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Review

Innovating at the food, water, and energy interface

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ABSTRACT

Food, energy, and water (FEW) systems are inexorably linked. Earth's changing climate and increasing competition for finite land resources are creating and amplifying challenges at the FEW nexus. Managing FEW systems to mitigate these negative impacts and stresses is a pressing policy issue. The FEW interface is often managed as three independent systems, missing disruptive opportunities for streamlined integrated management. We contend that existing technologies can be reframed and emerging technologies can be harnessed for integrated FEW management, changing the way that each resource system operates within the broader system. We discuss solutions to three main challenges to integrating FEW system management: resolving spatiotemporal disconnections over multiple scales; closing resource loops; and creating actionable information. Sustainable resource management is critical for humanity, as well as for functioning trade systems and ecological health. Embracing integrated management in FEW systems would enable policy makers and managers to more efficiently and effectively secure critical resource systems in the face of global change.

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Contents

1. Introduction	17
2. Resolving spatiotemporal disconnections	18
3. Closing the loop and waste management	19
4. Creating actionable information	20
5. Conclusions	20
Acknowledgements	21
References	21

1. Introduction

Reliable food, energy, and water (FEW) are fundamental to modern society. Inextricable links between the often siloed systems mean the nexus is more vulnerable to stress than each of its parts (Olsson, 2013; Berardy and Chester, 2017). These stresses impede

resource security and promote non-sustainable practices (Ericksen, 2008). While linkages between these systems are recognized (Ringer et al., 2013), applied management often overlooks these links due to the complexity of understanding and governing interrelated FEW systems (Leck et al., 2015). However, growth in population and wealth as well as a changing climate makes it critical that a unified approach is undertaken to manage FEW systems. Interdisciplinary approaches are needed to build resilient resource systems that can withstand these shocks (Howarth and Monasterolo, 2016).

Climate change is making environmental stressors more

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frequent and intense, impacting FEW systems economically and environmentally. These impacts demonstrate the need for integrated resource management. For example, droughts increase irrigation demand while reducing surface water flows, curtailing water deliveries to farmers (Clark et al., 2006; Dai, 2011), decreasing hydroelectricity production (Clark et al., 2006; Dai, 2011) and promoting unsustainable groundwater extraction. In addition, residential cooling and agricultural water-pumping energy requirements are increasing and becoming more volatile due to shifting climate (Brown et al., 2013) and urbanization (Madlener and Sunak, 2011). Heat waves reduce surface and groundwater recharge, while increasing the water and energy needed for irrigated food production and air-conditioning (Procupez, 2016). Finally, changes in climate are already altering crop suitability in some places, leading to reduced yield or increased resource requirements to maintain current growing schedules, exacerbating energy demands (Lobell et al., 2008). This may cause farmers to grow crops that are better suited to their future climate than to local demand, increasing the long and energy-intensive distances food is transported (Lobell and Burke, 2008; Wheeler and Von Braun, 2013).

Facing these challenges to FEW systems requires acknowledging and exploiting their linkages in a dynamic and adaptable way (Endo et al., 2015; Smajgl et al., 2016). There is potential for great synergies between these resource systems; they all rely on each other for production and transport (Scanlon et al., 2017). However, trade-offs are forced where they compete for the same land and resources (Kurian, 2017). For example, biofuels directly compete with land that could produce food crops (Rathmann et al., 2010), and solar or wind power can make land unavailable for other uses (Fthenakis and Kim, 2009). Likewise, water used in one sector must be recycled before being available to other sectors (Miller, 2006). They are also linked through waste, which can either harm the other systems or be used as inputs. For example, food waste can be used as an energy or fertilizer source, but more likely is transported to landfills further contributing to climate change and degrading land (Parfitt et al., 2010).

Despite increasing clarity that mismanagement of each component can affect the nexus (Bazilian et al., 2011; Al-Saidi and Elagib, 2017), the integrated nature of FEW systems is not currently reflected in their management and governance (Leck et al., 2015). To date, approaches to the FEW nexus have remained largely focused on one or two resource systems (Hussey and Pittock, 2012; Kajenthira et al., 2012; Pergola et al., 2013; Nair et al., 2014; Wang et al., 2017) or on loosely-coupled systems which incorporate flows between largely independent constituent systems (Grant et al., 2012; Howells et al., 2013; Walker et al., 2014; Berardy and Chester, 2017). Australia's integrated response to the Millennium drought is an exception. It spurred that policies that bridged the water-agriculture, water-urban, and water-energy connections, that previously had been rarely utilized for applied resource management at a large scale (Sharmina et al., 2016). Additionally, Taniguchi et al. (2017) outline integrated management case studies from the Asia-Pacific region.

Our objective is to identify major challenges preventing integrated management from being implemented and describe how existing and emerging technologies may be used to overcome these barriers. Below, we describe interdisciplinary research, technology innovation, management and stakeholder engagement strategies available to address the three fundamental resource challenges. First, the supply and demand of water, energy, and food are often disconnected both spatially and temporally. Second, emphasis on waste disposal rather than waste utilization means that opportunities to close resource loops across the systems are missed. Outputs from one system are often not recognized as inputs to another

beyond basic reuse. For example, wastewater is considered as a source of water for reuse in water-scarce regions, but recapturing heat and nutrients from wastewater is overlooked in loosely coupled models. Finally, stakeholder diversity and the division of natural resource policy space means that information is not shared within and between FEW systems (Leck et al., 2015). While the solutions to nexus challenges are likely to come from sectoral research (Wichelns, 2017), to achieve holistic management in practice, these solutions must be applied to the FEW systems as one integrated system of interconnected inputs, outputs, and processes. By approaching FEW sectors as one integrated system, we aim to highlight collective problems and broad solution mechanisms that are shared across each sector.

2. Resolving spatiotemporal disconnections

Spatial and temporal disconnections abound in FEW systems. Solar energy peak production in daytime fails to coincide with evening peak energy demand (Lewis, 2007); for agricultural production, peak solar irradiance occurs during the dry season in many arid regions (De Souza et al., 2005); and food is produced far from populated urban centers (Weber and Matthews, 2008). In arid areas, water may be moved over long distances and stored to address seasonal or inter-annual discrepancies in supply and demand. While individual components of FEW systems can be managed to address these disconnections, it is at the expense of efficiency and sustainability of the whole system. Utilizing nonrenewable fossil fuels to meet peak energy demands pollutes water, land, and air (Jacobson, 2009; Erol-Kantarci and Mouftah, 2010). Energy is often required to pump groundwater or transfer surface water long distances for irrigation when precipitation is insufficient (Liu et al., 2016) and transporting food long distances to supply urban centers depends on energy-intensive refrigerated storage and transportation (i.e., the 'cold chain') (Coulomb, 2008).

These disconnections can be resolved while maintaining or improving whole-system efficiency using integrated management of FEW systems with diverse technologies (Ringler et al., 2013). Efficiency gains can be made by optimizing cold chains (Parfitt et al., 2010), transport networks (Jedermann et al., 2014), and the spatial distribution of water and energy centers (Parker et al., 2010; Newman et al., 2014) including with on-site wastewater bioenergy production (Mo and Zhang, 2013) ("minimizing 'pumping', 'treating', 'transport'; Fig. 1). Temporal resource management takes advantage of peaks and valleys in supply and demand across FEW systems. For example, the use of household smart meters allow energy prices to track demand: when demand is high, so is price, which can act to curtail usage (Beyea, 2010).

Radically transforming FEW systems will require more pervasive adoption of emerging technologies and repurposing of existing technologies. Energy, and increasingly water, systems will benefit from the expansion of smart grids, and the decreasing cost of small-scale infrastructure to enable resources to be produced, stored and used optimally in space and time. Storage and recovery technologies that utilize the integrated nature of FEW systems can reconcile temporal disparities in supply and demand; for example, renewable energies can be used at peak times to pump water into centralized or distributed elevated storage, recovering potential energy later as small-scale hydropower (McNabola et al., 2014). Opportunities to implement this strategy will expand if in-line turbines become smaller, more efficient, and more cost effective. Spatial disparities can be improved with distributed infrastructure that allows the storage and treatment of water to be spatially targeted to where it is needed (Makropoulos and Butler, 2010). For example, to minimize water pumping, managers could construct artificial or open-water wetlands (Hering et al., 2013), or

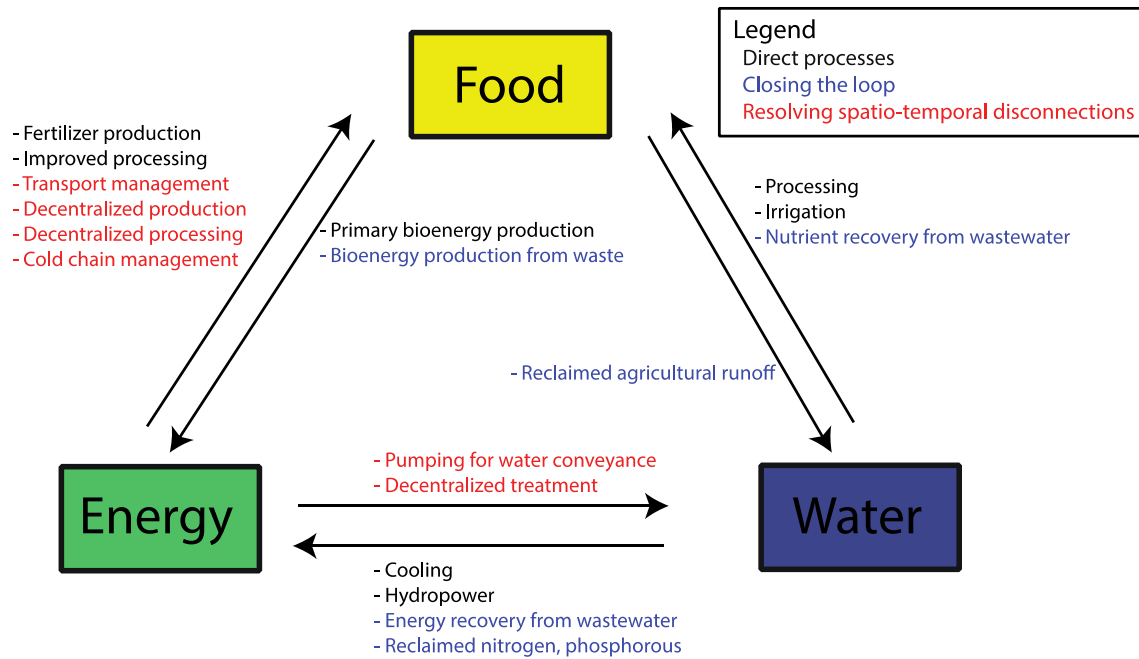


Fig. 1. Direct and indirect links between food, energy, and water systems that create one integrated system. Blue links are addressed by closing the loop, and red by resolving spatio-temporal disconnections. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

implement decentralized wastewater and reuse systems (Gikas and Tchobanoglous, 2009; Kavvada et al., 2016). Incorporating green infrastructure in urban areas, especially when it is engineered to remove contaminants, will save the resources that are lost in allowing water to run off or treating it at a remote centralized plant, and pumping it back to customers (minimize ‘pumping’; Fig. 1). Finally, in food systems, initial costs and requisite knowledge are barriers to integrating agroecological farming practices with the advanced technologies of precision agriculture. Addressing these barriers and increasing the use of precision agriculture could greatly reduce energy and water use in food production (Tey and Brindal, 2012). Shifts in technology will have tradeoffs, some of which are understood and others of which have yet to be anticipated. Yet, the sheer scale of the FEWs challenge necessitates an innovative and iterative approach to leverage new and mature technologies to achieve transformative efficiency gains.

3. Closing the loop and waste management

Pollution and waste pervade FEW production, transport, and consumption. Food production pollutes soil, water, and air with fertilizer, herbicides, and pesticides (Foley et al., 2005). Excessive groundwater pumping and irrigation pollutes soils by increasing their salinity through concentration of salts (Scanlon et al., 2007) and/or saltwater intrusion into a lowered water table (Schoups et al., 2005). Energy and water are wasted through inefficient and spatially-disparate provision, storage, and transport of food and water (Tassou et al., 2009; Stokes et al., 2013; Taptich et al., 2015); food is wasted at unsustainable levels, reducing global food security and creating a waste-treatment challenge (Foley et al., 2011). Wasting food translates to wasting the energy and water inputs that went into producing and transporting the food (Kummu et al. 2012; Food and Agricultural Organization of the United Nations (FAO) 2013). Globally, wasted food (excluding emissions from land use change) is estimated to result in 3.3 gigatonnes per year of carbon dioxide equivalents, more than the total annual greenhouse gas emissions of Russia (Food and Agricultural Organization of the United Nations (FAO) 2013). Similarly, energy is wasted when water

is wasted, and vice versa (i.e., through leaks, losses or inefficient use) (Colombo and Karney, 2002; Stokes et al., 2013). Preventing waste and harmful by-product generation and recovering and reusing waste products to close the loop in FEW systems can alleviate negative impacts on environmental and human health. Solutions should improve resource efficiency and recovery and, ideally, feed waste products back into other FEW systems.

There are substantial opportunities for resource recycling and recapture within FEW systems (Walker et al., 2014). The growing demand for fresh water can be stemmed by urban and agricultural water recycling because food and energy production do not necessarily require potable water (Daigger, 2009). Instead, quality can be targeted to end-use by considering and analysing application-specific constituent thresholds, preventing water loss, energy wastage, and chemical overuse (Norton-Brandão et al., 2013; Meneses et al., 2017). Extractive technologies can reclaim nutrients from urban and agricultural wastewater (‘wastewater nutrient reclamation’ in Fig. 1; Verstraete et al., 2009, Mo and Zhang, 2013). Reclaimed nitrogen and phosphorous can be used as fertilizer, and recovered organic nutrients are increasingly useful for human and animal consumption (Kavvada et al., 2017; Tarpeh et al., 2017). Heat, biogas, and energy-generating microbes for fuel cells can be extracted from wastewater (‘sludge bioenergy’ in Fig. 1; Meggers and Leibundgut, 2011; Logan and Rabaey, 2012; Frijns et al., 2013) and food-sector wastes (‘waste bioenergy’ in Fig. 1; Kapdan and Kargi, 2006; Cantrell et al., 2008; Franchetti, 2013; Breunig et al., 2017), providing alternative energy.

Roadblocks exist preventing efficient application of these technologies, including cost and tradeoffs between potential reuse streams, as well as overcoming the spatiotemporal disconnects discussed previously. Though capital costs for treatment facilities are high and the electricity costs are expected to rise, the cost of extracting resources will decrease with better technologies so the relative efficiency of resource recovery is expected to increase in the future (Zakkour et al., 2002; Logan and Rabaey, 2012). Considering FEW as a unified system can help to alleviate high capital costs by combining digestion of food waste with sewage sludge (Iacovidou et al., 2012). Trade-offs arise in prioritizing

resource recovery alternatives (Guest et al., 2009). For example, food waste has the potential to either provide nutrients to be used as fertilizer (Stabnikova et al., 2005) or to generate energy (Curry and Pillay, 2012). Similarly, biosolids can be incinerated or digested to generate energy and heat (Roy et al., 2011). Further, cost projections associated with strategies that close the waste loop should account for future conditions. Overall, tradeoffs must be made carefully and transparently while considering the function of the entire FEW system as well as ecological and social thresholds and requirements.

4. Creating actionable information

Data availability and reliability have dramatically increased in the data science and computing era. Methods for collecting, analyzing, and communicating complex information are constantly evolving. An unprecedented amount of data is available, and it is easier than ever to share this data with other resource sectors. Precision agriculture has developed over decades to combine state-of-the-art soil, satellite, aerial and ground sensors for tailored agricultural actions (Mulla, 2013). Precise on-farm fertilizer application and water management reduces energy and water waste, while monitoring of the entire food chain to improve efficiency and food quantity control (Gebbers and Adamchuk, 2010). Remote sensing combined with radar can accurately and continuously monitor snowpack to estimate future water supply (Patel et al., 2012; Heilig et al., 2014). Smart grid technologies facilitate optimized energy use and consumption-driven resource management across the entire network, using information and communication technologies to update an electricity sector for society's increasingly complex demands (Gungor et al., 2011; Gilbert and Zivin, 2014).

Beyond data collection of individual resources, a complete understanding of FEW systems requires identification of relationships between the different resources to understand environmental tradeoffs, avoid unintended consequences, and reveal interconnections at the FEW nexus (Curran, 1996). Lifecycle assessment (LCA) is a quantitative method for tracking inputs, byproducts, and waste of a product that integrates siloed data about each resource into an analysis of the others. LCAs can inform more resilient and sustainable FEW systems by identifying inefficiencies, synergies, or other improvements needed in the system (Stokes and Horvath, 2010; Stokes et al., 2014; Kavvada et al., 2016). Further, incorporating metrics that account for the political, institutional, and socio-economic conditions can promote effective decision-making (Kurian, 2017). For example, integrated indices could be developed paralleling indices that have been used in single systems such as the Wastewater Reuse Effectiveness Index (WREI) (Endo et al., 2015; Kurian, 2017). Such indices as well as new modeling tools being developed in the FEWS space (Daher and Mohtar, 2015; Kaddoura and El Khatib, 2017) could be instrumental in communicating complex synergies and tradeoffs between FEW system components to the public and decision makers.

However, effecting change within FEW systems relies on more than information and data (Cooke and Vermaire, 2015), but also on promoting behavioral changes with societies. For example, consumer flexibility in power use will be key to moving to less predictable renewable sources of energy (Powells et al., 2014). Increased interaction among scientists, policy-makers, and practitioners results in increased uptake of information as compared to top-down knowledge generation (Weichselgartner and Kaspersen, 2010; Lemos et al., 2012). If information or policy choices are communicated and framed in ways that do not garner sufficient support, they may fail to enter the arena of policy debate or decision-making (Vogel et al., 2007). Engaging dozens of stakeholders in decision-making that spans sectors, entire countries, and

multiple time horizons requires participatory and interdisciplinary approaches for discussion amongst stakeholders (Howarth and Monasterolo, 2017).

Without collaborative action of a diverse stakeholders, integrated management to address FEW challenges is unrealistic. Success will require coordination and cooperation between FEW professionals, resource planners, policymakers, and the public, who all have different motivations, terminology, geography, discourse, and perspectives (Ringler et al., 2013; Leck et al., 2015; Cairns and Krzywoszynska, 2016). Additionally, consumers play a key role in driving market demands, changing behaviors, and influencing policy. Research has shown that effective solutions are possible in complex situations if stakeholders have equitable access to information, and use common language (Cook et al., 2013). Emerging data-collection technologies coupled with widespread application of advanced communication strategies can bridge the data divide between the resource systems and facilitate technology transfer between urban and rural settings. Advances in ontology engineering can help all stakeholders to adapt to a common language and discourse to help cross-collaboration and communication (Kumazawa et al., 2017).

Knowledge and understanding of FEW system challenges and solutions must flow bidirectionally between experts and stakeholders. Stakeholders generate increasing amounts of data that can inform our understanding of FEW systems. However, for that information to truly be actionable, experts and scientists must also be viewed as a valuable resource for stakeholders. This can be achieved by direct consumer and stakeholder engagement, ranging from wide-ranging, passive techniques such as better labelling of FEW products (Shen and Saijo, 2009) to targeted, active strategies such as educational initiatives (Rickinson, 2001). Effective stakeholder engagement has improved drought management in Kenya (Pohl et al., 2010) and the United States (Kirchhoff et al., 2013), even though public values and understanding have complex impacts on acceptance and success of renewable energies (Bidwell, 2013). Data collection and information creation must take into account the significant heterogeneity of stakeholders within the FEW systems to increase their engagement (Ericksen, 2008). For example, information that might catalyze change by large commercial farms may not work for smaller or subsistence farmers.

Understanding these needs is not only important for instigating change, but also ensuring equity for the various actors in FEW systems. As pointed out by Cairns and Krzywoszynska (2016), questions of power have been inadequately addressed in FEWs thinking. The social, political, and decision-making power embedded in FEW systems are siloed just as technology and science are (Lebel and Lebel, 2017). Trade-offs within the FEW nexus force a negotiation between objectives and stakeholders. Subjective trade-offs can compound issues of disparate power between stakeholders (Weitz et al., 2017). Increases in public awareness of FEW nexus issues will be necessary for any broad policy changes (Portney et al., 2017). While awareness of FEW solutions can promote technology adoption, so too can technology significantly increase the scope and reach of FEW awareness campaigns. For example, urban water users with intermittent supply in Bangalore, India, are sent real-time data via SMS about when they will next be receiving water, allowing them to manage their resource-use carefully (Welle et al., 2015). While technology does not guarantee improvement in resource equality issues, increased access to and production of actionable information helps stakeholders maintain knowledge and power (Lele et al., 2013).

5. Conclusions

Climate change coupled with increased population growth,

wealth and density threaten the security of FEW systems. Meeting this security challenge requires embracing an integrated paradigm for understanding and managing FEW systems. We have highlighted existing and emerging technologies and information-driven communications strategies that can help overcome the complexities and feedbacks inherent in FEW systems. By combining technologies, management changes, and accessible information, FEW resources can be managed more effectively as an integrated system. Efficient and effective FEW management is critical for humanity as well as for functioning trade systems and ecological health. Embracing integrated management will help minimize the inevitable and stark tradeoffs policy makers and planners are likely to face in deciding how to best utilize Earth's finite resources to meet the needs of quickly growing populations.

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