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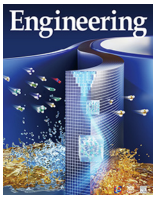

Views & Comments

Can Food–Energy–Water Nexus Research Keep Pace with Agricultural Innovation?

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1. Introduction

The interconnection among food–energy–water (FEW) systems in meeting societal demands is broadly acknowledged [1]. Similarly, competitive or synergistic allocations of water and energy resources for agricultural production, manufacturing, and human consumption are understood, and their economic impacts can be predicted [2]. Far less appreciated and understood are the outcomes of the FEW nexus in response to operation changes in agricultural practices and the associated technological innovations for future generations [3,4]. Also, the inter-scale and feedback effects of emerging technology-driven resource reallocation and decision-making on FEW systems are largely unknown. For example, how do the agroeconomic feedbacks of intelligent technologies influence the FEW nexus of agricultural production under environmental and demographic changes? How does the necessary water allocation for powering non-powered dams and pumped-storage hydropower generation influence agricultural production and municipal water supply maintenance? How do solar and wind energy farms influence land use for agriculture and the rural economy? In turn, how can the generated solar and wind energy help reduce the cost of groundwater extraction or water desalination?

Internationally, it has been a persistent challenge to achieve equality in the agricultural benefits of FEW resources among neighboring countries that depend on the same riverine system (e.g., Mekong River in Southeast Asia) [5–10]. It is evident that the complex and extensive implications of the FEW nexus demand a reorganization of supply chains; however, the required pace of sectoral reorganization and the rebalancing of resource utilization put a strain on the efficient adaptation of agricultural FEW systems to emerging technologies, both locally and globally. The transition phase of sectoral reorganization presents a particular challenge for both developed societies, which are accustomed to a diverse range of FEW resources in terms of availability, abundance, and quality, and developing societies, which suffer from FEW poverty as a result of rapid population growth and low resilience to environmental change. Unfortunately, current FEW models fail to bridge the heterogeneously responding elements of FEW systems from local to regional to global scales and vice versa, as more and more variables and interrelationships (e.g., artificial intelligent technology and deglobalization) are being realized. These problems become even more challenging when changing environmental conditions, along with unpredictable economic, social, and political consequences, are integrated into the framework of the FEW nexus in rural regions [11]. This opinion article highlights the increasing challenges due to emerging technologies for agriculture, identifies relevant knowledge gaps, and discusses technological tradeoffs. Systems approaches are suggested to promote our understanding of the agricultural FEW nexus as emerging technologies are applied to food production.

2. Challenges of increasing complexity

Agricultural activities have major impacts on the environment. For example, agriculture directly contributes 34% of global greenhouse gas (GHG) emissions and consumes approximately 70% of global fresh water [12,13]. Intensive groundwater pumping for agricultural irrigation depletes aquifers and deteriorates regional water supplies. Moreover, agriculture remains a major source of water pollution due to the application of excess synthetic fertilizers, sludge, and pesticides. On the other hand, agricultural production needs to increase by approximately 70% by 2050 in order to provide sufficient food to a population growing by an annual average of 64.5 million [14]. This goal is further challenged by degrading land, water, and energy resources and increasing competition from non-agricultural use (e.g., the energy and industry sectors). It is predicted that global water and energy availabilities will fall 40% and 50% short by 2030, respectively [15–18]. Environmental change, the rising costs of energy, labor, and agrochemicals, and supply chain disruption will exacerbate these problems [19–21]. Fortunately, technological innovations, such as precision agriculture and automation, can remedy some of these problems [22]. However, the extent of alleviation and the unintended

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consequences of emerging technologies are unclear due to their inherent sustainability tradeoffs.

3. Technological tradeoffs

Emerging technologies can play a central role in preparing agriculture to meet various restrictions and survive competitive threats involving water, energy, land, and labor resources. Remote sensing and global positioning system technologies have revolutionized commodity agriculture. The rapid development of sophisticated technologies (e.g., telecommunications, artificial intelligence, advanced sensor technology, and real-time aerial imaging), autonomous mechanical agricultural platforms, and their implements is expected to generate a new area of mechanized agriculture [23]. On the one hand, these advanced technologies will allow farms to be more profitable, efficient, safe, and environmentally friendly. For example, modern machines reduce labor requirements and fossil energy use, facilitate online trading and e-commence, reduce the consumption of water and agrochemicals by streamlining their provisioning, and lessen impacts on ecosystem health. On the other hand, application of these technologies raises concerns regarding, for example, the high maintenance cost of modern machinery, the demand for investing in and learning to use such technologies, and the liability issues of driverless agricultural machines. In addition, the use of such machines may cause farmers to lose control of their own fate and livelihood. The increasing use of modern technology-based farm equipment mainly benefits large-scale farmers because they can afford the investment, while small farm owners still depend on traditional methods. It is worth noting that 80% of food in the developing world is produced by smallholders. As a result, there is a possibility that new technologies will enlarge the equality gap between large and small farm owners—and likely between developed and developing countries as well. Therefore, prior to the adoption of an emerging technology, a nexus framework must be developed to ensure balanced resource governance among farm owners, sectors, and countries and the inclusive participation of policymakers and investors [24].

Emerging technologies can influence the FEW nexus in three zones of society: rural zones (low in both population density and FEW consumption); agricultural production zones (low in population density but high in energy and water consumption); and urban zones (high in both population density and FEW consumption) [25]. Rural and agricultural zones, which represent concentrated animal-feeding operations (CAFOs), are mostly overlapped and are responsible for ecosystem services and food production. As modern technologies are increasingly applied to agriculture, urban zones will become concentrated human–animal feeding operations (CHAFOs). This trend implies that agricultural zones will expand into urban zones. If so, a number of questions must be answered to avoid any unintended consequences. For example, can the current water resources, aging infrastructure, and energy consumption support the sustainability of CHAFOs? Will technology-intensive FEW systems become so dehumanized that it will be virtually impossible, from an economic and intellectual perspective, for populations to return to agriculture once their jobs are eliminated by a society accustomed to unmanned technologies? Will urban agriculture emerge as a meaningful alternative lifestyle and, if so, what are the social consequences of this technology-driven new FEW model in CHAFOs [26]? Can emerging technologies allow modern societies to implement urban agriculture in a sustainable manner and benefit the regional FEW nexus? How will emerging technologies influence farmers' business decisions and the global trade of FEW products? Addressing these questions will help not only in gaining the support of political groups to improve the laws, regulations, taxes, and infrastructure in the three zones but also in understanding the potential roles and tradeoffs of individual emerging technologies in securing the socioeconomic sustainability of agricultural FEW systems in the 21st century. These efforts will help to develop transdisciplinary technology systems by incorporating the favorable functions of siloed technologies into transdisciplinary solutions in a complimentary manner.

4. Research gaps

The interconnectedness and feedback mechanisms among the components of FEW systems are well acknowledged in terms of food production, water resource consumption, and energy modeling perspectives. However, existing FEW nexus models seem to lack the depth and resolution needed for assessing and predicting the complex impacts of emerging technologies on agricultural development at local to global scales. This is partly because technological innovation has not been explicitly considered in the current paradigm. For example, digital agricultural technologies provide new approaches for further optimizing the management of water and energy resources, increasing food productivity and profitability, reducing environmental impacts, and eventually reshaping the agricultural FEW nexus [23,27].

Another factor that causes uncertainty in FEW nexus modeling is resource governance, which is closely related to politics. For example, emerging technologies can increase resource use efficiency yet simultaneously lead to new sectoral interlinkages in terms of FEW demands, socioeconomic benefits, and political success [28,29]. As the known and unknown consequences of the new technologies emerge, the scope of research on the agricultural FEW nexus will broaden. As examples, 24 key research topics, challenges, and opportunities are identified in Fig. 1 [23,24,28,30–49].

5. Systems approaches

Due to the inevitable consequences of environmental change and the rapid increase in human needs, either through population growth or increased consumption, science and technology are challenged ① to advance the systematic understanding and prediction of the dynamic nature of the FEW nexus on multiple scales, and (② to develop technologies that improve, manage, and control agricultural FEW output to meet societal needs while reducing environmental impacts and improving—or at least maintaining—ecosystem services. To generate solutions to these challenges and make agriculture adaptable to the application of emerging technologies, endeavors are required to establish transdisciplinary research networks and make cross-sectoral demonstrations. These efforts should emphasize the removal or redrawing of the boundaries that currently define (and often sequester) the research of specific disciplines and the roles of governmental agencies. Here, we propose following a systems approach that can integrate different disciplines and sectors at local to global scales. Subsystems may have a scalable resolution scheme—that is, high resolution for processes within the system boundary for an inherent problem and low resolution beyond the system boundary for extrinsic influences. Global or regional information may be necessary for the predictive analysis of a local agricultural issue, but there is no need to have the same resolution at all scales. At the global scale, high model complexity, inadequate data, and limited computational capability may cause modeling overfitting and therefore hurt predictability. For example, integrated assessment modeling (e.g., the global change analysis model) connects energy, economy, agriculture, land use, and climate systems mainly through economic models. As models and variables are added, the integrated assessment modeling becomes less robust and has lower

— Marginal/compromised land use for increasing the resilience of FEW nexus [30,31]
— Agricultural by-products for strengthening FEW nexus [32]
— FEW-efficient technologies for climate-smart agriculture [23]
— Impacts of farmland-based renewable energy generation on FEW nexus [33]
— Influences of digital technologies on agricultural FEW nexus [23,34]
— Networking, standardization, and calibration of distributed FEW data resources [35]

— Impacts of FEW nexus on pest/predator life-history synchrony [36]
— Impacts of FEW nexus on adaptive and unfavorable species [36]
— Impacts of bioenergy crop landscape on FEW nexus [37]
— Role of FEW nexus in the adaptation of agroecosystem to climate change [38]
— FEW nexus technologies for developing nature-based built ecosystems [39]
— Mitigation of greenhouse gas emissions via FEW-reshaped ecosystem [40]

— FEW nexus technologies for circular bioeconomy of agriculture [41]
— Risks and benefits of FEW nexus to agricultural investors [24]
— Stakeholder economy facilitated by FEW nexus [42]
— Supply chain decarbonization via FEW nexus [43]
— Interactions between FEW nexus and agribusiness value chain [44]
— Agent-based computational economics of technology-driven FEW nexus [45]

— FEW nexus policy for circular food production [32,41]
— Governance structure to reduce FEW nexus tradeoffs across sectors and scales [46,47]
— Political mechanisms driving stakeholder participation in FEW policy process [28,48]
— FEW nexus-driven innovations of agricultural infrastructure and rural society [24,34]
— Incentives and regulations for synergizing FEW nexus benefits across sectors [48]
— Assessment and simulation of the governance of agricultural FEW nexus [49]

Fig. 1. Research gaps in the agenda of the FEW nexus of agriculture.

predication accuracy. In this case, global sensitivity analyses can help reduce the number of parameters but are still sometimes impractical, due to parameter correlation/distribution and computational complexity. It is thus necessary to develop resolution-hierarchical models across the local to global scales of specific FEW problems. In order to achieve this goal, integrated models should be more scalable and have robust connections while being able to capture major dynamics between local and global models. With more data for a specific local problem, the models can be better calibrated while avoiding overfitting at the global scale.

A systems approach enables the integration of a wide range of data, models, services, technologies, and governance. Here, we propose a conceptual approach to reorganizing numerous disciplinarily siloed systems (e.g., soil, crop, hydrology, economy, energy, and machinery) into five major transdisciplinary systems: distributed data networking, systems modeling, smart governance, converged technologies, and decentralized services (Fig. 2).

Distributed data networking connects data from multiple sources—especially those from different disciplines or sectors—and allows secure access to much more FEW data than a single or centralized site can offer. The networking provides data that can be customized with different resolutions for specific FEW problems at multiple scales, thereby supporting a scalable modeling paradigm. The data networking effort must be accompanied by input from a broad array of stakeholders—including a culturally and academically diverse public representing a range of values and behaviors—if it is to achieve technological acceptance and inform decision-making through governmental agencies in various sociopolitical systems. Such an effort is expected to identify feedback interactions in complex systems via crossing-scale analysis, prediction, visualization, sharing, and querying.

Systems modeling promotes the adoption of disciplinarily centered modeling approaches for the holistic analysis and prediction of the processes and impacts of the technology-driven FEW nexus in agriculture at local, regional, and global scales. The modeling must go beyond parameterization and optimization through model feedback analysis in order to readjust the systems modeling process. This effort can not only inform policymakers of the tradeoffs of emerging technologies but also identify and integrate local solutions for solving problems at regional and global scales.

Smart governance is the process of using innovative technologies to support decision-making and resource efficiency in a dynamic manner while minimizing risks. It creates platforms for transparent communication and collaboration between citizens and governments in FEW resource utilizations. Thus, smart governance improves not only public service delivery but also democratic processes.

Converged technologies are an integration of independent technologies into system-level engineering solutions to difficult, complex problems. This transdisciplinary system considers the chaining, fusing, complementing, and synergizing of various technologies along the intertwined chains of FEW problems. This effort

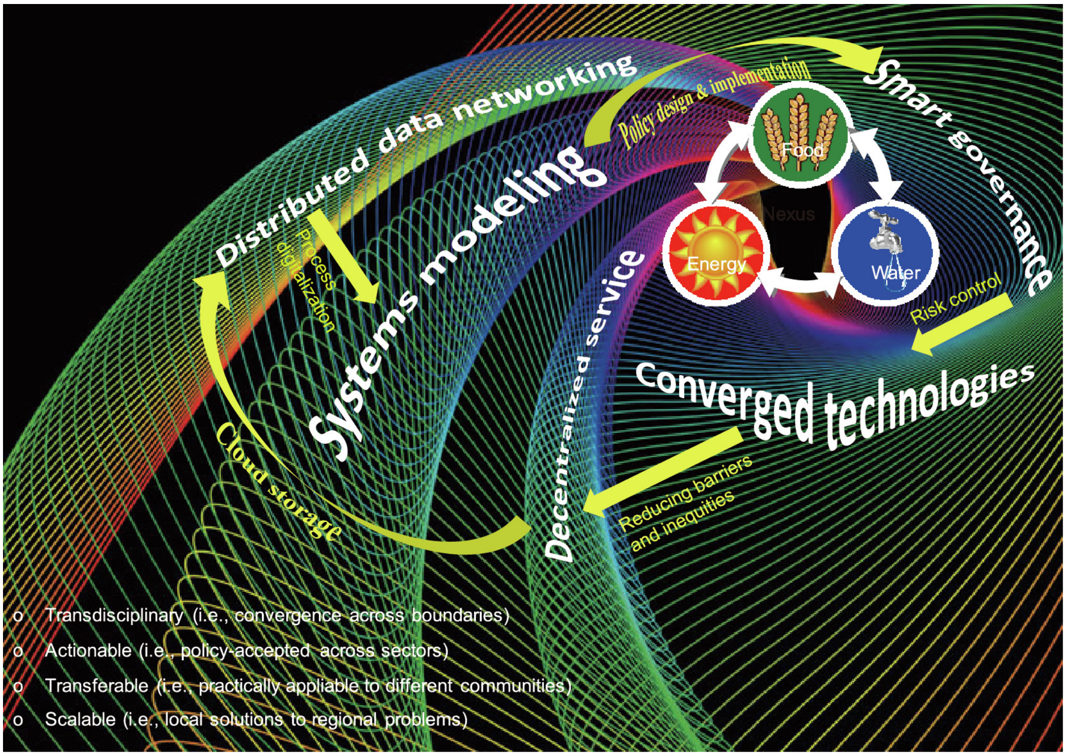

Fig. 2. Framework and characteristics of a systems approach to addressing the networked interactions associated with the agricultural FEW nexus.

reduces the counterproductive impacts of any limited, non-comprehensive approach while facilitating the efficient delivery of tangible solutions at reduced costs.

Decentralized services focus on radiating the functions and services that are usually provided by centralized facilities and/or inequitably distributed resources. Due to the broader participation of agricultural and non-agricultural sectors, decision-making is highly decentralized among various FEW stakeholders (e.g., producers, processor, and distributor), but their needs should be coordinated through teleconnections between high- and low-density areas of resources, population, production, and consumption. Decentralized services can also promote private–public collaborations across scales and sectors and accelerate the acceptance of FEW-converged technologies by farmers, investors, and policymakers.

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Compliance with ethics guidelines

Jie Zhuang, Tom Gill, Frank E. Löffler, Mingzhou Jin, and Gary S. Sayler declare that they have no conflict of interest or financial conflicts to disclose.

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