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Trade-offs and Decision Support Tools for FEW Nexus-Oriented Management

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Abstract
Purpose Existing assessment and decision support tools have limited application to real-world food-energy-water (FEW) Nexus challenges. Integrated assessment approaches are often discipline-specific or highly theoretical, lacking grounding in real-world FEW issues.
Recent Findings FEW systems require application of integrated techniques that address multiple attributes of trade-off analyses, dynamic and disparate datasets, and difficult decision contexts. Research must enable: appropriate tool sets matched with FEW Nexus hotspots; customizing existing tools to fit local specifics; compatibility between collected data and integrative nexus assessment tool needs; evaluation of these assessments through incorporation of stakeholder input and guidance forward for solution implementation.
Summary The core challenge is *identification and design of a set of strategies that are robust under various future conditions (scenarios).* Successful strategies must address natural, technological, and human system settings. Approaches that clarify the range of beneficial and potentially adverse trade-offs will support the identification of decisions and intervention options.

Keywords Decision support · Participatory modeling · Trade-offs · Integrative assessments · Resource allocation and planning · Sustainability evaluation · Dialog

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Introduction

The interconnected nature of food, energy, and water (FEW) systems motivates recognition of the need to understand a broad range of processes and interactions that require the synthesis of knowledge across multiple disciplines, technologies, and stakeholder groups. The complex, interconnected nature of these processes exceeds our ability to understand them without the use of integrated approaches and tools to assist in the assessment of the trade-offs between possible future trends, conditions, and outcomes. The development and use of integrated resource analytics, decision support tools provide frameworks that have a strong potential to catalyze dialog among engaged scientists, stakeholders, and decision makers [1•].

The FEW Nexus faces many intertwined social, engineering, and economic considerations that cut across the three, highly heterogeneous landscapes of food, energy, and water. Within this heterogeneous landscape, there is a need for new, interactive, and analytical tools. These tools can be used to model, analyze, and optimize the decision-making processes of stakeholders, and the overall operation of the nexus nodes, in terms of resource allocation, system optimization, and resilience.

The following are examples of critical questions at different scales (Figure 1):

Global Scale

– What is the extent of the global impact on food prices of allocating corn for ethanol production in major corn producing countries?

National Scale

– What is the impact of increased food subsidies on national water security?

Urban City Scale

– What are the implications to food security of promoting water reuse for urban agriculture?

Farm Scale

– How would policies set to incentivize farmers to increase food production impact water quality?

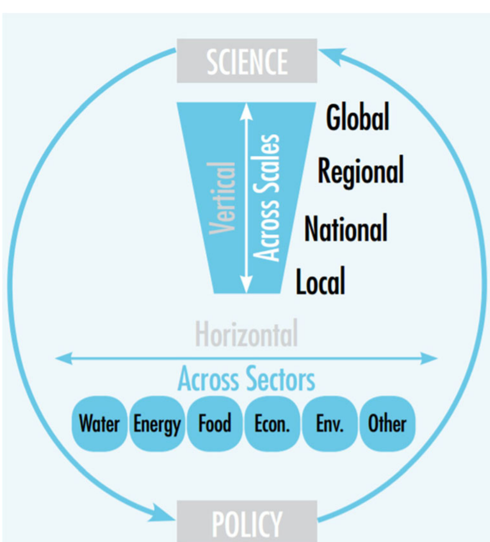

Fig. 1 The interconnectedness of FEW Nexus issues across multiple scales vertically and across sectors at each scale [2]

Business/Industry Scale

– What are the implications for long term sustainability of business operations of investing in water efficient technologies?

Key Challenges to be Addressed for Nexus-Oriented Decision Making

The increasing acknowledgement of the tight interconnectedness between water, energy, and food challenges has led to the growing need for integrative assessments and the development of a large number of FEW Nexus tools, such as WEAP [3], LEAP [4], MuSIASEM [5], CLEWS [6], WEF Nexus Tool 2.0 [1•], among others [7•, 8•].

Core to any complex integrated assessment problem for environmental or resource challenges [9] are a set of dimensions that can be used to frame strategic directions in FEW research. Many of the necessary research advances can be expected to coalesce in these dimensions, which are grouped into subcategories: key drivers for integration (e.g., issues of concern, governance settings, and stakeholders), aspects or characteristics of the systems to be integrated (e.g., natural and human systems, across spatial and temporal scales), and methods, tools, and subject matter expertise (e.g., disciplines, methods, models, other tools, data, sources, and types of uncertainty) (Hamilton et al. 2015).

Critical questions for addressing different FEW Nexus hotspots vary across scales and across stakeholders within the same scale. Different tools address different questions at specific scales. Those questions could be at national, regional, global, city, farm, or business/industry level. At the national scale, stakeholders might include ministries or departments, such as agriculture, water, energy, economics, and environment. All of those must be considered while putting together a new national water strategy. Decisions made at the farm scale might include farmers, water utility companies, environmental protection agencies, and land commissioners. While it is necessary to identify the proper analytics to address a water-energy-food nexus hotspot, identifying the criteria upon which resulting assessments are evaluated and communicated to stakeholders in order to catalyze an informed trade-offs dialog is a key challenge.

A sample of questions to develop such criteria and identify overall challenges includes:

– At what scale and complexity do we need to model? What is the appropriate resolution in which assessments could be effectively communicated to different decision makers?

- Which analytical and trade-off tools must be used to simulate and evaluate different scenarios of resource allocation, climate change, population growth, drought, different water sources, and technology choices?
- How might approaches for resource allocation assessments be evaluated?
- How can stakeholder input be incorporated into the criteria for scenario evaluation?
- How do we address lack of coherence or competition between different decision-making entities across sectors and scales? How can that lack of coherence be factored into the assessment of the scenarios being evaluated?
- How can human behavior and perceptions be merged and integrated into technologically sound solutions for the FEW Nexus?

A number of key decision-making challenges cut across the scales identified in "Key Challenges to be Addressed for Nexus-Oriented Decision Making" section, i.e.:

- *At a global scale*, there is a need to understand how global policies can impact national policies, subsidies, and efforts to create national-scale FEW Nexus.
- *At a national scale*, governmental agencies must work together to provide subsidies, improve FEW resource security, and bring together stakeholders across food, energy, and water sectors.
- *At an urban scale*, beyond policy making decisions occurring within the city, there is a need to understand how resources can be allocated across water, energy, and food systems, while being cognizant of policies and decisions at broader scales.
- *At a farm scale*, tools are needed to analyze how farmers might react to the higher-level decisions done at national and city scale, and to investigate the impact of such decisions on the actual farm production.
- *At the business/industry scale*, there is a need to analyze the economic decision making processes of the players, in an effort to understand new market opportunities that arise from the FEW Nexus vision, and how those new markets may be affected by decisions at other scales.

Data/Knowledge Gaps

Some of the most common data gaps and challenges within the water-energy-food nexus modeling community include:

- Lack of interlinkages data. The majority of available data is disciplinary; data at the interface of different disciplines is not yet fully developed.
- Access to data within the private sector or within specific industries, energy data for example, could be more challenging for the research community to obtain.
- Incompatibility of collected disciplinary data with the needs of nexus tools and the lack of coherence and compatibility of data across scales.
- Lack of sufficient "nexus training" for professionals (lack of institutional capacity) to work with nexus assessment tools.

Addressing these data gap challenges requires an integrated approach that makes use of various data sources, while at the same time, developing or complementing monitoring programs that take into account the requirements imposed by sustainable development goals (SDGs) monitoring. Data sources to be considered include station data (meteorological/hydrological, etc.), earth observation data, and modeling outputs. Linking these data sources in a smart way is addressed in various ongoing projects within the TIGER initiative [10]. Thus, nexus-oriented decision support systems (DSS) should always be embedded in a comprehensive knowledge management system that goes full circle, taking into account: defining the nexus problem at hand, defining data requirements, respective monitoring programs, etc., to visualization of outcomes and communication of these outcomes to stakeholders [11]. One way to put such an approach into a wider perspective of nexus governance and bridging the science-policy gap is making it part of a nexus observatory [12].

Multi-Attributed Trade-off Analyses and Integrated Modeling

No single modeling tool is capable of capturing all conceivable interactions and trade-offs within the FEW Nexus. Given the complexity of sectoral trade-off analyses and their respective modeling tools, it has been proposed that the most feasible approach for tackling nexus modeling should be to couple and make use of existing models for specific nexus applications, as required [13]. These authors proposed and described a first version of a Nexus Tools Platform to facilitate the selection of appropriate modeling tools. If such a platform for model comparison is widely embraced and supported within the nexus modeling community, in terms of updating and complementing information, providing and publishing feedback about specific tools, codes and frameworks for linking models, etc., it could provide valuable support to facilitate nexus modeling as part of a knowledge management systems and DSS.

Difficult Decision Contexts

Since the overall goal of model-aided trade-off analysis and assessment of management options is to support decision makers at various levels, outcomes of the analysis should be provided so as to enable evidence-based decisions for sustainable resources management. Ellis et al. [14] defined the following requirements for a DSS:

- focused on the what, where, and how
- capable of addressing multiple issues
- developed with user participation
- suitable on multiple spatial scales
- a loosely coupled suite of tools
- amenable to standardization of data formats

A comprehensive, scalable, user-friendly, easy to understand, multi-purpose, flexible, extensible, and easy to access (web-based) DSS appropriate for developing countries and that can simulate and predict the influence of future land management practices and considering climate change, is still lacking. Examples of recent efforts towards such a system include the LandCare 2020 project (www.landcare2020.de), which developed the model-based LandCare-DSS [15]. The model framework prototype was developed, tested, and calibrated under temperate climate in Germany. It combines models that address climate, phenology, crop production, hydrology, irrigation, and erosion. Depending on the capabilities of models included in the framework, the DSS can be adapted to other regions: one such application has been set up in Mexico [16]. A similar system, developed by FAO [17, 18], is based on coupling of models and required databases. Adaptation to other climate and economic regions requires integration of region-appropriate models, assessment of user-specific needs, biophysical DSS parameterization (e.g., site condition, crops, economics), and inclusion of region-appropriate management recommendations.

Available DSS that focus on land-use management do not adequately account for seasonal variations in water availability, such as drought, flood, or erosion events. Recommendations on how to react to short-term weather forecasts are needed to adjust land management effectively, and must include suggestions regarding where and when to irrigate or harvest. For this reason, an effective DSS must be flexible in terms of data sources needing (near) real-time data. Automatic updating of DSS with real-time data can be used for identifying and monitoring (i) soil fertility pattern and problems, (ii) climate (change) patterns, (iii) soil erosion risk, and (iv) plant productivity, among others. This gives insight regarding when, where, and how to fertilize, irrigate, protect for erosion, or whether a crop type should be changed to improve economic performance or adapt to changing climate. Monitoring also contributes to answering questions about future monitoring needs, such as which nutrient variables need assessment, which can actually be influenced, and which need frequent or occasional monitoring. Similar issues must be considered when dealing with DSS focused on Integrated Water Resources Management, some of which have been developed by (transboundary) basin organizations, e.g., ZAMCO. Common to all resources management-related DSS is the need to include climate projections in a region-specific manner, in itself a huge challenge.

These, and similar, issues are typically considered by a wide spectrum of stakeholders, each with varying preferences, data needs, targets, and goals. Each stakeholder or group of stakeholders may require a different approach, and a customized way to communicate the outcomes and recommendations of the DSS. For example, communicating agricultural or land-use-related DSS output to farmers requires an easy to read format with high temporal and spatial scale. Several pilot projects used cell phone technologies such as “smart ICT” for this level (IWMI). Extension officers and regional managers, on the other hand, might require long-term projections. Research must support matching appropriate tools or sets of tools with both specific and differing FEW Nexus hotspots. It must also offer the ability to customize existing tools to fit local specifics, ensure the compatibility of collected data with the requirements of integrative nexus assessment tools, and the evaluation of these assessments through incorporation of stakeholder input in a manner that provides guidance for solution implementation.

Potential for Transformative Research

By inspecting these challenges from the perspective of decision making, one can identify a common denominator: large-scale interdependencies between the decision-making processes that exist within each scale and across multiple scales. Such interdependent decisions must be mathematically and practically analyzed such that they organize the seemingly chaotic and complex environment arising from the FEW Nexus. To this end, a broad range of theoretical and software decision tools can be used to model and analyze the FEW nexus across scales and, subsequently, provide integrated solutions and key insights about the underlying trade-offs. Within the FEW nexus, trade-offs analysis and decision making can be supported by:

– *Technology*: data-driven scientific discovery, an essential component of FEW problems. Analysis and visualization provide the means by which “data” is transformed into information, insight, and knowledge. Software engineering and decision support efforts serve the generation of knowledge by driving the discovery process or helping to convey analytical or scientific results to key stakeholders and decision makers. Advances needed in the development of computational tools include: computing to support field studies and sensing, analytics for high-dimensional data, fusion of disparate data sources, machine learning interactive dashboards, and visualization to communicate complex science to a broader audience in support of participatory processes [19].

- *Methodologies*: game-theoretic and integrated modeling tools [20] provide a set of methods that can be used to model the way in which resources can be efficiently allocated across the FEW Nexus. Indeed, game theory [21] provides a formal analytical framework with a set of mathematical tools to study the complex interactions between rational decision makers whose goals, actions, and objectives are interdependent. Throughout the past decades, game theory has had a revolutionary impact on several disciplines, including engineering, economics, political science, philosophy, or even psychology [21]. More recently, game-theoretic tools have become prevalent in the analysis of engineering systems, such as wireless networks [22] and smart energy systems Saad et al. [23]. Within the FEW Nexus, one can define games in which the players will be individual nodes at the production, distribution, and consumption levels of a nexus; and the actions will essentially pertain to the amount of resources a node requires, distributes, or produces. Games can also be defined among humans in order to better understand their behavior and decision-making processes and the impact of those processes on the FEW Nexus. Both non-cooperative and cooperative game models are applicable in this context. Non-cooperative solutions would better model scenarios in which individual system nodes have no means of coordinating their strategies, while cooperative models can be suitable for analyzing how one can pool resources across interdependent nodes that have a means to coordinate their system parameters. Another promising framework for resource allocation is that of matching theory [24], a Nobel-prize winning theory that allows understanding of how to match resources across two sets of distinct players. Within the FEW Nexus, matching games can be used to stably and efficiently match resource production to resource consumption. Overall, and from a FEW Nexus technology perspective, game-theoretic frameworks will provide analytical approaches that can shed light on how distributed resource allocation in the FEW Nexus can occur efficiently and across possibly heterogeneous types of actors or nodes. In addition, such game-theoretic solutions can be useful for theoretical analyses of human decision making in the nexus, enhanced resilience of the resources allocation processes of the nexus, and their responses to potential failures.
- *Policy/governance*: integrated modeling, decision support, and game theoretic approaches are natural frameworks to model interactions of FEW systems and the interactions between stakeholders. These approaches lend themselves to participatory and co-design with decision makers or stakeholders so that any candidate solution may achieve a higher chance of implementation. As noted, within the FEW Nexus, interactions across human and natural systems can occur at multiple scales. Modeling approaches can play an important role in facilitating the required transition to sustainable management [25]. The key objectives are to: (a) identify economic, political, and regulatory actors, their interactions, and their cumulative effects on the overall FEW Nexus system; (b) define and develop effective means of communication between and within stakeholder groups, including traditional means (dialog forums, panels, workshops, etc., as wells as serious games, virtual communities and platforms and social media); (c) understand what type of subsidies can be provided at different scales to bring together FEW stakeholder (an example on the use of game-theoretic approaches for analyzing subsidies can be found in [26]); (d) design incentive mechanisms that can promote cooperation between stakeholders and positively impact the technological landscape of the nexus; (e) provide policy recommendations that can render the FEW Nexus more efficient, resilient, and environmentally sensitive.
- *Community Building*: to leverage innovation in the three pillars of the nexus, there is a need to build integrated, interdisciplinary communities of researchers that cut across engineering, behavioral economics, social sciences, and information technologies. Such interdisciplinary community building efforts are necessary to foster research that can truly capture all facets of the nexus. To initiate such community building efforts, one can start at the level of individual universities, creating interdisciplinary courses that bring together students across at least two disciplines (e.g., engineering and economics, computer science, and social science). Such efforts can then expand to the broader community via workshops and tutorials that can, in turn, lead to the creation of nationwide teams working together to build the FEW Nexus. Various means and opportunities should be explored to facilitate and extend the required community of practice in regard to the FEW Nexus. While many organizations and stakeholders have embraced the nexus concept, institutionalized support is needed for continuity and sustainability. Some specific platforms already exist to facilitate this institutionalization, among them the Nexus web platform (https://www.water-energy-food.org/start/) and Dresden Nexus Conference (http://www.dresden-nexus-conference.org/).

Impact on Science and Society

Improving the developed nexus analytics and trade-off assessment tools would allow us to be better prepared to address the interconnected resource challenges. It would allow policy makers to have the information needed for informed decisions and would put incentives in place to push towards future, sustainable resource allocation. Realizing the need for such analytical tools would also provide impetus towards building scientific and institutional capacities for professionals to carry forward those assessments and communicate them to stakeholders. Not less, it would also increase awareness of the pressing need for collecting different kinds of interlinkages data not currently collected. Nevertheless, while game theory has a broad range of tools that can address these problems, key challenges remain to be addressed; including:

– *Utility design*. Most analytical solutions (e.g., game theory or optimization) typically rely on individual utility or objective functions defined per individual FEW Nexus players. Within the FEW nexus, such utility designs must directly stem from practical considerations of the FEW nexus, as well as from the data itself. To design such realistic, data-driven utility functions, one must overcome the data gaps identified in "Potential for Transformative Research" section.
– *Multi-scale and dynamic nature of the nexus*. As outlined, the FEW Nexus will have agents interacting at multiple scales and the system will dynamically evolve over space and time. Thus, there is a need for new game-theoretic models that can inherently integrate multiple timescales in the decision-making processes. Notions of stochastic games [21]) can be useful to capture the spatio-temporal FEW dynamics that evolve over time. Moreover, to practically capture decisions at multiple timescales, such stochastic game constructs can be merged with emerging game-theoretic frameworks, such as multi-game solutions [27] and multi-resolution games [28] that enable analysis of the co-existence of multiple, interdependent games, at different scales.
– *Models of spatio-temporal interdependencies*. To create realistic decision-making models, there is a need to properly model the spatio-temporal interdependencies across the FEW Nexus. Such interdependencies can be technological (e.g., dependence between infrastructure nodes) or policy-oriented (e.g., which actors truly impact others). Here, one can combine game theory with tools from graph theory, such as the notion of temporal network analysis [29] to help identify interdependencies across time and space. These can then be fed into game-theoretic constructs for analysis of the decision-making processes.

Conclusions

No single tool can address the complexities of all the different nexus challenges across contexts, scales, and stakeholders. Based on identified critical questions and the associated stakeholders, a tool or suite of tools could be prescribed or customized to perform the required assessments. A better understanding and quantification of the interconnections between different resource systems, and of the interactions between the various involved players, will improve the value of the developed assessments and the proposed solutions. Moving forward, there must be a push for collecting data that is in sync with assessment needs and the tools required for those needs. There must also be incentives for capacity building in quantification, analysis, modeling, and communication of water-energy-food nexus challenges between both the scientific and policy making communities.

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Compliance with Ethical Standards

Conflict of Interest Bassel Daher, Walid Saad, Suzanne A. Pierce, Stephan Hülsmann, and Rabi H. Mohtar declare 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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