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

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## 1. Introduction

The interconnection among the elements of food, energy, and 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 FEW nexus in response to operation changes in agricultural practices and the associated technological innovations for future generations [3, 4]. Also, largely unknown are the inter-scale and feedback effects of emerging technology-driven resource reallocation and decision-making on the FEW systems. For example, how do agroeconomic feedbacks of intelligent technologies influence the FEW nexus of agricultural production under environmental and demographic changes? How does water allocation necessary to meet the needs for powering non-powered dams and pumped-storage hydropower generation influence agricultural production and municipal water supply maintenances? How do solar and wind energy farms influence land use for agriculture and 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 the equality in 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 FEW nexus demand reorganization of supply chains, but the required pace of sectoral reorganization and rebalance of resource utilization strain efficient adaptation of agricultural FEW systems to emerging technologies, both locally and globally. This transition phase of sectoral reorganization presents a particular challenge for both developed societies accustomed to a diverse range of FEW resources in terms of availability, abundance, and quality, and developing societies, which are suffering from FEW poverties as a result of rapid population growth and low resilience to environmental change. Unfortunately, current FEW models fail to bridge heterogeneously responding elements of the 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. The problems become even more challenging when changing environmental conditions, along with unpredictable economic, social, and political consequences, are integrated into the framework of 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 instance, agriculture directly contributes 34% of global greenhouse gas (GHG) emissions and consumes ~70% of global fresh water [12, 13]. Intensive groundwater pumping for agricultural irrigation depletes aquifers and deteriorates regional water supplies. Meanwhile, agriculture remains a major source of water pollution due to applications of excess synthetic fertilizers, sludge, and pesticides. On the other hand, agricultural production needs to increase by ~70% by 2050 to provide sufficient food to a growing population of annually averaged 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., energy and industry sectors). It is predicted that the global water and energy availabilities will fall 40% and 50% short by 2030, respectively [15-18]. Environmental change, 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 alleviation extent and unintended consequences of the emerging technologies are unclear due to their inherent sustainability tradeoffs.

**3. Technological Tradeoffs**

Emerging technologies can play a central role for preparing agriculture to various restrictions and competitive threats of water, energy, land, and labor resources. The 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) and autonomous mechanical agricultural platforms and their implements are expected to generate a new area of mechanized agriculture [23]. These advanced technologies will, on the one hand, allow farms to be more profitable, efficient, safe, and environmentally friendly. For example, modern machine reduces labor requirement and fossil energy use, facilitate online trading and e-commence, reduce consumptions of water and agrochemicals by streamlining their provisioning, and lessen impacts on ecosystem health. On the other hand, application of these technologies also raises concerns. For example, the high maintenance cost of modern machinery, demand for investing in and learning to use the technologies, and liability issues of driverless agricultural machine. In addition, farmers may 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 ways and methods. Worth noting is that 80% of food in the developing world is produced by smallholders. As a result, there is a possibility that the new technologies enlarge the equality gap between large and small farm owners and likely between developed and developing countries. Therefore, prior to adoption of an emerging technology, a nexus framework must be developed to ensure a balanced resource governance among farm owners, sectors, and countries and an inclusive participation of policymakers and investors [24].

The emerging technologies can influence the FEW nexus in three zones of our society. They are rural zone (low in both population density and FEW consumption), agricultural production zone (low in population density but high in energy and water consumptions), and urban zone (high in both population density and FEW consumption) [25]. The rural and agricultural zones, which represent concentrated animal feeding operations (CAFOs), are mostly overlapped and responsible for ecosystem services and food production. As modern technologies are increasingly applied to agriculture, the urban zone will become concentrated human-animal feeding operations (CHAFOs). This trend implies that agricultural zone will expand into urban zones. Then, a number of questions must be answered to avoid any unintended consequences. For example, can 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 make modern societies implement urban agriculture in a sustainable manner and benefit regional FEW nexus? How will the emerging technologies influence a farmer’s business decisions and the global trade of FEW products? Addressing these questions will help not only gain supports of political groups for improvements of laws, regulations, taxes, and infrastructure in the three zones but also understand the potential roles and tradeoffs of individual emerging technologies in securing the socioeconomic sustainability of agricultural FEW systems in the 21st century. The efforts will help develop transdisciplinary technology systems by incorporating the favorable functions of siloed technologies into the 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 on local to global scales. This is partly because technological innovation has not been explicitly considered in the current paradigm. For instance, digital agricultural technologies provide new approaches to further optimizing management of water and energy resources, increasing food productivity and profitability, reducing environmental impacts, and eventually reshaping agricultural FEW nexus [23, 27]. Another factor that causes the uncertainty of FEW nexus modeling is resource governance that is closely related to politics. For instance, emerging technologies can increase resource use efficiency but also simultaneously derive new sectoral interlinkages in terms of FEW demands, socioeconomic benefits, and political success [28, 29]. As known and unknown consequences of the new technologies emerge, the scope of research on agricultural FEW nexus will broaden. As examples, 24 key research topics, challenges, and opportunities are identified in Fig. 1.

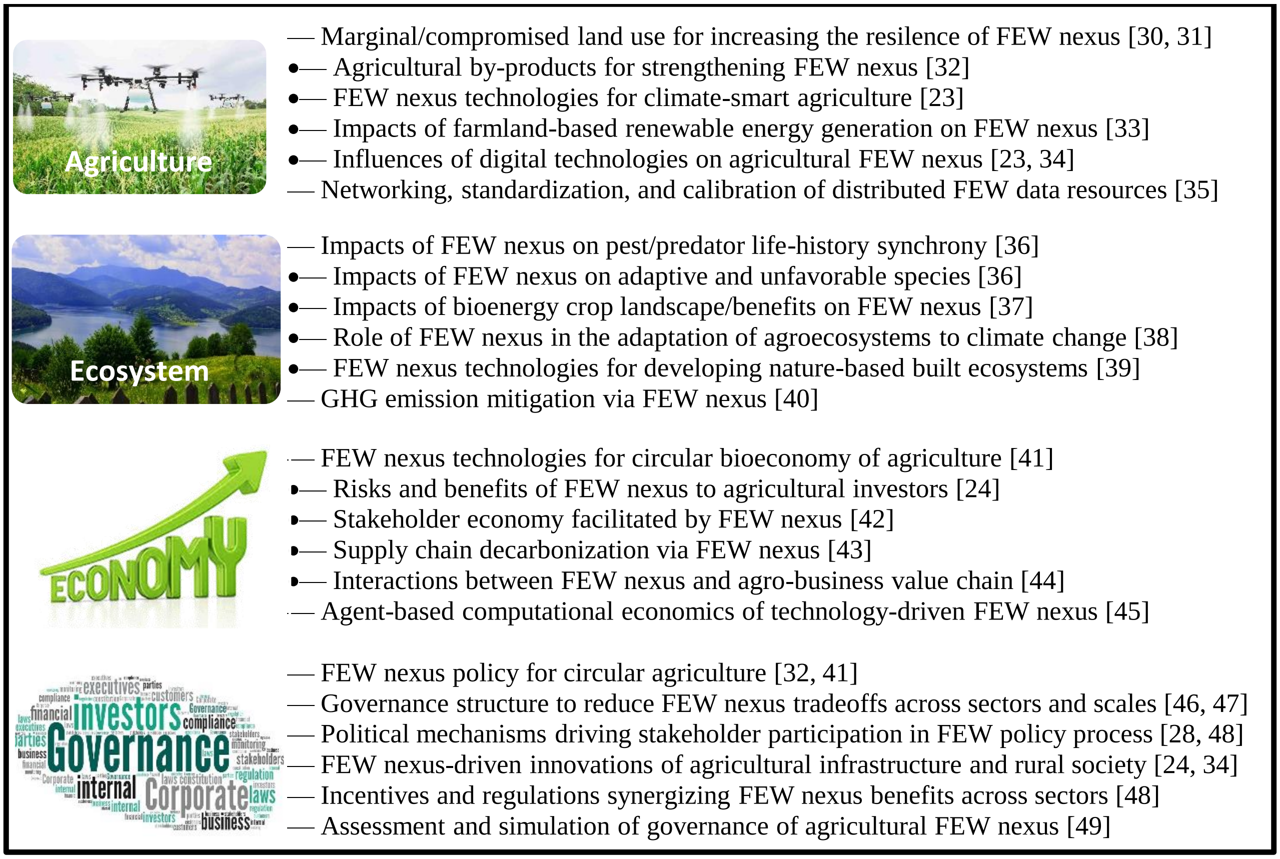


**Fig. 1** Research gaps to consummate the agenda of food-energy-water (FEW) nexus

## 5. Systems Approaches

Due to the inevitable consequences of environmental change and rapid increase in human need either through population growth or increased consumption, science and technology are challenged (1) to advance systematic understanding and prediction of the dynamic nature of 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 application of emerging technologies, endeavors are required to establish transdisciplinary research networks and make cross-sectorial demonstrations. The efforts should emphasize removing or redrawing the boundaries that currently define and often sequester the research of specific disciplines and the roles of governmental agencies. Here we propose to follow a systems approach that can integrate different disciplines and sectors at local-to-global scales. Subsystems may have a scalable resolution scheme—high resolution for the 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 predictive analysis of a local agricultural issue, but there is no need to have the same resolution at all scales. At 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., global change analysis model) has connected 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 predication accuracy. In this case, global sensitivity analysis can help reduce the number of parameters but is 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, the 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 integration of a wide range of data, model, service, technology, 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, decentralized service, converged technologies, and smart governance (Fig. 2). The 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 that 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 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 that represent a range of values and behaviors—if they are to achieve technology 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. The dynamic systems modeling is to promote the adoption of disciplinarily centered modeling approaches for holistic analysis and prediction of the processes and impacts of technology-driven FEW nexus in agriculture at local, regional, and global scales. The modeling must go beyond parameterization and optimization by making model feedback analysis in order to readjust the systems modeling process. This effort can not only inform policy-makers 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. The converged technologies refer to an integration of independent technologies into a system-level engineering solution to difficult, complex problems. It considers chaining, fusing, complementing, and synergizing of various technologies along the intertwined chains of FEW problems. The effort reduces counterproductive impacts of any limited, noncomprehensive approach while facilitating efficient delivery of tangible solutions at reduced costs. The decentralized service focuses 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 tele-connections between high- and low-density areas of resources, population, production, and consumption. The decentralized service can also promote private-public collaborations across scales and sectors and accelerate acceptance of FEW-converged technologies by farmers, investors, and policymakers.

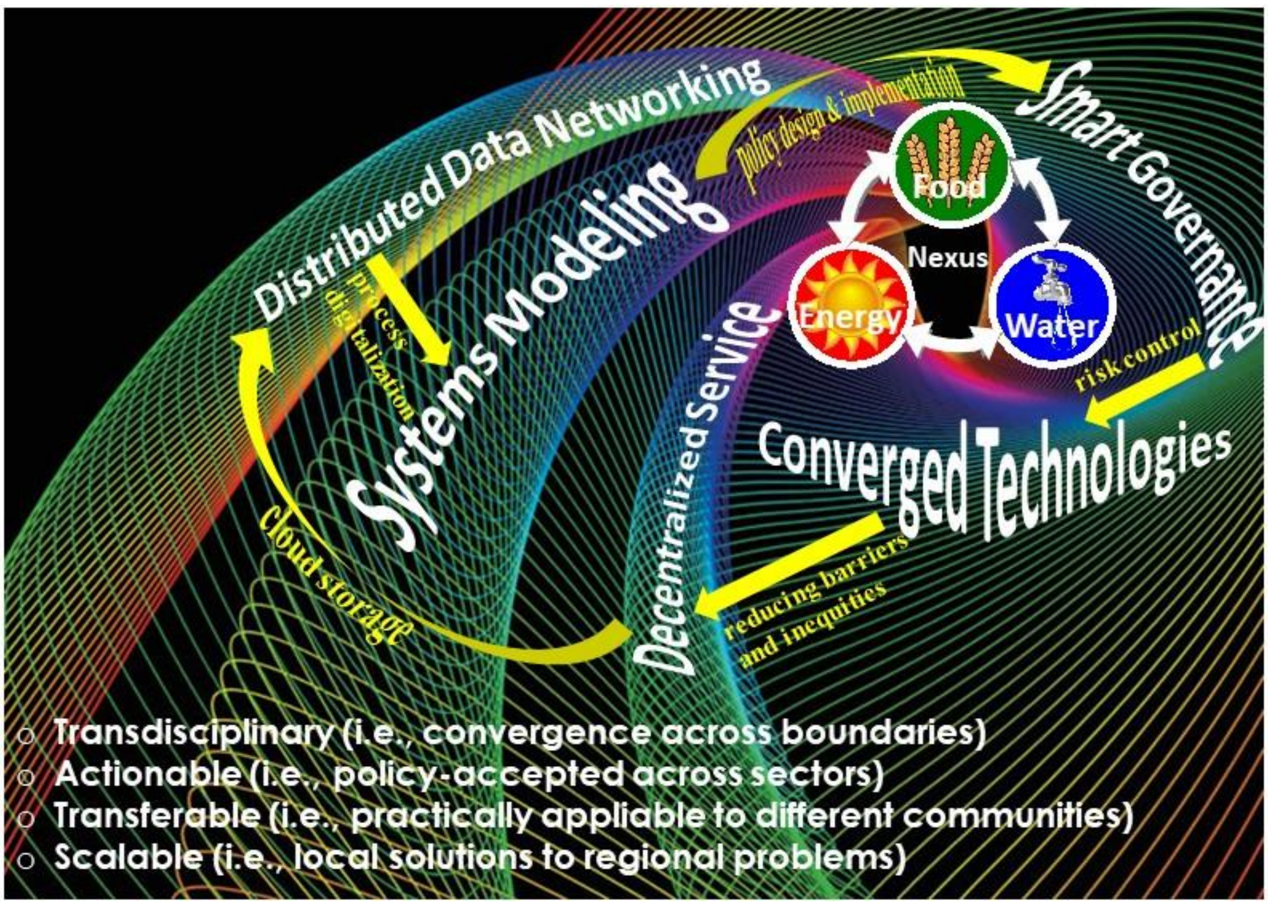


**Fig. 2** Framework and Characteristics of a Systems Approach to Addressing the Networked Interactions Associated with Agricultural Food-Energy-Water Nexus

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- Marginal/compromised land use for increasing the resilence of FEW nexus [30, 31]
- Agricultural by-products for strengthening FEW nexus [32]
- FEW nexus technologies for climate-smart agriculture [23]
- Impacts of farmland-based renewable energy generation on FEW nexus [133]
- 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/benefits on FEW nexus [37]
- Role of FEW nexus in the adaptation of agroecosystems to climate change [38]
- FEW nexus technologies for developing nature-based built ecosystems [39]
- GHG emission mitigation via FEW nexus [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 agro-business value chain [44]
- Agent-based computational economics of technology-driven FEW nexus [45]


- FEW nexus policy for circular agriculture [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 synergizing FEW nexus benefits across sectors [48]
- Assessment and simulation of governance of agricultural FEW nexus [49]

**Fig. 1** Research gaps to consummate the agenda of food-energy-water (FEW) nexus

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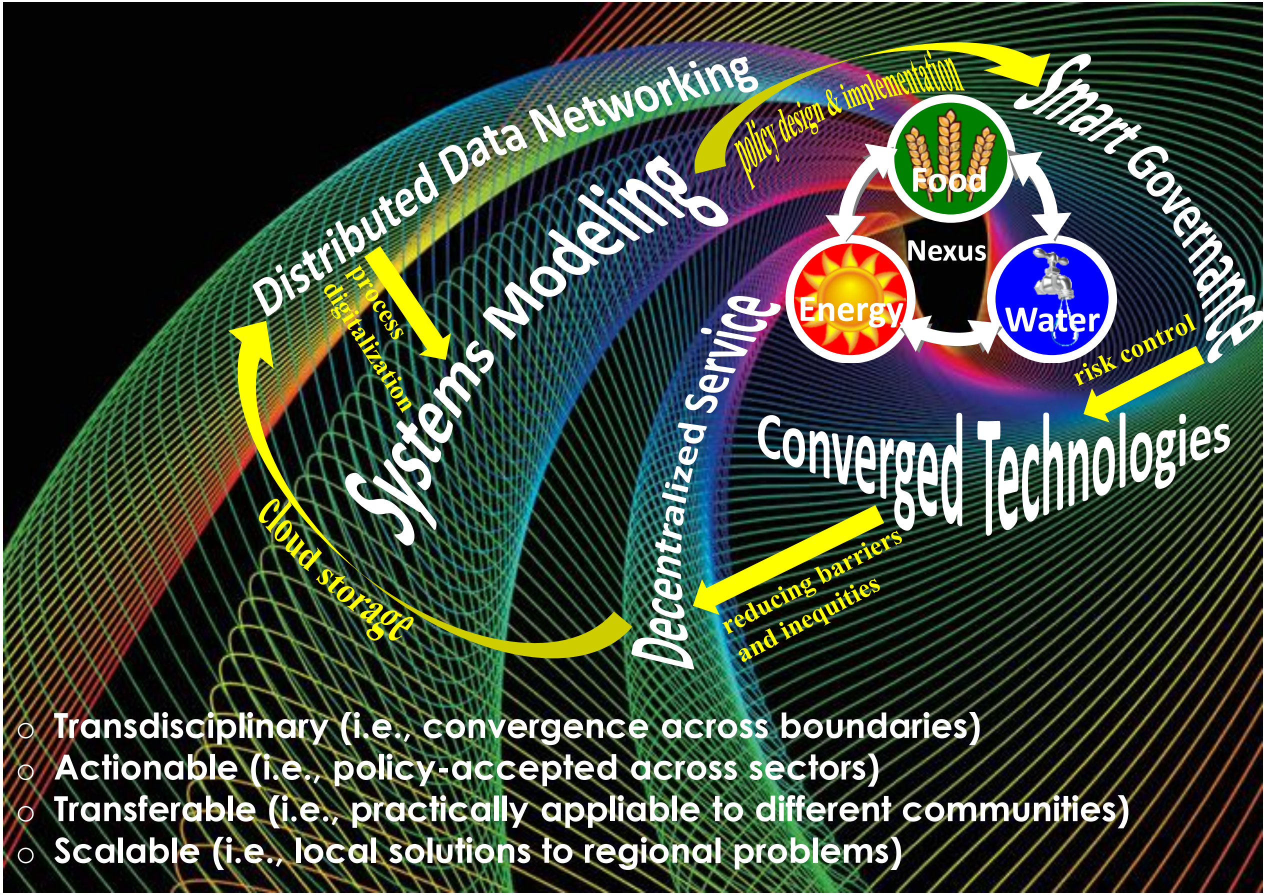
**Fig. 2** Framework and characteristics of a system-of-systems approach to addressing the complex interactions associated with the agricultural food-energy-water nexus



**Declaration of interests**

☒The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: