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NEXUS OF FOOD, WATER, ENERGY (R MOHTAR, SECTION EDITOR)

Model Use in WEF Nexus Analysis: a Review of Issues

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Abstract

Purpose of Review The purpose of this review was to discuss challenges regarding model use in water energy food nexus analysis.

Recent Findings Water, energy, and food (WEF) nexus analysis endeavors are relatively new. Modeling systems are just evolving and there are challenges that arise in performing high-quality analysis. We discuss many of these.

Summary Nexus modeling must represent and describe complex interrelationships among WEF systems. Modeling is a necessity as the nexus approach is about widening perspectives to unexplored levels. Nexus analysis systems must consider situations that vary from place to place and over time while integrating a family of models that address various components. Challenges arise in representing an appropriate geographic region while encompassing the relevant WEF using/producing activities along with heterogeneous, situation-specific, component interrelationships in a manner that supports decisions. Accounting for uncertainty and the evolution of population along with changes in biophysical, socioeconomic, economic, and climatic elements over time further compounds the challenge. In addition, challenges arise when one needs to describe previously unimplemented strategies both now and into an uncertain future represented by climate change, population growth, and other interacting forces. Comprehensive studies are needed to address these challenges and show the value of WEF nexus analysis. This paper addresses modeling-related challenges that arise when considering how to perform informative and accurate WEF nexus analyses.

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Introduction

Water, energy, and food (WEF) nexus[1] topic focuses on decision-making in the face of complex interrelationships among systems that produce, deliver, and use WEF goods and resources. The purpose of considering such interrelationships is to identify and capitalize on synergies between,

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[1] We limit the nexus definitional discussion as many papers review, define, discuss dimensions of and interconnectedness within the WEF nexus (see [1••, 2, 3, 4•, 5]).

for example, water and energy actions and the consequent impacts of coordinated actions relative to uncoordinated actions. The basic assumption is that decisions based on the nexus-wide considerations rather than just a focus on individual elements are likely to produce additional benefits. However, to achieve such gains requires cooperation and coordination among traditionally more domain-focused actors.

Additionally, challenges arise in adequately representing system elements that change over time because of the following: (a) growing populations that alter WEF demands; (b) climate change that alters water supplies as well as regional food, water, and energy demands; (c) ongoing aquifer and fossil fuel reservoir depletion; (d) evolving technological change that influences WEF nexus-related supplies and demands; and (e) WEF nexus involved infrastructure depreciation and resource stock/availability reductions. These dynamic elements make significant nexus management adjustments necessary both today and in the future.

Uncertainty is another complicating force. Weather fluctuations and climate change influence WEF production and input use. Technological evolution is uncertain as are future population increases and WEF consumption levels. Rates of aquifer and fossil fuel reservoir depletion can only be estimated with limited precision, a shortcoming that also afflicts our understanding of the pace and geographic extent of climate change. Collectively, such uncertainties raise needs for stochastic modeling and/or broadly scoped alternative future scenario analysis (as commonly done in climate change analysis with scenarios spanning different future levels of greenhouse gas emissions).

Addressing these issues would be greatly facilitated by WEF nexus modeling systems that assist decision-makers in consideration of WEF decisions. Such modeling systems must depict or inform on couplings, linkages, and intersections across the WEF complex, while also being dynamically capable of representing future challenges raised by population rise, climate change, resource depletion, technology change, and infrastructure depreciation along with other forces. Information is needed on many different items, including the following:

- Regional impacts on the economy, income distribution, and jobs
- Food, energy, and water demand and supply, including associated price levels
- Alternative ways of producing WEF nexus-related commodities
- WEF commodity conveyance and energy demands
- Emissions of greenhouse gases, particulate matter, soil erosion, nutrients, and contaminated water, among other items
- Allocation of land and water
- Export and import possibilities and needs
- Water treatment requirements
- Stocks of groundwater, agricultural land, oil, and other fossil energy

Efforts to model the WEF nexus must also recognize the inherent heterogeneity across regions. WEF relevant elements will vary substantially across locations. For example, some regions produce food and energy while others do not; some regions confront significant water scarcity while others perhaps have surplus; some regions are food or energy self-sufficient and are net exporters, while others are importers of energy and food; some regions rely on local supplies of water with others relying on water that originates in distant regions. It is critical for nexus models to be able to represent the heterogeneity that exists across regions and situations.

Also, one must recognize that a family of models is likely needed. Many models have evolved addressing different WEF nexus elements. Such models and elements include, for example, crop models like EPIC by Wang et al. [6] and DSSAT by Hoogenboom et al. [7], hydrologic models such as SWAT by Arnold et al. [8], regional economic crop mix and urban use models like EDSIMR by Gillig et al. [9], agricultural sector and market models such as FASOMGHG by Beach et al. [10], energy systems models such as MARKAL [11, 12], regional economic models like IMPLAN [13], economy-wide dynamic computable general equilibrium models similar to those discussed in Diao and Thurlow [14], global computable general equilibrium models such as GLOBE [15], international models of sectors and resources such as IMPACT [16, 17], and groundwater models like MODFLOW [18]. Domains of relevant models include those listed above, plus water extraction and conveyance; crop/livestock mix; crop management possibilities; population growth; climate change effects; thermal, hydropower, fracking, and bioenergy production; and energy conveyance.

Integrating these models can be challenging for a number of reasons. First, some models use very fine time steps while others assume annual or multi-year steps. Second, some models have a local focus, while others are scaled at the regional or even global level. Typically, the models focus on different nexus components although often these overlap requiring reconciliation or redesign to reflect comparative strength in element representation. Such overlap introduces the complexity of simultaneously using very fine time and space disaggregated models but yet looking at the total issue regionally, sectorally, nationally, or globally along with portraying single or multiple years in models focusing on different nexus elements. Efforts to integrate quite disparate models, whether it be over time and/or space, raises the need for a unifying overall systems model as well as clear procedures for multi-model integration.

Key Challenges/Research Questions

While the above discussion reveals many challenges associated with implementing WEF modeling and analyses, several of the more prominent and challenging aspects require additional attention and are presented below.

Scope of Nexus Issue

A fundamental challenge involves properly establishing system scope. First, decisions as to the geographic scope of the analysis must be determined with the understanding that actions in one geographic region often influence, and are influenced by, actions in another geographic region via markets or natural linkages (e.g., river systems). For instance, water withdrawals in the upper reaches of the Colorado or Indus Rivers impact the availability of agricultural and hydropower water downstream.

In addition to geographic scope, decisions regarding appropriate sectoral and resource scope are necessary and critical. An ongoing Texas case study (being done by a team including the first two authors of this paper) illustrates the complexity and challenges regarding choices related to scope. In that study, the nexus scope spans ground and surface water, electrical energy production reliant on cooling water, little hydropower, hydraulic fracturing, rapid aquifer recharge, significant irrigated agricultural acreage, rapid regional population growth, dire climate change projections, alternative water supplies from brackish and wastewater treatment plant sources, and the possibility for interbasin water transfers. Alternatively, in a prior Egyptian analysis, there are upstream water flows that need to be considered along with world markets for fruits and basic grains [19•]. In a US bioenergy production setting, one needs to consider how alterations in US agricultural commodities affect prices and, in turn, production elsewhere in the world [10]. Analysts have to regularly deal with the relative merits associated with alternative economic and geographic scope knowing that as the scope increases, one often loses depth and must increasingly model more aggregate processes (e.g., markets, income) at much cruder scales.

Complexity Considerations

Another challenge is the appropriate selection, development, and integration of diverse component models, plus development of unifying models portraying trade-offs. In the nexus context, this could involve a need for models of ground and surface water hydrology, regional economics and environment, energy production, agricultural cropping and land use, urban growth and WEF commodity usage. While some of the analysis can be performed by off-the-shelf models, including some of those listed above, often times the analysis may require the development of regionally specific data-based relations. Component models need to interact with each other and export results that can be input elsewhere while allowing for feedback effects.

Developing Useful Models for Decision Support and Dialogue

In our experience, we have found that more interactive models that provide output in a form that is easy to understand by decision-makers enhances model usefulness and longevity. Achieving this requires continual dialogue between developers and users, both to create user-friendly output as well as ensure consideration of the appropriate range of policy and management options. Strong stakeholder involvement generally improves model conceptualization, increases accuracy and representation of the feasible array of management possibilities, and reduces uncertainty surrounding the validity and reliability of results. Often integration with visualization capabilities can enhance communication and stimulate dialogue.

Modelers must also recognize that models are most useful because of the insights they provide regarding implications of novel alternatives, identification of data gaps, and key interactions (hot spots) within the nexus and as test beds for strategies. In fact, these predictive roles are often more attractive to policy makers relative to models that are confined to more normative roles which focus exclusively on identifying best strategies or conclusive "numbers."

Characterization of Uncertainty

As mentioned above, the characterization of uncertainty is critical. Uncertainty may involve year-to-year variations in water supplies and commodity prices caused by drought plus potential longer run levels of population growth, energy and commodity prices, or climate change incidence. Such uncertainties may either be explicitly represented in the model structure and/or can be the subject of alternative scenarios or Monte Carlo simulation. In the south-central Texas EDSIMR model [9], for example, shorter run uncertainty was addressed by including a representation of nine joint distributions of water availability, drought-impacted groundwater recharge, and crop yields. For long-run uncertainty, the model was run under alternative scenarios involving population and climate change futures.

Model Coupling

A major challenge is developing an automated model coupling interface that permits rapid scenario analysis. Achieving such a coupling involves establishing a multidisciplinary dialogue that facilitates proper information flows. Furthermore, model coupling greatly facilitates the identification of resource and management trade-offs and synergies as well as the economic consequences across the scope of the nexus activities.

Representing Technological Alternatives

Another challenge to useful WEF modeling and analysis is the representation of new technological and resource development alternatives that have not previously been adopted in the region. Such developments include new strategies for water and/or energy conservation, alternative land use choices, new crop and livestock enterprises, use of new interbasin transfers, desalination, increased water reuse, movement of new crops into the region, agricultural use of saline waters, use of new forms of renewable energy resources, and/or management/technology changes to mitigate greenhouse gas emissions. In this context, a key challenge is simply the identification of heretofore-unused nexus alternatives. Identification of these alternatives can be achieved via multiple pathways, including stakeholder dialogue, literature searches, examination strategies used in similar regions elsewhere, and/or scientific discussions. Once these alternatives are specified, one confronts the challenge of incorporating them into the modeling system while specifying possible alterations in model structure and developing appropriate data.

Representing the Future

Another challenge is the means of representing many diverse future forces as they influence resource supply, nexus-related production, and commodity demand such as effects of climate change, population growth, altered technology, economic growth, institutional/regulatory changes, and interregional and international trade. To further out the analysis and consideration, the more challenging it is to represent the feasible set of possibilities and effects. It should also be emphasized that the future is not likely well represented by a scenario that assumes conditions in the present are held constant over time.

Addressing Numerous Economic Issues

Demonstrating the economic benefits and costs of alternative policy options and management choices is typically essential in supporting decision-making, thereby allowing more informed decisions. Such estimated benefits and costs can also illustrate the distributional impacts of decisions on society, particularly across different income level groups. Here, we list economic considerations for WEF nexus modeling drawing upon issues identified in McCarl [20••].

Incorporation of Market Reactions and Prices

Changes in WEF use/production or allocation may lead to market price alterations. For example, corn ethanol production has raised prices which, in turn, lead to the conversion of additional land to corn cultivation resulting in altered water use in many regions as well as a more rapid depletion of groundwater stocks. Additionally, large-scale production of biodiesel resulted in market saturation in the glycerol market, a by-product. Consequently, prices dropped severely. Consideration of the direct effects from both of these outcomes on the prices of WEF production and products is warranted.

Alterations in Production Practices

Nexus type analyses are conducted frequently under the assumption of continued current practices. Thus, for example, when improving water delivery, one can assume that the same crop mix will be employed. Nevertheless, farmers may switch to crops that use more water per unit of land or expand into previously unirrigated lands [21•]. The basic issue is “How can such alterations and their implications be appropriately included in the modeling system?”

Income Distribution and Third Party Effects

Nexus actions will not make all parties better off. Actions such as drip irrigation installation or system changes to employ saline waters will often increase production costs on behalf of one party to the benefit of others but may release water for more valuable uses by others. Additionally, certain actions may result in less groundwater recharge and increased land subsidence, thereby affecting others. It is important to estimate the incidence of benefits and costs across different parties, because such information can potentially be used to design incentive and project finance systems. Third party affects are pervasive in the nexus. For example, prominent third party externalities include the health effects of particulate matter emissions from coal-based power generation, or the reductions in downstream flows from enhanced reuse upstream. Environmental externalities may also be prominent, including diminished water quality due to changes in agricultural erosion and chemical runoff or discharge of produced fracking water. Such effects need to be estimated and provided to decision-makers, although they may be difficult to estimate and may require substantial non-market valuation exercises (see discussion in Freeman et al. [22]).

Value of Water in Alternative Uses

It is important to develop information on the value of water in alternative uses, such as irrigation, ecological support, downstream urban, pollution dilution, hydroelectric use, cooling, and fracking. Such information gives insight for decision-makers when considering possible water reallocation needs and groundwater extraction rates.

Adding Consideration of Barriers to Strategy Adoption

One needs to examine and quantify the barriers that will limit the extent to which strategies can be adopted. Many things lead to or constitute barriers. These include, but are not limited to (a) lack of information, (b) limited funds, (c) target population level of education, and (d) state of technology adoption. For a more comprehensive list, see the companion data paper in this issue or the coverage in the IPCC (2014) report in chapters 16 and 17. This also implies that WEF analyses may need to include strategies that alleviate barriers such as educational programs, extension programs, loan programs, technology subsidies, and grants.

Benefits Transfer

In many cases, results from studies in other locations or contexts can be incorporated into WEF analyses, and this has stimulated a large and active benefit transfer literature as reviewed in Brouwer [23•]. For example, estimates of the value of water elsewhere could be used in the focus region. Findings from this literature indicate such transfers need to be done with caution as there are often location-specific influences. Brouwer [23•] argues that most transfers appear to result in substantial transfer errors.

Representing and Evaluating the Effects of Incentives

Nexus strategy implementation may require incentives to stimulate adoption of costly practices by groups operating within the WEF nexus that can carry out actions costing them but yielding benefits for others. Incentives can be implemented by establishing markets, regulations, technology standards, subsidies, or taxes. For example, one can introduce a water marketing mechanism that allows water transfers while also providing incentives for water transfers that increase regional benefits. One can also subsidize equipment for energy and water-conserving practices. The modeling issue is modifying the modeling framework to incorporate potential incentive schemes and then simulate decision-maker response to the availability of the incentives. Nevertheless, analysis and possible revision of incentive designs can be a valuable input into decision processes. For example, Keplinger et al. [24] in an analysis of a dry year option water market design found that early exercise of a municipal option to buy water from farmers led to lower payments while a late exercise of the contract resulted in a payment that needed to be several times higher. Their modeling solutions also suggested that the municipality should not exercise the option during El Nino years. Interestingly, in 1997—an El Nino year—the option was actually exercised only for the region to experience significantly wet conditions.

Scenario and Analysis Design

A key challenge is design of an overall analysis scheme that yields information on WEF choices. To achieve policy relevance, such scenarios generally need to be developed in consultation with stakeholders.

Data/Knowledge Gaps

Challenges also arise in data availability, use, and assembly. These issues are covered in the companion article in this issue, “Data for WEF nexus Analysis: A Review of Issues” [25].

Potential Transformative Solutions Needing More Research

Analyses of WEF nexus issues are relatively new and, consequently, many of the challenges mentioned above require more research and dialogue. The biggest transformative action currently in short supply is demonstration of the benefits to coordinated multi-sector, nexus-wide decision-making versus uncoordinated siloed domain-specific decision-making. Additionally, there is a substantial need to enhance understanding on the means to achieve broader acceptance and participation in overall nexus solutions from decision-makers in the separate domains. Consideration of both alternative institutional design and incentive structures are likely required to enhance WEF nexus collaboration.

There is also substantial need for research on model integration and the potential to incorporate visualization tools into the overall WEF efforts.

Toward an Integrated Nexus Modeling Framework

The interaction of energy, water, and food, and the value of coordinated strategies can be analyzed by integrating a coupled bottom-up family of energy, food, and water domain models with a top-down integrative and unifying model, as portrayed in Fig. 1. Developing an integrated modeling framework is essential for incorporating the full nexus scope and analyzing the impact of issues across that scope. A comprehensive assessment would encompass energy, agriculture, and water as well as environmental matters, and household welfare; such an assessment would also allow for the identification of trade-offs across sectors to guide robust WEF-related management and development activities.

Such analyses can be conducted at various levels. Analysis of specific regional management strategies requires regionally detailed models representing spatial locations of water facilities, energy and food flows, urban demands, rural energy and

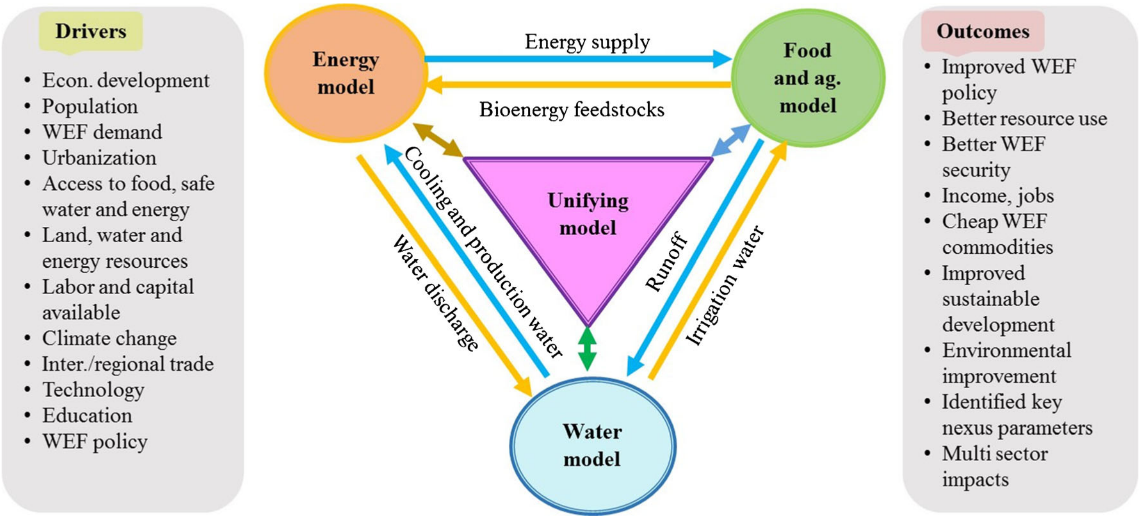

Fig. 1 An integrated WEF nexus modeling framework

water use, water supplies, flows and aquifer recharge, among other items. Broader analyses are also important and include representing items at national or global scales where markets and income considerations are important. Here, we discuss and reference nexus analyses that have been done at very different geographic scales in an effort to illustrate scale-based concerns that arise.

Regional Scale

At the regional scale, one typically represents rather spatially detailed locations of farms, water withdrawals, river tributaries, points of aquifer recharge and discharge, energy generation and mining operations, energy conveyance, energy demand, food demand, and both imports and exports among other items. Gillig et al. [9] performs such an analysis regarding WEF issues in the area surrounding San Antonio Texas. Their unifying model depicts regional dryland and irrigated farming, water diversion/pumping, river water flow in five rivers, environmental indicators, and aquifer elevation status. The unifying model when solved generates output on water prices, water use and allocation, farming crop mix, irrigation strategy, aquifer levels, spring flow discharge into rivers, farm incomes, municipal and agricultural pumping, pumping lifts, and energy use among other items. The model integrates inputs from (a) ground water models that simulate aquifer level, pump lift, and spring flow discharge given alternative amounts of pumping in different modeled regions; (b) crop growth models that simulate dryland and irrigated crop yields along with water use plus erosion and nutrient flows under different irrigation strategies and climate conditions; (c) river hydrology models that simulate levels of aquifer recharge, net inflows at river locations, evaporation and reservoir operations, and water quality characteristics given erosion and nutrient discharges again under different climate conditions; (d) economic models of urban water demand given water price and climate conditions; and (e) engineering models of the cost, water availability, and conveyance requirements from a number of water development alternatives (reservoir construction, water pumping and conveyance from distant locations, and conservation incentives among others).

This unifying model, then, solves for a simultaneous economically optimum water and land allocation across urban, industrial, and agricultural users coupled with an optimal choice among the water development alternatives. Iterative linkage of the models has been used to refine estimates between the unifying and supporting models. Additionally, depending on the focus of the study, price changes may be brought in for agricultural commodities from national or global models to represent such things as the price effects of climate change (see the San Antonio, Edwards Aquifer study of climate change by Chen et al. [26] that incorporated prices from Reilly et al. [27] that were generated using a national model). Another study with this model addressed regional performance with and without water markets [28].

Today, the model is being expanded to in the energy dimension by including thermal energy cooling, hydropower, and hydraulic fracturing.

National Scale Partial Equilibrium

A number of national scale WEF nexus analyses have been completed that employ components such as agricultural and energy sector models. For example, the National FASOMGHG model [10] was used to examine marginal land use for bioenergy with a focus on food, water, and energy trade-offs [29]; climate change mitigation that examines bioenergy and other agricultural alternatives for greenhouse gas emission reduction and their implications for food production, energy production, and water use/quality implications

[30•]; and the implications of alternative renewable fuel standard provisions [31]. Here, we discuss broad characteristics of those studies.

This modeling system and its component models are portrayed in Fig. 2. Component models include and account for river water flows, aquifer pumping costs, crop and livestock yields/water use, pest incidence under different climates, GHG emissions from bioenergy production, transport costs, commodity demand, climate change, and downscaled climate. The unifying FASOMGHG model is run under scenarios related to carbon prices, renewable energy requirements, and marginal land yields for energy crops. In turn, the FASOMGHG output includes agricultural commodity market prices and quantity levels, land allocations, crop and livestock mixes, total agricultural production, water use, bioenergy processing and production, total GHG emissions, nutrient and erosion discharges, domestic consumption, exports and imports, feed mixes, commodity transport, and many other factors. Model solutions can be scaled down to the county level with water quality and transport simulators used to further examine scenario consequences, as done in Murray et al. [30•]. Such a framework could also be linked to a general equilibrium framework when the scenarios lead to significant price effects and income changes. Similarly, links with regional analyses can convey market information into regional models.

National and Global Scale General Equilibrium

Aggregate analysis can also be performed at the national or global scale using general equilibrium approaches to examine the implications for the prices and quantities produced of energy, water, and food under various scenarios.

At the global scale, Ringler et al. [17] combined a global CGE that included energy and food considerations with the IMPACT partial equilibrium, agriculture, and irrigation sector model to analyze the impact of a carbon tax on water and food security. They found that increased fossil fuel prices would affect energy fossil fuel production and refined petroleum importing regions but would not have large impacts on global food prices. Additionally, they found a 9 million person increase in those at risk of hunger and an increase in water security. On the other hand, they found positive effects from a lessening in extent of climate change.

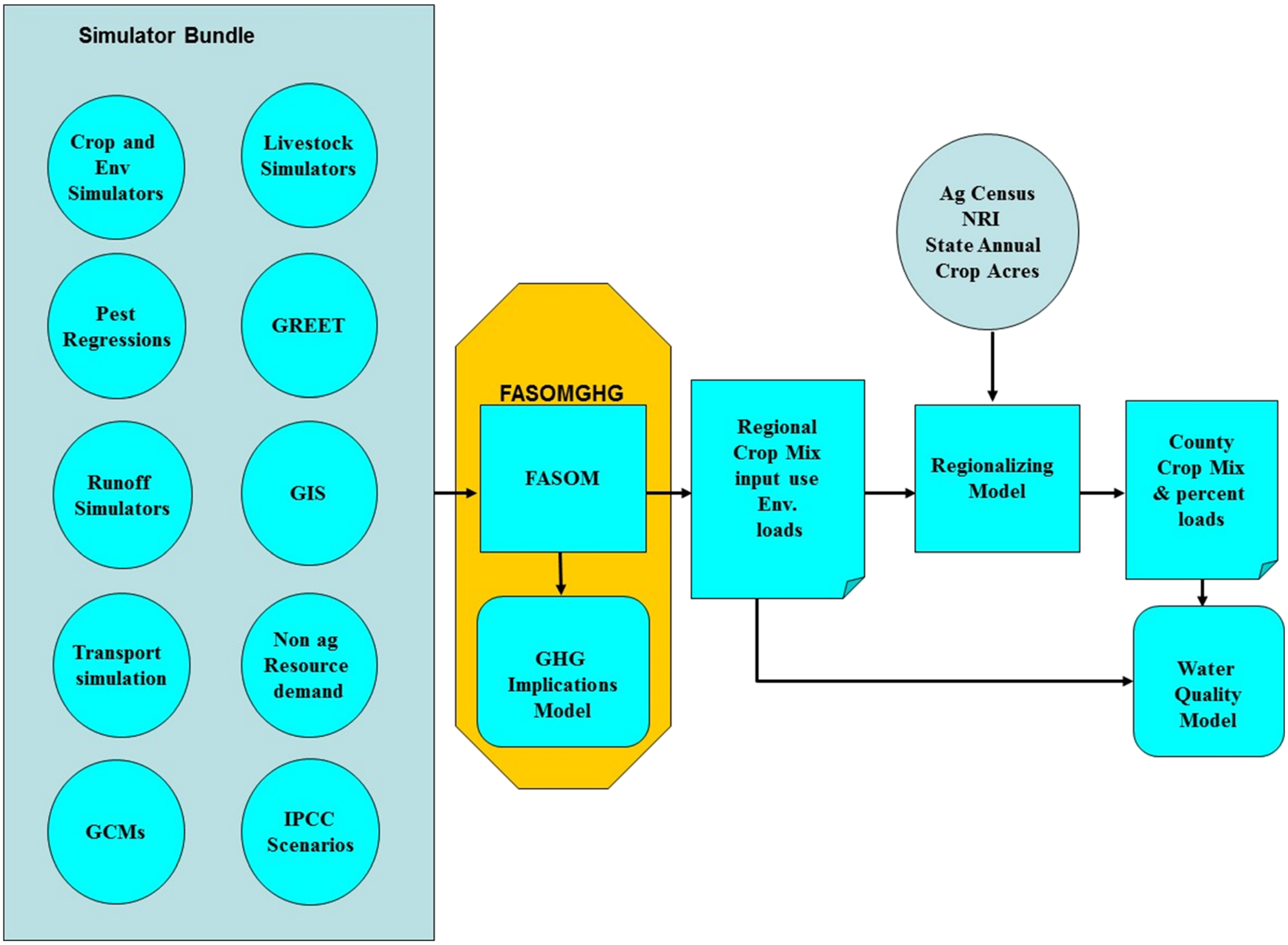

Fig. 2 Overview of FASOMGHG modeling system

At the national scale, Al-Riffai et al. [32] propose a modeling system that links an economy-wide CGE model with component models for energy (MARKAL/TIMES) and water and food (IMPACT) to analyze WEF issues. They then carry out a Nile Basin, three-country study of climate change impacts on the country water, energy, and food sectors. The policy interventions they consider are altering cropped area, changing energy mix to one relying more on renewable electricity generation, increasing desalination, and investing in more efficient irrigation systems.

Impact on Science and Society

In this paper, we identify challenges to WEF nexus-related modeling and, when possible, identified studies that have confronted the challenge. Our intention was to increase community knowledge regarding nexus analyses and improve the contribution of model supported nexus analyses. In turn, this effort hopefully will enhance stakeholder and policy maker understanding of the cross-sector implications of actions within the water, energy, or food sectors and facilitate the development of more efficient, equitable, and sustainable policy. Additionally, we hope that by highlighting the challenges we stimulate others to conduct research on these issues and together expand and enhance the state of the science in the WEF nexus context.

Conclusions

While many papers deal with the overall importance and structure of WEF nexus decision-making, the focus of this paper is exclusively on modeling.[2] Here, we identify challenges that we feel if overcome will improve the ease, accessibility, usefulness, and accuracy of WEF analyses. Such well-designed WEF models will advance the ability to analyze water, energy, and food nexus issues in several ways, including the following: (a) increasing stakeholder and analyst understanding of nexus-wide linkages across and within WEF sectors; (b) improving understanding of management action implications; and (c) facilitating appropriate linkage of unifying models with component crop, water, and food modeling systems.

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Compliance with Ethical Standards

Conflict of Interest Bruce A. McCarl, Yingqian Yang, Kurt Schwabe, Bernard A. Engel, Alam Hossain Mondal, Claudia Ringler, and Efstratios N. Pistikopoulos declare that they have no conflicts of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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