainability and other performance metrics with a special focus on resilience in the face of shocks and stresses.

The U.S. FEW network can be empirically observed and reconstructed at the county and city scales to gauge how interconnections have shifted over time as: (a) populations have grown at a slower rate and become older and more urban, (b) economic growth has occurred at different rates in different places, (c) globalization has built new teleconnections, (d) agriculture has become larger scaled and more specialized, (e) climate change has become an increasing drag on yield improvements achieved through technological progress, and (f) shocks and stresses have impacted established networks. A temporally dynamic dataset holds the key to unlock the dynamics of

vulnerability and risk in an interdependent system subjected to shocks and stresses (Srinivasan et al. 2017).

Natural science is the starting point but, in the social sciences, our awareness and understanding of the system become part of the system. The scientific objective is then to empower agents with salient information. Systems are fundamentally elusive targets for policy because they are difficult to simplify and visualize, and it is hard to motivate change based on problems that people cannot directly see. Policymakers and the U.S. public need to see clear, simple, and appropriately localized (i.e., mesoscale or finer) descriptions of their FEW systems before they can understand what they may wish to change.

If these data are translated into accessible information, residents and decision makers of each U.S. county or city will be able to accurately identify where their food, energy, and water resources come from, and will be able to see the associated footprints and interdependencies (Fig. 6). With this knowledge base, they can gauge their vulnerability or resilience to a shock and the sustainability of their consumption patterns in a spatially and temporally precise manner. This kind of public visualization provides interactive guidance on how a county, city, or private-sector company can reduce impacts and vulnerability, and solidify resilience by changing FEW consumption, production processes, or trade connections. Armed with detailed, user-friendly information on an evolving position within the FEW system, each locality's leaders and supply-chain managers can take deliberate local action to improve that position. A FEW system's model and dataset should provide the information needed to facilitate this manner of ongoing adaptive management.

Taken together, the NSF INFEWS projects aim to provide the science of the human–environment with a coherent understanding of how the FEW system produces, transports, and consumes natural resources and emits wastes in a manner that integrates with, and becomes part of, the foundation of our understanding of water, energy, and biogeochemical cycles at the heart of Earth system science, which is, in the Anthropocene, interwoven with the social sciences. As a key interface between the natural and human components of the Earth system, modeling of mesoscale FEW systems is essential to the twenty-first-century science in the Anthropocene.

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