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Current Opinion in Environmental Sustainability

Optimizing resource use efficiencies in the food–energy–water nexus for sustainable agriculture: from conceptual model to decision support system

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Increased natural and anthropogenic stresses have threatened the Earth's ability to meet growing human demands of food, energy and water (FEW) in a sustainable way. Although much progress has been made in the provision of individual component of FEW, it remains unknown whether there is an optimized strategy to balance the FEW nexus as a whole, reduce air and water pollution, and mitigate climate change on national and global scales. Increasing FEW conflicts in the agroecosystems make it an urgent need to improve our understanding and quantification of how to balance resource investment and enhance resource use efficiencies in the FEW nexus. Therefore, we propose an integrated modeling system of the FEW nexus by coupling an ecosystem model, an economic model, and a regional climate model, aiming to mimic the interactions and feedbacks within the ecosystem–human–climate systems. The trade-offs between FEW benefit and economic cost in excess resource usage, environmental degradation, and climate consequences will be quantitatively assessed, which will serve as sustainability indicators for agricultural systems (including crop production, livestock and aquaculture). We anticipate that the development and implementation of such an integrated modeling platform across world's regions could build capabilities in understanding the agriculture-centered FEW nexus and guiding policy and land management decision making for a sustainable future.

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Current Opinion in Environmental Sustainability 2018, **33**:104–113

This review comes from a themed issue on **System dynamics and sustainability**

Edited by **Bojie Fu** and **Yongping Wei**

Received: 22 January 2018; Accepted: 06 April 2018

https://doi.org/10.1016/j.cosust.2018.04.003

The concept of food–energy–water nexus and sustainable agriculture

Food, energy, and water (FEW) are three most important resources to sustain human life and well-being [1,2]. Due to growing needs from human beings, these three types of resources are increasingly interconnected to influence social stability and economic development [3]. Agriculture is the primary sector affecting secure provision of food, energy, and water, but also one of the key sources releasing greenhouse gases to the atmosphere and moving nutrients into aquatic systems [4,5,6••]. Many studies have indicated that the increasing crop yield was obtained at the expense of losing some important ecosystem services [7••]. Agricultural production has been co-limited by the availability and accessibility of critical resources globally. Furthermore, excessive resource uses caused severe ecological and environmental consequences that affect the security of freshwater and energy [8]. Increasing water demand and conflicts among water uses in industry, urban households, and agricultural irrigation make water scarcity and water pollution a pressing issue in many regions. Agricultural practices contribute to an increasing proportion of global energy demand. To meet the growing demands for food, energy and water in a way that is ecologically and environmentally sustainable is a paramount challenge facing U.S., China, and beyond [9,10]. Although the Integrated Assessment Model (IAM) has been applied to understand the FEW nexus at the global level [11], it remains uncertain to what extent more efficient water and energy uses could improve the potential of food production while reducing its environmental damage over different regions.

Prominent cases with growing conflicts within the FEW nexus

Driven by rapid global changes such as frequent climate extremes (drought, flooding, heat wave, etc.), urbanization, and growing population, increasing pressure on available resources (e.g. land, water, energy, and nutrient) has led to more conflicts in the food–energy–water nexus across the world. As the conflict extent as well as primary drivers for FEW provisions vary over regions, stakeholders need region-specific solutions in order to maintain a sustainable agriculture system. Here we have provided three prominent cases from China, the United States and Africa to illustrate these conflicts within the FEW nexus:

China

We take the Yellow River Basin (YRB, including irrigated area of Yellow River) in China as an example. YRB is the largest river basin in northern China, draining 11.5% of national land area, which is a key food and energy-producing region in China [12,13]. Half of national coal reserves and 18% of national crop production were located in the YRB [14]. However, water shortage is a severe problem in the YRB, which has only 4% of national water resources. Agricultural water use accounts for 75% of total water consumption in this region in 2015. Over the past three decades, one third of national total crop production increase came from the YRB, which can be attributed to a 2.4-fold fertilizer use, and an 80% increase in agricultural water use. In the meantime, however, total water resources in this region declined by 11%, accompanied by serious water contamination. The annual nitrogen-related grey water footprints (water required to assimilate pollutants) of crop production grew by 24 folds [13]. The storage volume of present reservoirs along the Yellow River can irrigate 24% of cropland, but only generate 0.12‰ of the total agricultural energy consumption in its basin. More energy demand was met by coal electricity generation, which is a high water-consuming and polluting industry [15]. This FEW conflict would be worsened as the area of mechanized, irrigated agricultural land continues increasing in the YRB.

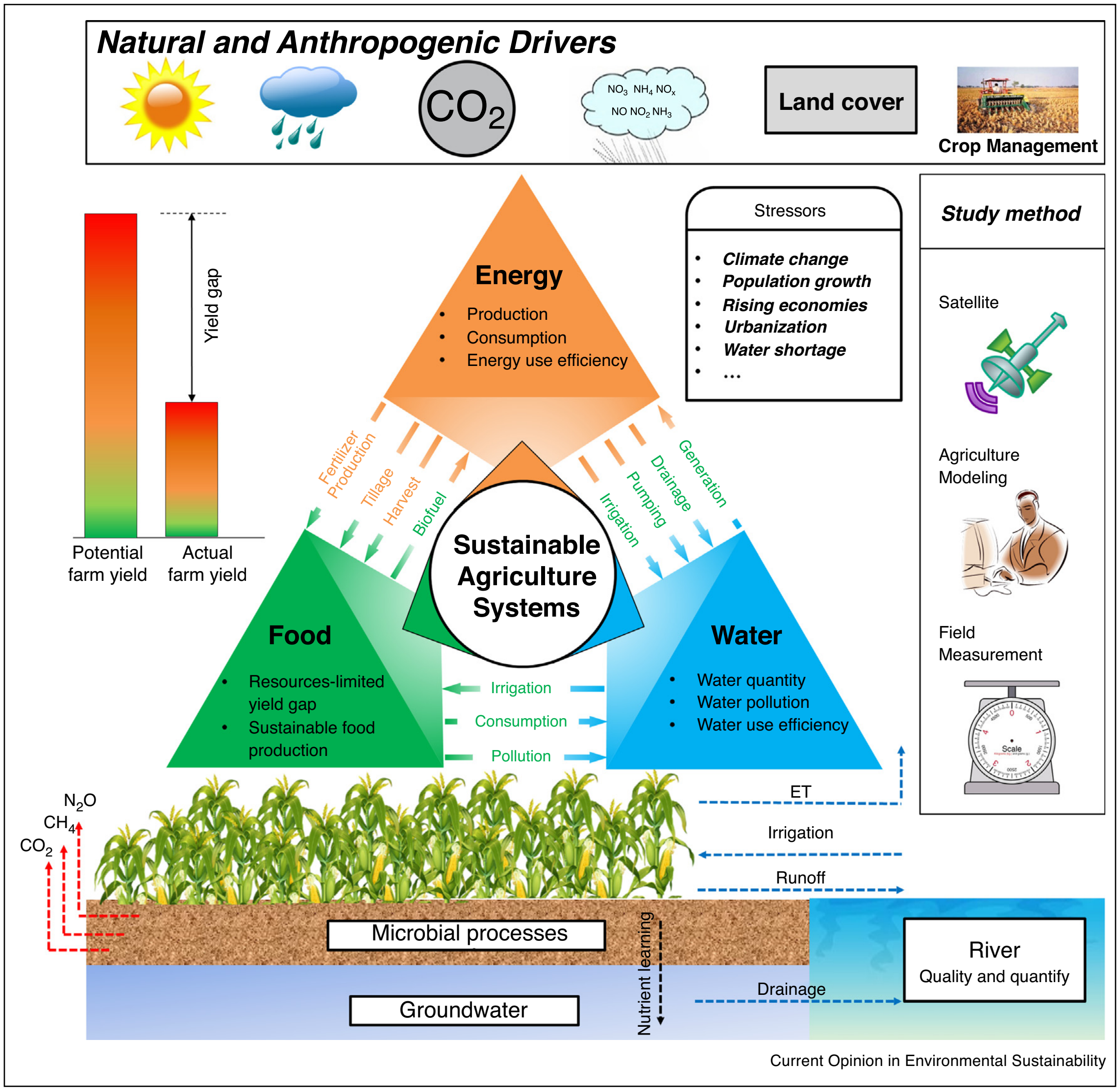
USA

Another example of growing FEW conflicts is the Mississippi-Atchafalaya River Basin (MARB), the world's third largest river basin, draining about 41% of the conterminous U.S and most area of the U.S. Corn Belt [16]. With 58% of the basin area being covered by cropland, MARB is the basis of a $100 billion annual agriculture economy [17]. Over the past half century the U.S. average corn yield has increased by three folds with a 20-fold increase in nitrogen fertilizer input [18]. A large fraction of corn grain is used for ethanol production in the U.S. [19], and this rate might be further raised because of growing biofuel demands [20••]. Roughly 36% of U.S. corn is used as animal feed [21], and animal manure contributes to 5% and 37% of nitrogen and phosphorous delivered to the Gulf of Mexico, respectively [22]. Fueled by growing bioenergy and livestock feed demands, increasing agricultural water demand, water pollution, and the consequent eutrophication and hypoxia, and damaged aquaculture and coastal ocean fisheries became a growing problem for this region [16,23,24•]. Rise in energy demand makes the conflicts between food and water even sharper. Modeling study predicts that a target of 15 billion gallons of corn ethanol would increase land-to-aquatic nitrogen export by 10–18% in the MARB [25]. Meanwhile, energy consumption in agricultural practices such as harvesting, tillage, fertilizer application, as well as water pumping and irrigation also affect crop production by limiting availability of other resources.

Africa

The African countries, where are currently experiencing food and water crisis, inadequate energy provision, and the world's fastest population growth rate, especially need renewable FEW resources [26••], but they also need to improve their livelihoods and reduce the negative environmental and social impacts [27]. To meet the food needs, large area of forest and savanna ecosystems were converted to cropland for growing food crops, with more than 80% of vegetation loss was for fuel and food production during the past several decades [28•]. The expansion of cropland area and increasing crop yield due to intensive management will in turn result in more water use through irrigation and vegetation evapotranspiration, and affect water quality through enhancing nutrient exports to the riverine systems, leading to or worsening water shortage in Africa [29]. More than 40% of its population lives in arid and semiarid regions, where insufficient rainfall limits agricultural and plant productions. Africa's agricultural systems are particularly vulnerable to climate change and climate extremes [30]. A large fraction of Africa's crop production depends directly on rainfall. Except for climatic factors, the less intensive cropland management practices (e.g. fertilizer use, irrigation, seedling improvement) are major contributors to low crop yield in the Sub-Saharan Africa as compared to other continents [31•]. The irrigated cropland area is barely 3.7% in Sub-Saharan Africa, while it is about 10%, 28%, 29%, and 41% in South America, United States, East and Southeast Asia, and South Asia, respectively [32]. The global average

Figure 1



Conceptual framework for the food–energy–water (FEW) nexus research toward a sustainable agriculture.

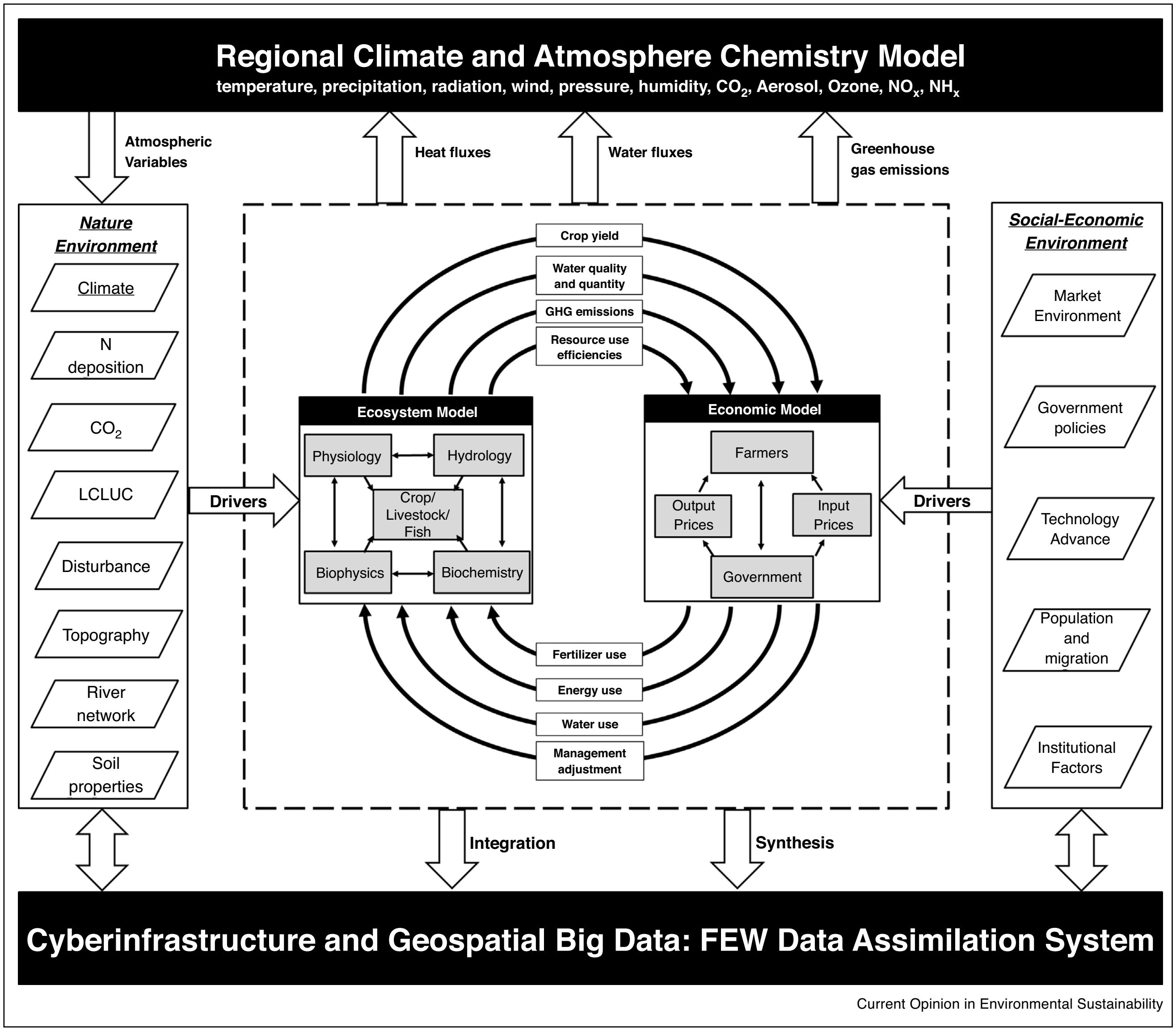
gated cropland fraction is 37.5% in 2014. The mean annual nitrogen (N) fertilizer use amount in the cropland of the Sub-Saharan Africa is only 1.6 g N/m^2 in 2014, while it is 13.6 and 27 g N/m^2 in the United States and China, respectively [32]. Given increasing resource scarcity and FEW conflicts, it calls for innovative solutions that combine sustainable FEW supplies with a series of benefits that will outweigh the economic, environmental and social costs [26••].

These regions like the YRB in China, the MARB in the US and countries in Sub-Saharan Africa are facing divergent FEW conflicts under different resource limitations. Our challenges are to develop a sustainable agriculture system suitable for a given region by optimizing resource use efficiencies, which essentially balance the functions of FEW provision and meanwhile reduce water and air pollution.

Potential solutions: resource demand, supply, and use efficiency in the FEW nexus

FEW nexus is an ideal systems framework that can guide food production toward a sustainable agriculture, that is, to meet increasing food demand for growing population but not at the cost of water and energy security. In this system, food production is co-limited by availability of energy, water, and nutrient (Figure 1). Different levels of water availability can affect crop growth, use efficiencies of resources such as energy and nutrient, and soil erosion; while crop production, in turn, consumes water and

Figure 2



The integrated modeling framework of food–energy–water (FEW) nexus for sustainable agriculture.

energy, and causes water pollution and GHG emissions by transporting excessive nitrogen and phosphorous to water and air [23,33••]. Energy availability limits practices of agricultural management such as fertilizer application, tillage, harvesting, drainage, water pumping, and irrigation, while crop production contributes to biofuel feedstock, and agricultural water consumption competes with water demand in energy generation [20••]. Overall, the imbalance between resource supply and demand in agroecosystems will impose a challenge for sustaining FEW provision and lead to increasing environmental problems [10]. Upon such a systems framework, it is urgently needed to improve our understanding and quantification of interactions and feedbacks in the FEW nexus, and agricultural uses of water and energy in competition with other sectors with a presumably constant total resource amount (that is, more agricultural water and energy use will reduce the consumption share of other sectors).

Assessing sustainability is essential for identifying vulnerabilities in the current agroecosystems so that actions can be taken to create a healthy crop production system for farmers and landowners [34]. Food, energy, and water are all crucial contributors to ecosystem sustainability, and the management toward sustainable agriculture through the FEW concept is 'a globally significant test for the implementation of this nexus thinking' [35].

Integrated modeling platform of FEW systems

A nexus-based systems modeling framework is an effective approach to evaluate to what extent the agroecosystem could sustain food provision in a way that energy and water resources can be efficiently used, and meanwhile, environmental quality would not be further damaged. Thus, it is essential to develop a regional modeling platform that can be used to quantitatively assess FEW balance and agricultural sustainability through a series of indices including crop production, efficiencies of energy, water, and nutrient uses, potentials in reducing agriculture-derived nutrient loads and GHG emissions, as well as the economic trade-offs between resource investment and product returns. We propose an integrated modeling platform of FEW nexus by coupling an ecosystem model, an economic model, and a regional climate model, aiming to mimic the interactions and feedbacks within the ecosystem–human–climate systems. It incorporates biogeochemical and hydrologic cycles, agroecosystem structure and productivity, ecosystem response and adaptation to climate system, socioeconomic processes (such as decision making and governance), and new technologies for more efficient resource utilization (Figure 2). The trade-offs between FEW benefit and economic cost in excess resource usage, environmental pollution, and climate consequences will be quantitatively assessed.

Ecosystem modeling

We adopt the Dynamic Land Ecosystem Model (DLEM) to simulate the functions and services of agroecosystem in response to climate variability as well as land use and management practices across regions. The DLEM is an integrated land system model that coupled biophysical, biogeochemical, hydrological, vegetation dynamical and land use processes in an earth system context [36•]. The DLEM is unique in incorporation of multiple environmental drivers, grid-to-grid connectivity through river systems, and simultaneous estimation of crop yield, hydrological processes (including evapotranspiration and runoff), land-to-aquatic mass flows, and land-atmosphere exchange of CO_2, CH_4 and N_2O [36•,37,38]. Its agricultural module has been intensively calibrated and validated in upland and lowland croplands across countries and entire globe in terms of crop productivity, grain yield, land-atmosphere GHG exchanges, and widely used to quantify the contributions of multi-factor environmental changes to ecosystem functions [36•,39,40]. Water and nutrient resource use efficiencies have also been examined in modeling assessment of cropland and livestock production [33••,41•]. The DLEM also simulates the effects of multiple agriculture management practices (such as irrigation, fertilizer application, tillage) on food production and GHG emissions. In addition, the DLEM is capable of simulating terrestrial carbon, nitrogen, and phosphorous yield, transfer, and decay through networked river system all the way down to ocean. It has been extensively used in the MARB and the East Coast of US to examine how climate change and human activities in upstream land ecosystem have affected downstream water quality [42,43].

Economic modeling

An economic optimization model will then examine the production efficiency by assessing the input and output of agroecosystem model from a social planner's standpoint that minimizes crop yield gap while accounting for both economic costs of water and energy and environmental externalities of using water and energy for food production. The examination of production efficiency will lay down the foundation of future studies regarding how crop trade within and between regions or nations will further improve the efficiency of FEW nexus at a country or global level.

The economic model includes three management options that differ in consideration of production constraints. The first management option, which serves as a benchmark, assumes that a social planner's target is to solely minimize the crop yield gap for a region, without accounting for the water and energy constraints in the region nor the negative environmental externalities created by using water and energy for crop production (e.g. water pollution and GHG emissions). The second management option assumes that the social planner minimizes the crop yield gap while accounting for the constraints on water and energy availability as well as the economic costs of water and energy. In the third management option, the social planner minimizes crop yield gap, accounting for both economic costs of water and energy and environmental externalities of using water and energy for food production.

Regional climate modeling

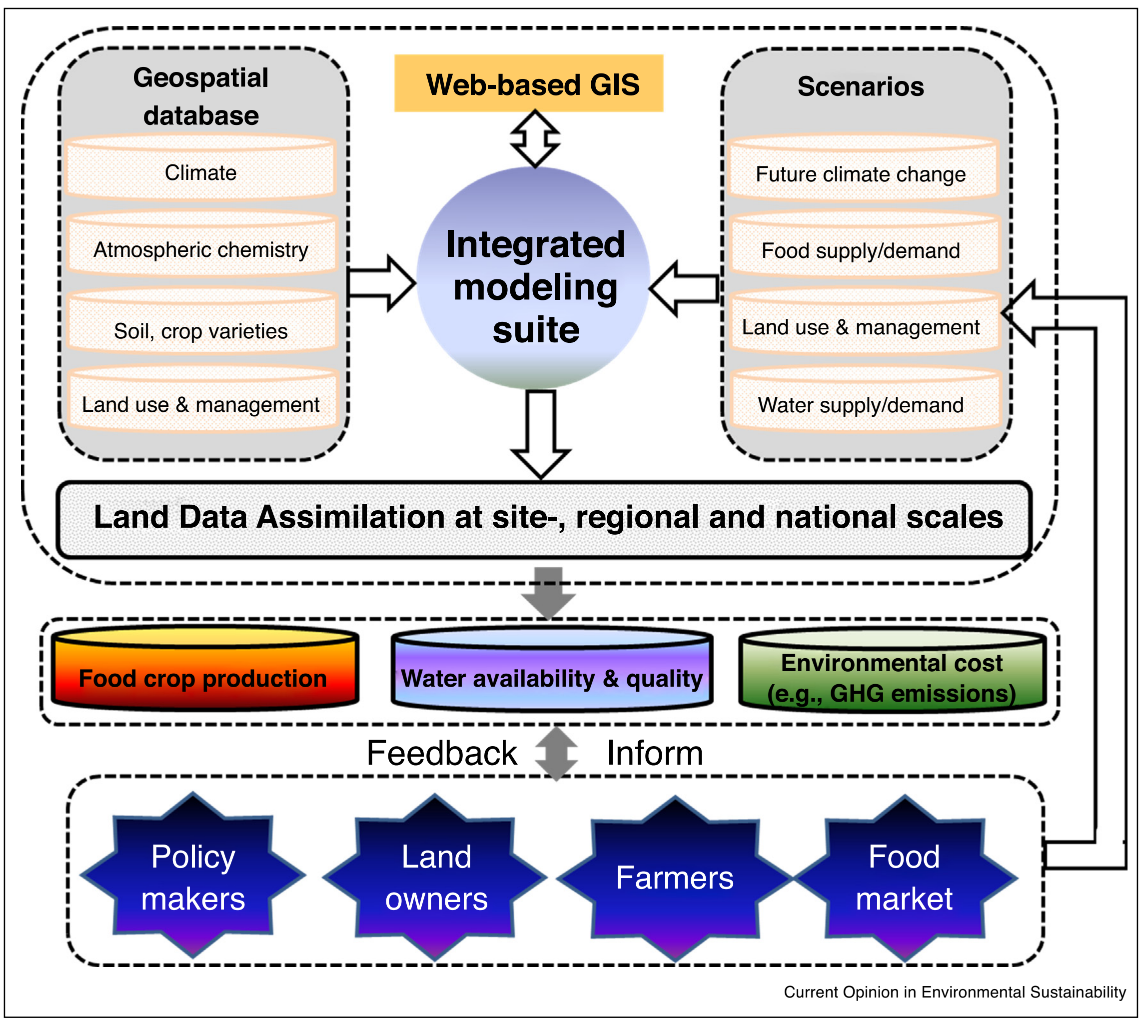
Human management practices in agricultural systems have changed land surface properties, GHG emissions, and thereafter, land–atmosphere interactions. For sustainable agricultural systems, it is important to quantify to what extent agricultural activities have influenced climate conditions and how the changed climate has feedbacks to agriculture. The Regional Climate Model (RCM) is a dynamic downscaling approach to provide high-resolution climate data. Compared to General Circulation Model (GCM), the RCM has more complex parameterization schemes and better performance in simulating the small-scale land and atmosphere physical processes. It is more suitable for applications in regional studies. In the regional modeling frame, lateral boundary conditions will be provided by the simulations of GCM, for example, Community Earth System Model (CESM) [44]. RCM provides high-resolution of climate data (e.g. precipitation, temperature, and atmospheric humidity) and atmospheric composition data (e.g. nitrogen deposition and ozone concentration) for driving land ecosystem models. Meanwhile, surface boundary conditions (e.g.

land cover type, heat fluxes, and water fluxes) simulated by the land ecosystem model will be used as input to drive the RCM.

Coupling of ecosystem, economic and climate system models

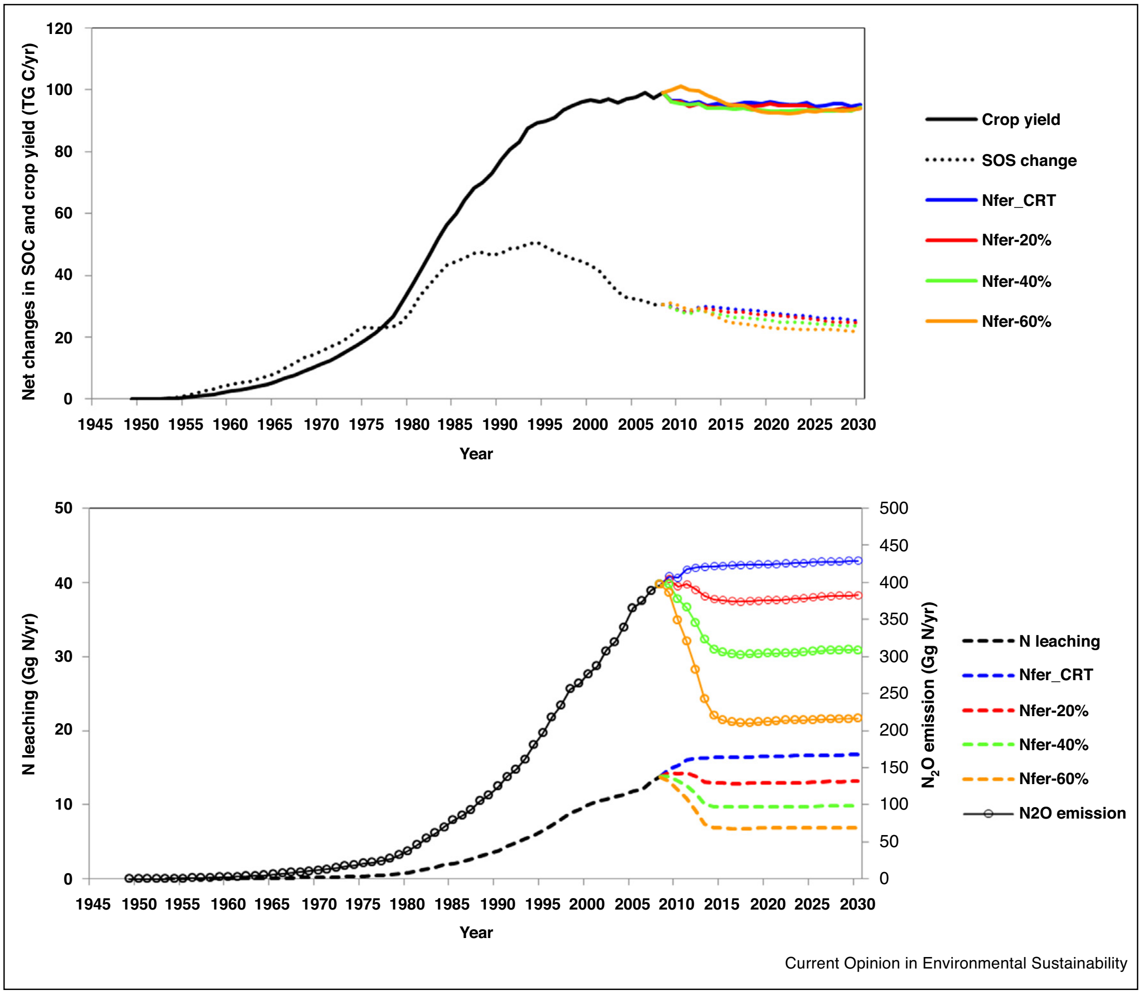
Here we present an integrated modeling framework coupling models of ecosystem, economic and climate systems (Figure 2). The integrated regional modeling framework is designated for the FEW system-modeling platform to depict major resource uses (energy, water, nutrient) and FEW linkages in agroecosystems (Figure 2). The prescribed and prognostic resource input (e.g. water, energy, and nitrogen investment in agricultural production) to drive the ecosystem model and outputs from the ecosystem model will be evaluated in economic model in terms of economic cost and benefit. The economic assessment will in turn feedback to the ecosystem model for optimizing the FEW management options. Social and economic conditions are critical elements in agricultural sustainability, and main drivers for modeling framework. We consider the impacts of multiple Shared Socio-Economic Pathways (SSPs) [45•] for specific regions, such as country-level population, gross domestic product (GDP), technology improvement, and urbanization projection. We use the systems-based modeling approach, through coupling the DLEM model with the economic decision model, to evaluate the effectiveness of the different management options that target on single or balanced outcomes of FEW indices. Land cover features and biogeochemical dynamics (e.g. albedo, GHG emissions) will be used as boundary conditions to drive the regional climate model. Ecosystem and economic models will in turn evaluate the agricultural responses and adaptation potential to the changing climate.

Figure 3



The decision support system for the food–energy–water (FEW) nexus.

Figure 4



Model sensitivity analysis: temporal patterns of N fertilizer-induced changes in SOC and crop yield **(a)**, and soil N_2O emission and N leaching **(b)** in response to N fertilizer reduction scenarios at levels of control (CRT), 20%, 40%, and 60% reduction in the over-fertilized areas of China.

Decision support system for sustainable agriculture

To support sustainable development in the FEW nexus, it is essential to develop a new cyberinfrastructure that seamlessly integrates various databases and modeling tools to provide information on resource availability (energy, water and land) and management scenarios at both management and policy making scales (Figure 3). By using geospatial BigData technology and integrated system modeling, the FEW decision support tool will integrate multiple sources of observational and projected data to directly inform and obtain feedback from users to identify the optimized land and water management practices for maximizing food production while reducing environmental costs. To develop this integrated system model and decision support system, investigators will need to develop historical and future data to drive the suite of models, analyze simulated results, and synthesize results to support decision making processes at multiple spatial and temporal scales. It is also important to develop and test a decision-support system to assimilate fine-resolution databases into the modeling suite for fully evaluating policies and management practices in sustaining agroecosystem production and reducing consequent conflicts in the FEW nexus. This system could provide stakeholders and landowners with valuable information regarding management practices to achieve the goal of sustainable agriculture, for example, fertilization amount and timing, irrigation frequency, and energy partition among different sectors.

Diagnosis and projection of FEW nexus: China's nitrogen nexus as a case study

During the development of aforementioned agroecosystem-centered FEW modeling platform, we have applied the nexus concept in modeling studies to understand a few aspects of the complex relationship among climate–

ecosystem–human systems within the integrated modeling framework. By using the DLEM model, we have quantified the role of increasing fertilizer use in stimulating crop production, net balance of greenhouse gases, and N leaching across China. Our estimations show that nitrogen fertilizer has been overly used in large cropping area of China during the past decades, and it has not further raised crop yield, but instead led to net GHG emissions from land to the atmosphere, and N leaching loss into water [33••,41•]. The hotspots of fertilizer overuse were identified as the areas where soil carbon sequestration has been fully offset (100% or more) by direct soil N_2O emissions driven by fertilizer applications. We further reduced the level of nitrogen fertilizer use in those 'over-fertilizing' areas in China by 20%, 40%, and 60%, and conducted model simulations to 2030. Model predicted that 60% reduction of fertilizer use could decrease national nitrogen yield and N_2O emission by 50% or so, but suppress crop production by only 2% (Figure 4, [33••]). Although our reduction scenario is set up with a uniform percentage, ignoring economic outcomes and feasibility, it still corroborates that China has the potential in improving agricultural resource management, maintaining crop production, and reducing environmental damage. It is essential to integrate food, energy, and water into a systems modeling framework to tackle the problems related to yield gap, inefficient resource use (limiting versus excessive), and environmental pollutions in the intensive agricultural landscapes. We expect that the integrated FEW modeling framework can improve our capability in estimation, prediction, and management support with a strong linkage in ecosystem–economic–climate components.

Closing remarks

Much effort has been made to build quantitative toolkits with a focus on part of FEW components in agroecosystem. However, it is essential to integrate key interactions and feedbacks within the ecosystem–human–climate system and provide comprehensive options for better management strategies. Here we propose to develop an integrated Regional System for FEW nexus for better understanding, evaluating and predicting dynamics and complex interactions of FEW nexus system at multiple spatial and temporal scales, which will shed light on optimizing resource uses, and building a sustainable agriculture across different regions of the world. The proposed modeling framework is composed of an ecosystem model, an economic model, a regional climate model as well as their interactions and feedbacks in the global context. It will be applicable in any agroecosystems that have the similar FEW conflicts and growing pressures from natural disturbance, increasing population and economic scarcity. In conjunction with emergent technologies such as satellite observation and BigData, we expect to provide a decision support tool for stakeholders and policy makers to make effective decisions. We anticipate that the implementation of such a coupled model and decision supporting system could allow us to evaluate how single and balanced focus of FEW pursuits will influence the agricultural sustainability, environmental quality, and economic profits across regions.

Acknowledgements

This study has been supported by National Key R&D Program of China (no. 2017YFA0604702), CAS STS Program (KFJ-STS-ZDTP-010-05), SKLURE Grant (SKLURE2017-1-6), National Science Foundation (1210360, 1243232), NOAA Grants (NA16NOS4780207, NA16NOS4780204), and AU-OUC Joint Center Program.

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