

# The Nexus of Food, Energy, and Water Resources: Visions and Challenges in Spatial Computing

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**Abstract** In the coming decades, the increasing world population is expected to increase the demand for food, energy, and water (FEW) resources. In addition, these resources will be under stress due to climate change and urbanization. Previously, more problems were caused by piecemeal approaches analyzing and planning those resources independent of each other. The goal of the FEW nexus approach is to prevent such problems by understanding, appreciating, and visualizing the interconnections and interdependencies of FEW resources at local, regional, and global levels. The nexus approach seeks to use the FEW resources as an interrelated system of systems, but data and modeling constraints make this a challenging task. Also, the lack of complete knowledge and observability of FEW interactions exacerbates the problem. Related work focuses on physical science solutions (e.g., desalination, biopesticides). No doubt these are necessary and worthwhile for FEW resource security. Spatial computing may help domain scientists achieve their goals for the FEW nexus. In this chapter, we describe our vision of spatial computing's role in understanding the FEW nexus from a spatial data life cycle perspective. We provide details of each of the spatial computing components. For each component, we list new technical challenges that are likely to drive future spatial computing research.

**Keywords** Food • Energy and water nexus • Spatial computing

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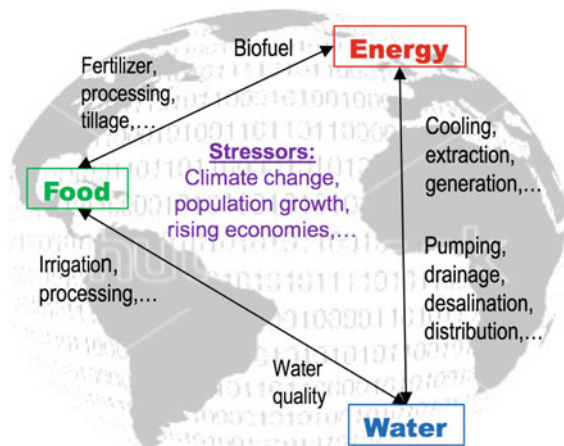
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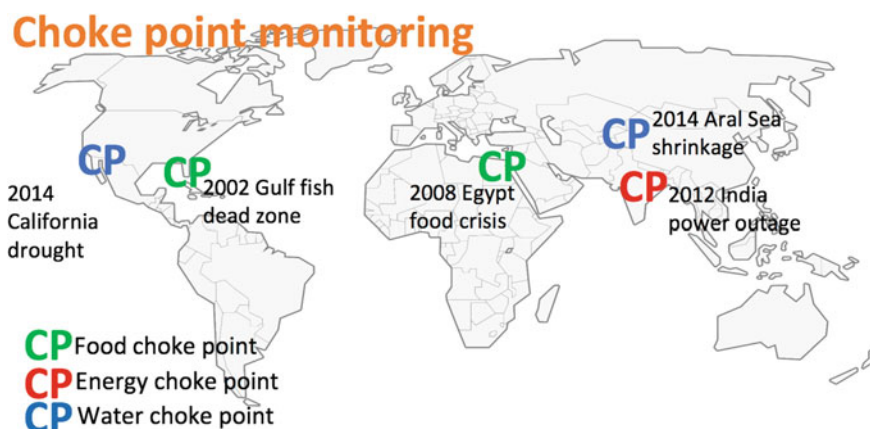
# 1 Introduction

Critical resources, such as food, energy, and water (FEW) are under increasing stress due to population growth, urbanization, and climate change (Andrews-Speed et al. 2014; Hoff 2011; NSF 2014). Although a doomsday scenario is unlikely, policy makers and industry need to take required precautions to avoid future FEW scarcities. Therefore, technological breakthroughs are needed to ensure the availability of FEW resources and to meet the needs of the world's future population (NIC 2012).

The FEW resources (NSF 2015; UNU-FLORES 2015; Holger 2011) are inextricably interconnected. This is often referred to as the FEW nexus, implying that constraints (or choke points) on one of the resources may limit the availability of another of the resources. For example, production of food or energy at a location (e.g., the California Central Valley) is limited by the availability of water. Figure 1 shows an illustration of the FEW nexus. The interdependencies can be seen in terms of the following aspects. First, necessary processes in energy production, such as cooling nuclear power plants, energy generation in hydroelectric power plants, and the extraction of coal bed natural gas for thermoelectric power plants, need water. Moreover, biofuel for energy generation needs food (i.e., agricultural products). In addition, energy is needed in water pumping, drainage, desalination, distribution, and fertilizer production for food production. However, sometimes unexpected interactions occur within FEW systems that cause harm and increase vulnerability. Examples are groundwater depletion due to high water use for irrigation purposes, groundwater pollution caused by extreme fertilizer usage in fields, surface water depletion due to energy production, and electricity blackouts due to the high energy requirements of extreme irrigation pumping.

**Fig. 1** Interaction of food, energy, and water systems





**Fig. 2** FEW choke point locations that occurred in the last decade

Significant issues arise from the interdependent and interconnected nature of FEW systems, which traditionally were analyzed and planned independently. Solutions implemented in one sector can have unintended and dangerous consequences in other sectors (NSF 2015). Figure 2 shows examples of such consequences that are shown with a choke point (CP) symbol. One example is the excessive use of fertilizers for crop production in the US Midwest, which caused nutrients to reach the Gulf of Mexico through rivers, triggering the large-scale growth of algae and a subsequent loss of dissolved oxygen in the water; this process killed fish and made the area a dead zone (Rabalais et al. 2002).

Similarly, excessive water usage for agricultural purposes caused the Aral Sea to shrink to less than half of its size in a couple of decades. In July 2012, the electricity subsidy for agricultural water pumps in South Asia during a drought led to power grid failure, triggering the largest blackout on earth (Webber 2015). An even larger cascade of events occurred across the globe in 2008, when major land use changes to boost biofuel production caused a worldwide food crisis, which in turn led to political and economic instability in Bangladesh and Egypt (Bobenrieth and Wright 2009).

The goal of understanding the nexus of FEW (Hoff 2011; Mohtar and Daher 2012; Scott et al. 2015) is to reduce the risks of unintended consequences associated with FEW resources, to improve the quality of life, to create economic opportunities, to build regulations to ensure the resilience and accessibility of FEW systems, to provide equity to people (Scott et al. 2015), and to appreciate interconnections and interdependencies across FEW systems. Better understanding the nexus of FEW also may benefit geodesign (Miller 2012), a technology that helps decide geographic-related resource arrangement. An illustrative example is that farm and water sources should not be too close because fertilizer usage may pollute

the water. In contrast, these two resources should not be too far apart because water is needed to irrigate farmland. A similar trade-off exists in deciding the distance between water resources and a power plant. By understanding the FEW nexus, geodesign may help find the “golden points” to locate the farms and power plants, critical elements in FEW systems.

We fail to anticipate and prepare for such interactions because we lack a full understanding of the FEW nexus. The world food price crisis, the South Asia blackout, and ocean dead zones are examples of the unanticipated consequences of attempting to solve FEW problems individually with incomplete knowledge of FEW interactions. We see three challenging areas that currently inhibit scientists and other stakeholders from learning what they need to about these systems. First, limited observability hinders data collection within and across FEW systems. Distributions of underground water and wind energy, for example, are very difficult to observe (Flammini et al. 2014). Second, data management and querying facilities for global FEW observations are inadequate. Without computational support, FEW datasets collected from different sources (e.g., remote sensing imagery, ground sensor observations, river networks, global supply chains) and from different geographical areas cannot be fully exploited together. Third, current research is hampered by the lack of effective data-sharing protocols across sectors and countries. Datasets from individual FEW systems are often in different formats of representation, hindering data sharing across owners (e.g., precision agricultural data from farm owners), governments, and decision makers.

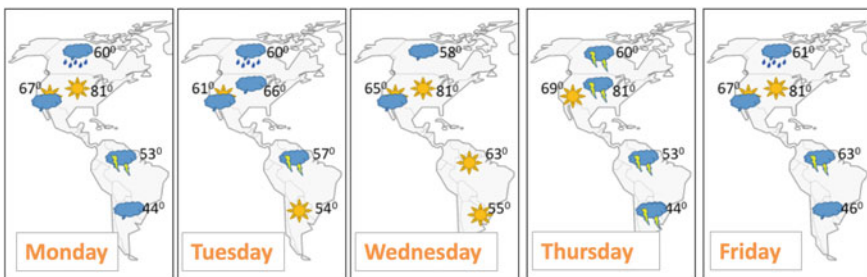
National and international agencies have begun to consider research challenges to understanding the nexus of FEW resources. A report by the Food and Agriculture Organization of the United Nations calls for stakeholder dialogue based on empirical evidence, scenario development, and response options (Flammini et al. 2014). A report by the National Science Foundation (NSF) Mathematics and Physical Sciences Advisory Committee identifies key areas where physical science could address FEW challenges (NSF 2014). Examples include developing desalination technologies to increase sustainable water supplies for agriculture and improving crop protection via biopesticides and genetic techniques. The US Department of Energy also published a report summarizing the challenges and opportunities for understanding the water-energy nexus. This report highlights promising technologies such as advanced materials, water recovery, and cooling technologies. However, all recent efforts address the problem from a social or physical science perspective without addressing geocomputational challenges in collecting, integrating, managing, analyzing, and visualizing spatial data related to the FEW nexus.

In this chapter, we identify key areas in which spatial computing can help achieve an understanding of the FEW nexus. We also list new technical challenges in each area that are likely to drive future spatial computing research. Next, we describe our vision of spatial computing’s role in understanding the FEW nexus.

## 2 A Spatial Computing Vision

We believe that spatial computing has the potential to provide transformative insights into the FEW nexus and to predict future FEW resource CPs similar to weather forecasting. In the early 1900s, weather predictions were limited to same-day forecasts. The use of radar and interpolation techniques after the World War II, however, allowed weather forecasting for three to five days, as well as early warnings before hurricanes and other extreme weather events. Figure 3 is an example of a weather forecast map that displays predictions of near-future weather event (e.g., rainy, sunny, cloudy). Similarly, spatial computing may help monitor or even project future events of either food, energy, or water resource risks (e.g., scarcity, environmental catastrophe) on a map (e.g., event type, location, time), just like weather forecasts.

Our vision is that spatial computing can offer insights into the interactions and interdependencies of the FEW nexus, as well as provide future projections and early warnings. The tools for achieving this vision will be spatial and spatiotemporal nexus data management, analytics, visualization, and decision support. For example, if we could identify and analyze the teleconnection patterns between the food crisis and biofuel production across countries that occurred in 2008, we might be able to avoid such a widespread crisis from happening in the future. Spatial analytics may improve water management at a global scale, rather than at regional or country-wide scales. For example, virtual water trade (Hoekstra and Hung 2002) could relocate water-intensive crops (e.g., cotton) from countries less endowed with water to those with a hydrological advantage (e.g., high rainfall) to leverage spatial variability of FEW resources. Spatial tools (e.g., CPs represented as critical nodes, paths, cut computations) could help support the resilience of individual FEW resources and prioritize system elements for increased redundancy. Another important theory for studying the FEW nexus is the life-cycle assessment (LCA, also known as life-cycle analysis or cradle-to-grave analysis). LCA (UNEP 2016) is a technique that determines and evaluates environmental impacts associated with all



**Fig. 3** Weather forecasts showing short-term weather predictions (temperatures in degrees Fahrenheit)

stages of a product's life cycle. Spatial computing is promising in analyzing and understanding FEW life cycles from a data science perspective.

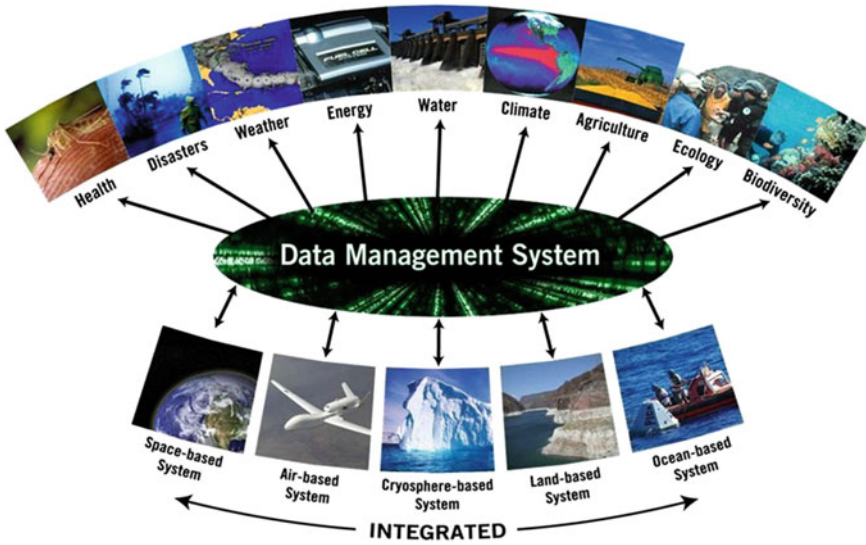
Spatial computing also will have the opportunity to tackle data paucity via remote sensing and volunteered geographic information (VGI), lack of data sharing via the exploration of common spatial data representations across sectors of food (e.g., agriculture), water (e.g., surface water and precipitation maps), and energy (e.g., wind velocity maps), and interchange methods. Spatial database management systems (DBMS) and cloud platforms (e.g., the Google Earth Engine) are also promising in providing support for efficient queries on large global FEW datasets. Another opportunity is to help discover novel, interesting, useful, but potentially hidden FEW interactions at different geographic scales via spatial and spatiotemporal data mining. Finally, spatial decision support systems may identify opportunities to relocate elements of supply chains and redesign landscapes to improve efficiency and reduce unnecessary waste in FEW systems.

## **2.1 FEW Observations**

Current spatial computing techniques, such as the global positioning system (GPS; GPS for US 2015), remote sensing satellites and planes, and ground sensor networks, already are widely used to collect rich data within FEW systems. Such data collections can provide opportunities to leverage rich geocontexts to support a global-scale redundancy of resources. In addition, advances in mobile technology, such as smart phones and location-based social networks, provide tremendous opportunities for collecting FEW data via crowdsourcing, also called VGI. For example, mWater, a mobile application for water quality monitoring, leverages mobile technology and an open data-sharing platform for water safety testing, and allows volunteers to easily find the safest water sources near them.

## **2.2 FEW Data Management**

Spatial computing techniques can support efficient management of FEW data. Recent spatial computing advances in three-dimensional (3D) modeling provide a more convenient representation of data collected from ocean and underground sensors (Heidemann et al. 2012), which was traditionally modeled by open geodata interoperability specification (OGIS) simple features in 2D space. Novel spatial big data infrastructures provide a platform to manage and analyze large-scale spatial datasets (e.g., remote sensing imagery of the entire earth) in the cloud. For example, the Google Earth Engine, for the first time ever, provides efficient storage and computation in the cloud of all kinds of remote sensing imagery of the entire earth surface over several decades. Moreover, a cloud environment nurtures the development of VGI from check-ins, tweets, geotags, and georeports (Shekhar et al.



**Fig. 4** An illustrative example of FEW data management from GEOSS (GEOSS Portal [2015](#))

[2016](#)). Finally, efficient support for spatial graph queries, such as critical node and path computation, can help enhance the resilience of FEW resources.

However, the FEW datasets are highly heterogeneous because the data collection processes are for various purposes and in various formats and spatiotemporal resolutions, limiting the potential value of the data. Spatial computing can help develop systematic data standards and data-sharing protocols considering various FEW applications as a whole (e.g., the Global Earth Observation System of Systems (Lautenbacher [2006](#)), the Nexus Observatory Platform (UNU-FLORES [2015](#)). Figure 4 illustrates a recent effort, namely, the Global Earth Observations System of Systems (GEOSS) (GEOSS Portal [2015](#)) platform, to create a unified data management system. This system stores and accesses FEW data from heterogeneous sources, including space-, air-, and land-based systems.

### 2.3 FEW Data Mining

Advances in machine learning, spatial statistics, and spatial data mining provide a data science approach for understanding the nexus of FEW resources. Traditionally, FEW systems have been studied via mechanistic process models. These models have many advantages, such as good interpretability and a capability to make future projections, but as observation data are being collected at much higher spatial and temporal resolutions, traditional mechanistic process models may fail to leverage the rich spatiotemporal contextual information that situational assessment of FEW resources require. For example, crop production used to be modeled and studied at

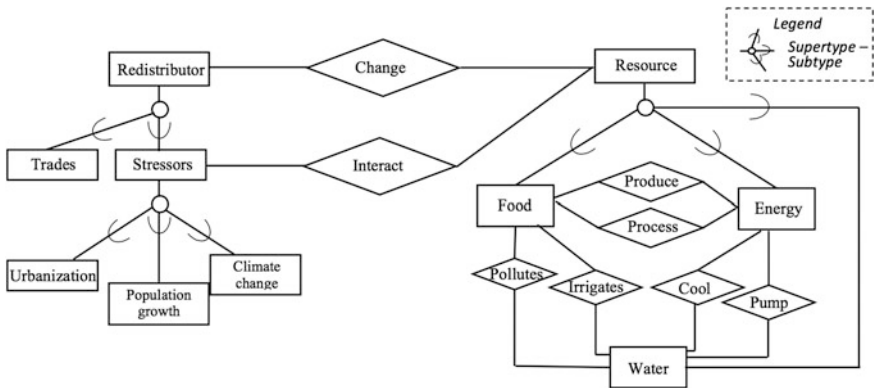


a county or state level, but with the availability of high-resolution remote sensing imagery from unmanned aerial vehicles and observations from field sensors a new discipline called precision agriculture (McBratney et al. 2005) has been developed to analyze crop production at the plot or subplot level. Spatial data science techniques will play a crucial role in providing a real-time computational analysis of the rich FEW datasets. These techniques may also identify previously unknown but potentially interesting patterns (e.g., spatiotemporal coupling or telecoupling, spatial hot spots) from FEW data. For example, LCA (UNEP 2016; Rebitzer et al. 2004) is a methodological framework that estimates and assesses the environmental impacts associated with all stages in a product's life cycle (e.g., material extraction, processing, production, usage, maintenance, and disposal). Examples of such environmental impacts include climate change, smog creation, acidification, resource depletion, water use, and land use. Using a LCA approach for the FEW nexus helps provide a more detailed perspective of impacts of a specific change in any of the food, water, or energy systems on other systems, and helps evaluate opportunities for reducing these impacts at different stages of a product's life cycle. Spatial computing is considered to be a promising data analytic technique for understanding a product's life cycle. Moreover, rich FEW data sources may improve the accuracy and timeliness of spatiotemporal predictions. Finally, spatial statistical approaches can help test the significance of these predictions.

## 2.4 *Decision Support*

Spatial computing can use FEW data in spatial decision support systems to increase the efficiency and sustainability of FEW resources. Such spatial decision support systems view FEW as a system of systems. A system is an interconnected set of elements for a purpose (Meadows 2008). Figure 5 shows an entity relationship diagram (ER-diagram) representing a system of systems view of the FEW nexus. For example, water is consumed for irrigating crops for food production and the cooling of energy plants, while energy is consumed for producing fertilizer for the process of food production and pumping water from underground for irrigation. In addition, the use of fertilizer in food production pollutes water, and food can be reused to produce energy. The system of systems view helps spatial decision support systems to increase efficient use of FEW resources (Housh et al. 2014). For example, GIS soil maps with nutrient, humidity, and chemical compound details allow users to determine optimal crop type selection in each field and to increase yields by location-aware fertilizer and pesticide use. Another example is hydro-electric production by demand instead of traditional all-time electricity production. Spatial decision support systems are used to determine the peak electricity demand hours, and electricity production is adapted accordingly. Finally, spatial decision support systems provide a unique opportunity to plan supply chain relocation and landscape redesign tasks, depending on the availability of FEW resources in specific locations.





**Fig. 5** A FEW system of systems

## 2.5 FEW Data Visualization

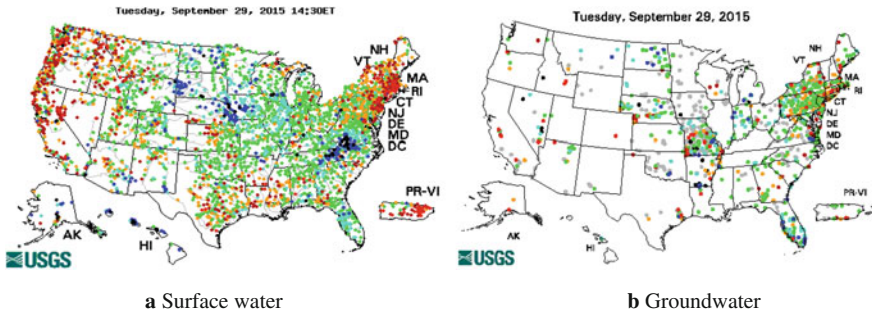
Virtual globes are already widely used to visualize environmental changes in different world regions. These visualizations not only provide historical records of FEW resources but also allow visualization of future scenarios on a global scale. Next-generation virtual globes (e.g., Google Earth, Google Map, Bing maps, and NASA World Wind) will provide a unique opportunity to visualize the interactions and interdependencies of FEW systems across the globe over a long period of time (Google Time Laps). These tools may allow users to have a common operational picture of FEW systems. Such visualization tools not only facilitate current FEW research about the effect of interactions within the FEW nexus but also assist decision-making agencies to demonstrate effectively future effects of their policies.

## 3 Spatial Computing Challenges

In spite of the potential transformative insights provided by spatial computing about the FEW nexus, significant technical challenges exist due to the unique characteristics of FEW data. This section discusses these challenges and suggests directions for future spatial computing research.

### 3.1 FEW Observation Challenges

Though recent earth observation platforms (e.g., GEOSS, Earth Observatory) show promise for collecting rich observation data, the observability challenge still exists. For example, collecting data about water quality and quantity is necessary for



**Fig. 6** Water source observation locations (USGS 2015)

understanding the water-energy nexus (Healy et al. 2015) and for determining water availability for energy production in the future. To collect water quantity data, a surface water gauging network currently is maintained by the US Geological Survey (USGS 2015) to monitor thousands of sites and groundwater observation wells nationwide. Surface water observation stations (Fig. 6a) have a larger spatial coverage and temporal frequency than groundwater stations (Fig. 6b). In contrast, to collect water quality data, the US Geological Survey operates continuous recorders at about 1,700 sites across the United States. Discrete samples are collected and analyzed by other programs as well. A need exists for remote sensing techniques that allow for the monitoring of water quality and quantity at a large scale at low expense and consuming little time. Moreover, developing new spatial data models for water quality characterization when observation data are missing is necessary.

Another challenge arises from data heterogeneity (e.g., data from different sources and in different spatial and temporal resolutions), which prohibits the integration of FEW observation data across different platforms. Therefore, spatial computing research is needed to design an acceptable standard for FEW data. Finally, data quality or accuracy is an important concern for the data collected from VGI systems.

### 3.2 FEW Data Management Challenges

Traditionally, FEW data were analyzed by individual disciplines. To facilitate interoperability for the FEW nexus data across disciplines, a comprehensive data management framework needs to be developed. However, such a framework raises new technical challenges. First, FEW data are in different representation models. For example, remote sensing imagery and climate model simulation data are often in raster form, while water census data are in vector form because they are collected at sample wells that are spatial points. Many FEW datasets are collected from 3D

Euclidean space (e.g., ocean data or subsurface data) or spatial network space (e.g., river networks), and often with the additional dimension of time, which requires novel data models and representations. Second, semantic heterogeneity exists in FEW data due to the unique data collection protocols and standards maintained by different agencies. For example, the data schema (e.g., representation, naming) used in water census data in the United States may be quite different from the ones used in China. Third, traditional spatial data management tools were designed to store and manage geometric and raster data. However, some FEW data are from VGI that often contains place-names and prepositions (e.g., near, in, at, along) instead of numerical coordinates (e.g., latitude and longitude). Therefore, a need exists for new methods to interpret these place-names and to clean data errors, evaluate trustworthiness, and avoid bias. Finally, critical node and path computation is very expensive for large FEW datasets, and efficient algorithms are needed to avoid decreases in redundancy.

### ***3.3 FEW Data-Mining Challenges***

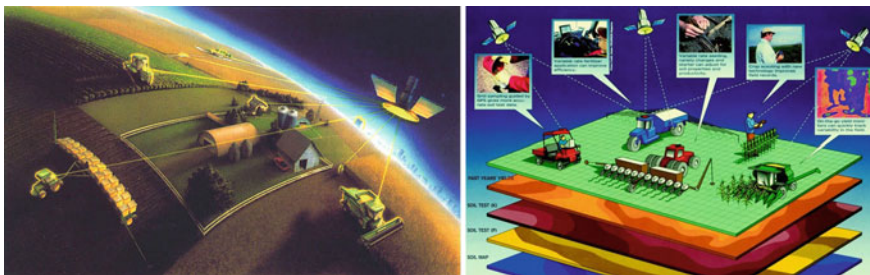
Spatial data science plays a crucial role in providing computational analysis with rich FEW data. However, significant challenges exist in utilizing these techniques, including the lack of tools for building 3D models and spatiotemporal network models (e.g., anisotropic and asymmetric spatial neighborhood), the inability to simulate the decision-making process of policy makers, and the difficulty of future projections when the assumption of stationarity does not hold.

Data science techniques, for example, have been widely used in land use change modeling, which is an important task in agriculture and water resource management (Geographical Sciences Committee 2014). Compared with other methods, data science approaches can be appropriate for situations where data concerning pattern are available and theory concerning process is scant. However, several challenges exist in utilizing data science techniques for land use change modeling. First, because machine learning and statistical approaches in data science are developed inductively on the basis of the input data, the models are particularly sensitive to an input sample. Second, both machine learning and statistical approaches generally assume stationarity in the relationship between predictor and land change variables (i.e., that the model fitted during the “training” interval can be applied to the subsequent time interval). In cases where such relationships change over time, these approaches cannot be appropriate for the projections of future scenarios. Moreover, machine learning algorithms can easily represent a variety of complex relationships but with a greater risk of overfitting. Finally, interpretation of output can be challenging because many machine learning algorithms are either “black box” or produce a map of “transition potential” for each land transition instead of producing transitional probabilities (NRC 2014).

### 3.4 FEW Decision Support Challenges

Current spatial decision support systems consider only a single resource (i.e., food, energy, or water). However, a FEW nexus approach requires that all resources be taken into account when decisions are made. In other words, a FEW nexus approach has a system of systems view. For example, in precision agriculture, as illustrated in Fig. 7, detailed observation data about crop fields collected by drones or ground sensors are used to monitor crop health and support decisions about how much water and fertilizer to apply to which plots or subplots to minimize water or energy consumption while maximizing production (NIC 2012). In general, three ways exist to capture the FEW nexus as a system of systems: mechanistic models, an empirical approach, and an optimization approach. FEW decision support systems should support users in the event that FEW resources cause spatial externalities. Also, these systems should take interconnections of FEW resources and the uncertainty of interactions into account for complicated tasks (e.g., supply chain relocation, landscape design, precision agriculture).

Therefore, precision agriculture requires monitoring and predicting FEW resources and taking required precautions. Similarly, FEW decision support systems should be able to monitor and make future projections to prevent FEW resource shortages. Some efforts have already been made to understand the FEW nexus as a system of systems. Currently, the Group on Earth Observations (GEO) (GEOSS Portal 2015), is an intergovernmental organization with 90 members and 67 participating organizations that provides an international framework for collaboration around various societal benefits, including agriculture, as shown in Fig. 8. Due to the international recognition of critical need for improving real-time, reliable, open information about global agricultural production prospects, GEO established the GEO Global Agriculture Monitoring Initiative (GEOGLAM) (Justice 2013), which provides a system of agriculture monitoring systems that uses coordinated, comprehensive, and sustained earth observations to inform decisions and actions in agriculture. The goals of GEOGLAM include supporting,



**Fig. 7** An illustration of precision agriculture (Plant et al. 2000)



**Fig. 8** An illustration of GEO (Justice 2013)

strengthening, and articulating existing efforts through the use of earth observations, developing capacities and awareness at national and global levels, and disseminating information.

### 3.5 FEW Data Visualization Challenges

Visualizing interactions between resources in the FEW nexus is one of the biggest challenges. First, such interactions happen in different spaces. For example, ocean and underground water data are often presented in a 3D Euclidean space, whereas surface stream flow data are in a 2D spatial network space. Visualizing all these water data in both Euclidean space and spatial network space is nontrivial. Second, previous visualization approaches focus on known information, but the FEW nexus requires more sophisticated techniques to visualize the uncertainty about location, value, recency, and quality of spatiotemporal information. For instance, the lack of site-specific data and the limitations of estimation models result in uncertainty when estimating water resource consumption. To visualize a map of water consumption with uncertainty or to compare two temporal snapshots with uncertain inferred change is nontrivial. Finally, FEW data visualizations should be able to handle unexpected spatial variability, such as the migration of population due to economic reasons.

## 4 Summary

The FEW nexus framework aims to view these three inextricable resources from a system of systems perspective. By understanding, appreciating, and visualizing the interconnections and interdependencies in FEW resources at local, regional, and global levels, the FEW nexus tries to achieve the goal of reducing unintended resource scarcities. To achieve the goals of resource sustainability and availability,

the FEW nexus approach applies the nexus framework at a local level of decision making and also at regional and global levels of policy-making processes.

National and international agencies recently started to focus on solving the sustainability and availability of FEW resources from a FEW nexus perspective. Current initiatives mostly focus on problems from a pure physical science perspective. For example, the NSF Mathematics and Physical Sciences Advisory Committee has a 2014 report identifying key areas where the physical sciences could address the FEW nexus, such as developing desalination technologies to increase sustainable water supplies for agriculture and improving crop protection via biopesticides and genetic techniques. Besides the physical sciences, which no doubt are necessary to solve FEW nexus challenges, spatial computing has the potential to play a critical role in helping domain scientists address the FEW nexus.

In this chapter, we aim to improve the efficiency of FEW nexus thinking from a spatial computing perspective. We envision several key components in the FEW nexus, including data collection, management, mining, and visualization, which may be how spatial computing can help improve our understanding of the FEW nexus. For each component, we also identify the main challenges from a computing perspective.

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