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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.

Contents

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 (Ringler 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