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Analyzing FEW nexus modeling tools for water resources decision-making and management applications

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ABSTRACT

Social changes such as growing population, urbanization, globalization, and economic growth, compounded with uncertainties due to climate change are expected to result in substantial shifts in the demand for food, energy, and water. Food, energy and water resource systems are tightly interconnected. Addressing challenges facing any of these resource systems requires a holistic understanding and quantification of the existing interdependencies and trade-offs. This study is aimed at analyzing FEW nexus modeling tools with a specific focus on addressing issues of water management through a nexus lens. In particular, an exploratory approach is taken to assess available FEW nexus modeling tools to determine their accessibility, knowledge gaps, and potential for including aspects that provide better insight into the nexus such as water quality, futuristic scenarios due to climate change, and varying scales within the nexus. A case study in an agricultural watershed in northeastern Indiana is presented which builds on the WEF Nexus Tool 2.0 framework and assessment criteria. For this case study, spatial and temporal analysis based on SWAT was implemented. This provided a water quality component to the framework enabling a more representative analysis of the FEW nexus.

1. Introduction

With the rising concern for how the world will be shaped by social changes such as growing population, urbanization, globalization, and economic growth, as well as with the uncertainties in future temperatures and precipitation due to climate change, there has been a shift towards holistic approaches to developing solutions for the future (Biggs et al., 2015; Mohtar, 2017). Estimates show that by 2030, expected global demand for food, energy, and water are expected to increase by 50%, 50%, and 40%, respectively (Martinez-Hernandez et al., 2017a). Given the interconnectedness among these sectors, the food-energy-water (FEW) nexus has recently emerged as critical framework for solidifying discussions regarding goals for a once ambiguous concept of "sustainable development" (Biggs et al., 2015). This framework is crucial to sustainable water, food, and energy security at different scales (Cai et al., 2018; D'Odorico et al., 2018), spanning from local through national to global scales. Globalization renders the FEW nexus much more complex due to sector interconnectedness across vast distances

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(D'Odorico et al., 2018). During the Bonn 2011 Nexus Conference, the concept of the FEW nexus was developed (Hoff, 2011; Endo et al., 2017) highlighting the need for a cross-sectoral dialogue around trade-offs associated with different resource allocation and planning decisions.

Water management is a critical component in natural resource management. Within the FEW nexus framework, water may be considered a driver; it is necessary for agricultural production and plays a role in energy production primarily as related to cooling (Daher and Mohtar, 2015; Rao et al., 2017). Both sectors (food and energy) can have adverse effects on water quality; for example, nitrogen and phosphorus continue to be among the most common pollutants in freshwater systems, these originating largely from agricultural sources (WWAP, 2009); energy production can result in increased water temperatures with associated negative impacts on aquatic ecosystems (Madden et al., 2013) even where the net water consumption might be zero. Furthermore, water availability is affected by pollution (WWAP, 2015). Without proper assessment and application of sustainable approaches for food and energy production, serious environmental degradation will continue to occur. In particular, unsustainable use and management of water resources in these two sectors can lead to: competition for water resources between food and energy production (Rosa et al., 2018a, 2018b); increasingly impaired waters (Cai et al., 2018); loss of biodiversity (Poff et al., 1997); and political tensions between communities sharing water resources (Richter, 2014), all of which negatively impact efforts towards environmental sustainability. Often, policy-making within the FEW nexus tends to occur without much consideration of the resulting effects of decisions made within other sectors on the water system (Mohtar and Daher, 2012; IRENA et al., 2015). Amongst the earliest attempts to incorporate the interconnections of the sectors within the FEW nexus was integrated water resources management (IWRM), which strives to analyze the life cycle of water within a system (Al Radif, 1999). The FEW nexus approach builds on IWRM, energy efficiency, and water input for crop production, and provides a cross-cutting platform which allows dialogue across sectors (Mohtar and Daher, 2016).

Currently, there are a limited number of FEW nexus modeling tools with which to quantify the interconnections and stressors both in and between each of the respective FEW sectors (IRENA et al., 2015; FAO, 2014a,b). These tools allow for more quantitative analysis of the intricacies of the FEW nexus, thus aiding policy- and decision-makers in understanding the complexities in securing FEW sources in an efficient, robust, and holistic manner. Nevertheless, they tend to rely on a static, singular scaling, which make it difficult to implement the tools at the local, regional and national scales simultaneously. Most also lack the ability to generate futuristic scenarios of the interrelationships that would give a better understanding of the shifts that could be expected and their impacts. These shortcomings could be due to the level of uncertainty due to climate change, as well as the reality that the development of these modeling tools is relatively new. Hence, the design of the framework of FEW nexus modeling tools must not only be informed by the significance of the interactions, but by how system boundaries are defined when assessing the suitable spatio-temporal scales for decision-making. Thus, there is a need to better understand how to outline these system boundaries as well as to develop a more unified framework to address the varying levels of scaling, significance of interactions, and sector perspectives that are present within these tools (Bazilian et al., 2011). One of the major concerns related to current FEW nexus tools is their failure to address the quality of water within a system. Thus, there is also a need to incorporate a water quality component into the FEW nexus framework for a better representation of the interconnectedness among the sectors of the nexus.

The aim of this study was to analyze FEW nexus modeling tools and provide a framework by which to better integrate water management—including water quality—as a primary component of the nexus. Specifically to: (1) review the availability of tools that model the FEW nexus; (2) determine the benefits and shortcomings of available tools for understanding potential tradeoffs; and, (3) use a state-of-the-art FEW nexus modeling tool in a case study to demonstrate potential applications incorporating water quality and futuristic scenarios related to climate change.

2. Methodology

A literature-based exploratory approach was taken as an initial step to assess the potential of incorporating FEW nexus tools in the development of necessary resource allocation strategies, as well as to better understand the trade-offs between the different sectors. This study included recently developed tools and demonstrated how to select a tool based on certain criteria. Finally, a scenario-based case study was conducted to assess how a chosen tool would perform in representing the interconnections between the FEW sectors including future perspectives, the flexibility in scale through assumptions and inputs and outputs of the framework, and its ability to capture potential trade-offs in various resource allocation strategies. Because water quality is a crucial component in water management, the study also assessed the extent to which water quality could be incorporated in FEW nexus modeling. The case study site was the Matson Ditch Watershed, a primarily agricultural catchment in DeKalb County in northeast Indiana, thus demonstrating the feasibility of incorporating a developed tool's framework to an agricultural-based site.

2.1. *FEW nexus modeling tools description*

Among the most commonly used FEW nexus modeling tools are the Climate Land Use Energy and Water (CLEW) model (Hermann et al., 2011), the Water Energy Food (WEF) Nexus Tool (Daher and Mohtar, 2015), the Water Evaluation and Planning system (WEAP)/Long-range Energy Alternatives Planning system (LEAP) (Sieber, 2006; Hoff et al., 2007; Sieber and Heaps, 2010), MuSIASEM (MultiScale Integrated Analysis of Societal and Ecosystem Metabolism) (Giampietro et al., 2009), and the Global Biosphere Management Model (GLOBIOM) (Ermolieva et al., 2015).

Developed by the International Atomic Energy Agency (IAEA), CLEW (https://www.iaea.org/topics/economics/energy-economic-and-environmental-analysis/climate-land-energy-water-strategies) is a systematic framework approach that uses multiple, unintegrated tools to illustrate synergies and trade-offs for decision making (Kaddoura and El Khatib, 2017). It provides outputs based upon collected data, assumptions, and user-defined scenarios (Hermann et al., 2011). The WEF Nexus Tool 2.0 (http://wefnexustool.org/) is a dynamic model that attempts to shift from silo decision-making to more integrative approaches. The model was originally developed to attempt to assess resource allocation due to national-level agricultural production, importation and exportation, as well as using desalinization and renewable resources as long-term solutions for Qatar. The tool provides comparisons between scenarios and provides a sustainability index for these scenarios (Daher and Mohtar, 2015). WEAP/LEAP (https://www.weap21.org) are scenario-based modeling tools developed by the Stockholm Environment Institute (SEI). WEAP incorporates water quality and quantity assessment, ecological and social demands, and water management policies (Kaddoura and El Khatib, 2017). LEAP is the energy planning software also developed by SEI and can be linked with WEAP. These tools' licenses are available for a fee for scientists from developed countries and for free for those in developing countries.

MuSIASEM (http://iaste.info/musiasem/) is an open framework tool that aids in determining feasibility and desirability of socio-economic systems (Giampietro et al., 2009). Developed in 1997 by Mario Giampietro and Kozo Mayumi (IASTE, 2019), the tool is managed by the Integrated Assessment: Sociology, Technology, and the Environment (IASTE). It uses Complex System Theory concepts, as well as a flow-fund model to encompass FEW nexus and social parameters. This can be used for diagnostics or simulations, and has been used in FEW nexus assessments (Kaddoura and El Khatib, 2017). There have been various applications in different countries with this model (IRENA et al., 2015).

GLOBIOM (http://www.globiom.org) is a global-scaled dynamic model that integrates the FEW nexus sectors for policy analysis and was developed by the International Institute for Applied Systems Analysis (IIASA, 2019). GLOBIOM incorporates price and trade flows for all the countries of the world, aggregating into 30 larger regions for convenience (Ermolieva et al., 2015; Havlík et al., 2012). Additionally, there are regional versions of the model, such as GLOBIOM-BRAZIL and GLOBIOM-EU, which were designed with stakeholder involvement to provide a more detailed analysis.

Other tools that have been used in FEW nexus modeling include: the Diagnostic, Financial, and Institutional Tool for Investment (DTI) (Salman, 2013) which provides a national framework for agriculture and energy, with a predominant focus on water management based on irrigation and hydropower (Kaddoura and El Khatib, 2017).; the Q-Nexus Model (Karnib, 2017; Karnib, 2018), which categorizes the FEW nexus sectors through a set of inflows, including irrigated crops and other agricultural products for the food sector; petroleum, electricity, and renewable energy for the energy sector; and groundwater, surface water, wastewater reuses and desalination for water (Karnib, 2018); Data Envelopment Analysis (DEA) (Li et al., 2016), a nonparametric framework for measuring the relative efficiencies of a set of “black box” decision-making units that have various inputs to yield multiple outputs; the Platform for Integrated Modeling and Analysis (PRIMA) (Kraucunas et al., 2015), a modeling system developed at the Pacific Northwest National Laboratory (PNNL) that integrates with models that simulate climate, energy, water and land use interactions for decision-making (Kraucunas et al., 2015); the Global Change Assessment Model (GCAM) (Edmonds et al., 1994), a dynamic-recursive model representing the economy and energy sectors, with particular interest in how climate change mitigation policies will impact the sectors (JGCRI, 2019); and, the Nexus Simulation System (NexSym) (Martinez-Hernandez et al., 2017a), a spreadsheet-based simulation tool (Yao et al., 2018) that simulates processes and local production systems to analyze the FEW nexus at a smaller scale.

With the DTI analysis is conducted at the country level through three different tools (context tool, institutional and policy tool, financial tool), that work synergistically. These are open-access and readily available at http://www.fao.org/land-water/databases-and-software/diagnostic-tools-for-investment/en/. The Q-Nexus Model uses an input-output Leontief matrices framework that integrates societal demands and technical efficiencies within the nexus (Martinez-Hernandez et al., 2017a; Karnib, 2017). This model has been used to analyze the FEW nexus in Lebanon (Karnib, 2017; Karnib, 2018). The DEA is integrated with the C2R, BC2, and Malmquist Index Model to provide more holistic analyses (Dai et al., 208) and has been applied to analyze the water and energy source consumption in cities in China (Li et al., 2016; Martinez-Hernandez et al., 2017a). External factors, such as environmental systems and social economic systems can be integrated into the framework (Li et al., 2016). PRIMA has been applied to assess how energy infrastructure in the U.S. Gulf Coast is effected by climate change (Dai et al., 2018). The modeling system, which takes into account stakeholder engagement (Kraucunas et al., 2015), is available through the open-source software platform, Velo (https://im3.pnnl.gov/platform-regional-integrated-modeling-and-analysis-prima). Aside from being an open source tool, GCAM (http://www.globalchange.umd.edu/gcam/) has tutorials, a community listserv, and a Github repository. The NexSym tool allows users to build system diagrams and provides summary outputs of the model. It has been applied to a bioenergy production system (Martinez-Hernandez et al., 2017a,b).

2.2. *Initial evaluation*

Several criteria were used to evaluate existing tools as follows:

Availability and accessibility: open-access tools allow decision-makers to conduct assessments or analysis in a manner that is affordable. Thus, modeling tools that require licensing and/or a subscription fee were not included in this study, as cost can be a major hindrance. Ease of access for potential users facilitates the use of the tool in decision-making processes (IRENA et al., 2015). Therefore, only tools that are readily available online were considered in this study.

User friendliness and simplicity: decision-making tools that are simple and easy to use are implemented more readily. One of the major drawbacks of many FEW nexus modeling tools is their need for large amounts of data (IRENA et al., 2015; Kaddoura and El Khatib, 2017). This requires that users be well-informed of where to access required data, and puts a burden on users to process, format, and import the data into the model. Additionally, due to the complexity of the nexus, it becomes challenging for the user to collect comprehensive data for all sectors of the nexus (Kaddoura and El Khatib, 2017; IRENA et al., 2015). Furthermore, learning how to use a tool due to said complexity may require time and effort and may not be feasible. In a review by IRENA et al. (2015), two models considered simple and user friendly are the WEF Nexus Tool 2.0 and the FAO’s nexus assessment methodology (FAO, 2014b).

Flexibility: some tools are static in terms of the scaling they propose; for example, DTI requires the user to select the country that they are interested in modeling. Other tools allow static scaling to be used across different boundary conditions; this is seen in the Q-nexus Model, which is based on Leontief matrices that have the potential for being altered for local or regional scales. For this analysis, we looked at the flexibility of boundary conditions for the FEW nexus modeling tools.

Comprehensiveness: although there are various types of models for a specific sector or sector interconnections such as LEAP (Long-range Energy Alternatives Planning System), WEAP (Water Evaluation and Planning), MuSIASEM, and GLOBIUM, finding tools that encompass the FEW nexus in a way that is representative, accessible, and easy to use presents a challenge (Daher and Mohtar, 2015; Kaddoura and El Khatib, 2017; Martinez-Hernandez et al., 2017a). Therefore, tools that have a fully-integrated approach and account for all three sectors of the FEW nexus and, to some extent, establish interconnections between them were preferable.

Predictive component: with the uncertainty of climate change, there is a need to assess how scenarios could change in the future, and how one could create robust solutions. Thus, the ability to use the tools to incorporate and compare futuristic scenarios was evaluated.

According to Kaddoura and El Khatib (2017) and Dargin et al., (2019), tools that are open-access, available online, simple, and user-friendly are more likely to find wide application. Thus these were considered as the primary criteria in the evaluation. Comprehensiveness was the next criterion, and was applied to the tools that were readily available. Tools that did not include all three sectors of the FEW nexus were eliminated from the analysis. The next factor considered was ease of use; tools that require extensive programming, multiple software usage, or a steep learning curve along with a high time investment were removed from the analysis. Finally, considerations were made as to whether the tool would be intuitive to use or had a tutorial and/or community resources available for the user to be able to guide themselves in using the tool effectively. Finally, user ability to input various scenarios and specify sectors within the FEW nexus was evaluated.

2.3. *Decision matrix analysis*

The tools selected for further evaluation were subjected to a multi-criteria decision analysis (MCDA) using a decision (or performance) matrix analysis (Dodgson et al., 2009) and based on the seven qualitative criteria as previously described. The decision matrix allowed for a systematic analysis and rating of the FEW nexus tools. The criteria were unweighted, given that priorities could change depending on the analysis objectives. The grading system was based on a ten-point scale, from 1 being poor to 10 being excellent. The overall score was then averaged across the criteria, and the model with the highest average score was selected as the tool that would be used for the case study.

3. Results and discussion

In this study, selected FEW nexus models were subjected to a preliminary screening based on pre-established criteria to determine the ones best suited for use in FEW nexus modeling and assessments. From this initial evaluation (Supplementary Table S1), tools which require a financial input were eliminated, as were tools with extensive data requirements, that were complex, with multiple software requirements, and limited scenario parameters. Based on the evaluation, three tools—GCAM, NexSym, and The WEF Nexus Tool 2.0—were selected for further evaluation and were subjected to a more thorough analysis through a multi-criteria decision analysis. Based on the evaluation criteria (Table 1), the WEF Nexus Tool 2.0 was ranked as the best fit (with a total score of 6.86/10), with the GCAM tool coming in second (6.14/10), and NexSym ranked as the least implement (5.57/10).

The WEF Nexus Tool 2.0 is a great example of a user-friendly tool that is available in open-access and facilitates trade-off perspectives of sustainable solutions with a focus on food security and agricultural production (Daher and Mohtar, 2015). This tool received a 9/10 in the "user-friendly" category, with NexSym receiving a 6, and GCAM receiving a 2 an inadequate user interface. The user interface for GCAM was not well established and required extensive time and tutorials to implement for water resource management. The complexity of the WEF Nexus Tool 2.0 was deemed moderate. It was the most intuitive of the three tools, as well as the tool that required the least amount of user inputs.

Table 1 – Decision matrix for FEW nexus modeling tools.

Tool	User-friendliness	Flexibility	Comprehensive	Availability	Predictive element	Economic component	Water quality	Rank
WEF Nexus Tool 2.0 (Daher and Mohtar, 2015)	Intuitive, easy to understand 9	Limitations on user-defined energy sources and agricultural practices 6	Nation-wide (Qatar), agricultural sector 8	Online 10	Multiple scenarios can be used as a predictive assessment 6	Incorporated for Qatar 8	Needed 1	1
GCAM (Edmonds et al., 1994)	Tutorials, Wiki, requires understanding in LINUX 2	Limitations on user-defined energy sources and agricultural practices with some user-defined components 9	Region-wide (USA, others) 8	Online, but requires downloading to computer for usage 6	Multiple scenarios can be used as a predictive assessment 6	Incorporated through policy files 6	Incorporate 6	2
NexSym (Martinez-Hernandez et al., 2017a)	GUI interface, allows for user inputs 6	User-defined components 10	Local (UK-town), limited spatial analysis 8	Not in a shareable format 2	Multiple scenarios can be used as a predictive assessment 6	Needed 1	Water-treatment and nutrient surplus integrated in model 6	3

While NexSym had potential in allowing users to define their boundaries and interconnections, the software was not available in a shareable format at the time of this study. Hence, NexSym availability was scored a 2. The WEF Nexus Tool 2.0 received a 10, as it was readily available online and can be accessed after the end user creates a profile, which is done in order for the user to be able to save any simulations they are generating. GCAM received a score of 6, because though one can access it online, it requires end users to download the program. For flexibility, though both the WEF Nexus Tool 2.0 and GCAM have similar limitations in both the agricultural and energy components, GCAM received a higher score despite these limitations, as the user has the ability to define some aspect of these sectors.

The WEF Nexus Tool 2.0 incorporates an economic component through the type of crops being produced. There are limitations to implementing policies and future pricing, and thus the tool received an 8. Policy files can be user-defined in GCAM, and taxes and subsidies can be represented. However, the user has to develop these files, which can become difficult if they are unfamiliar with the process. This tool, thus, received a score of 6.

In terms of comprehensiveness, all three tools received a score of 8 because each of these modeling tools have sufficient sector inputs and interconnections based on the scale and purpose; The WEF Nexus Tool 2.0 focuses on food security and has interconnections based on agricultural production and water consumption within Qatar at an annual basis (Daher and Mohtar, 2015). GCAM is a regional-scale model that is meant for coarse 5-year intervals (JGCRI, 2019). The NexSym tool focuses on more local systems, at the city scale (Martinez-Hernandez et al., 2017a). These systems account for necessary interconnections between the nexus despite the differing question and scales, and thus have appropriate comprehensive levels for the respective scale.

Though GCAM has the potential for climate change predictive analysis, the coarse interval time periods could make assessment of crop production difficult as crop growth varies seasonally. There are a variety of climate change projection data sets available, with differing radiative or climate forcings; the ability to incorporate these climate change projections into GCAM would be beneficial for robust decision making. One of these climate change scenarios, RCP 4.5 (Representative Concentration Pathway, 4.5 W/m^2), was simulated successfully with GCAM (Thomson et al., 2011), However, the learning curve for GCAM is steep for novice programmers and decision-makers with minimal coding experience, making predictive analysis challenging.

NexSym has a predictive component for consumption and nutrient modeling through bioenergy production, and provides flexibility in terms of user input and defining the system at hand. Additionally, it includes nitrogen and carbon cycling within the locally-scaled model, as well as a climate input. However, the tool currently does not have a spatial modeling component, but holds promise for incorporating one, as well as integrating aspects of uncertainties and connections with FEW modeling tools based on larger scales (Martinez-Hernandez et al., 2017a,b).

Though the WEF Nexus Tool 2.0 does not have a built-in predictive component, an end user could develop various scenarios in order to assess future climate conditions (Daher and Mohtar, 2015). The annual basis at which output is generated provides a coarse assessment – though finer than that from GCAM – that may be beneficial for decision-makers. Nevertheless, having a more fine-scaled assessment of the predictive component would aid in further developing the water component of the tool, as water availability may shift based on seasonal variations.

In general, FEW nexus tools span not only a range of modeling frameworks and system depths, but also a range of complexity, user-friendliness, and comprehensiveness in modeling FEW nexus interactions, underlying assumptions, and applicability with respect to location. While some tools are more comprehensive than others, there is not yet a single nexus modeling tool that simulates the FEW nexus holistically (Dargin et al., 2019). Furthermore, existing tools were built considering specific regions or localities and there applicability elsewhere may need to be tested more broadly. There is, thus, still room to enhance and expand existing tools and models. In this study, we demonstrate how one could narrow down on tools initially based on broadly applicable criteria, and then further based on their knowledge, expertise, resources, needs, and the range of tools available. Inherently, this process has elements of subjectivity; thus, it is not our intent to endorse one tool over another or others. With these considerations in mind, we present a case-study example application of the WEF Nexus Tool 2.0 framework.

4. Case study: Matson Ditch Watershed

This study used information from the Matson Ditch Watershed in DeKalb County in northeast Indiana, USA, to illustrate the use of the WEF Nexus Tool 2.0 at the watershed scale, and incorporation of a water quality impacts component. The study integrated the methodologies of the WEF Nexus Tool 2.0 and the 7-Question Guideline to Modeling the Water-Energy-Food Nexus developed by Daher and Mohtar (2015) and Daher and Mohtar (2012), respectively. Additionally, the case study integrated future climate projection scenarios to demonstrate how the WEF Nexus Tool 2.0 can be used to assess climate change effects on the stressors within the FEW nexus framework.

4.1. *Site description*

The Matson Ditch Watershed (Fig. 1) is an agricultural subsurface drainage-dominated catchment with an aerial extent of 4610 ha (11,392 acres). Cultivable agricultural land (67.8%) is primarily used to produce corn, soybeans, and winter wheat. About 5% of the land is developed area that includes residential properties (Mehan, 2018), 13% of the watershed is in pasture, and 9% in deciduous forest. Other land uses, such as barren, evergreen forest, range-brush, wetlands, water, and other crops including alfalfa, rye, oats, hay, constitute up to 4% of the area. The annual average precipitation over the entire watershed based on 2003–2012 data was around 1000 mm. The two major soil types in this watershed are a silt loam Alfisol (Blount: somewhat poorly drained) and a clay loam Mollisol (Pewamo: Poorly drained). (Mehan, 2018).

The Matson Ditch Watershed is monitored by the USDA-Agricultural Research Service (ARS) National Soil Erosion Research Laboratory (NSERL), and has sufficient data available to allow the application of the WEF Nexus Tool 2.0 methodology. Previous work in the watershed (Mehan, 2018) used the Soil and Water Assessment Tool (SWAT, Arnold et al., 1998) to assess how climate change would affect both surface and subsurface water and nutrient mechanisms. Using historical and

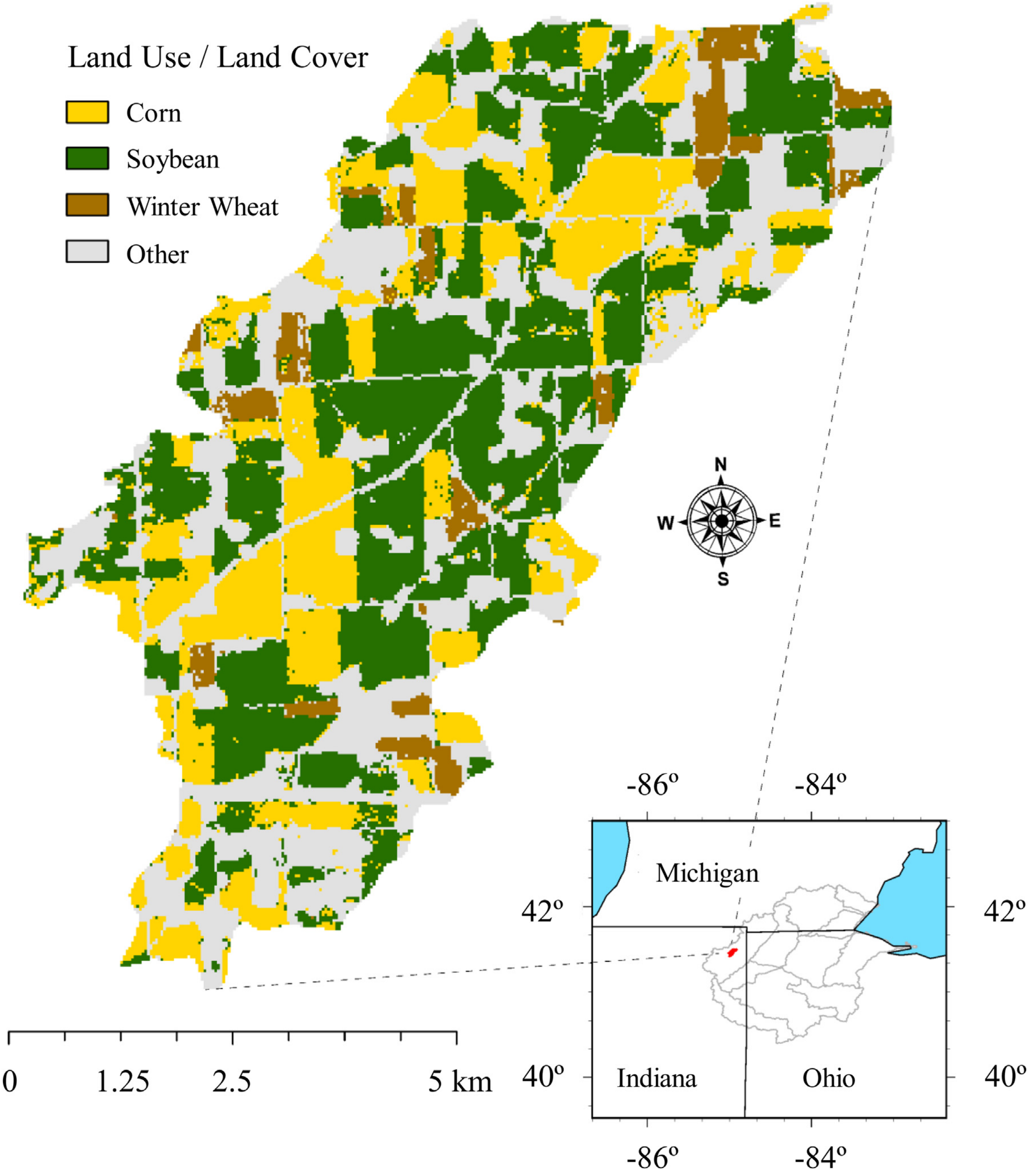

Fig. 1 – **Matson Ditch Watershed in DeKalb County, IN, USA.**

projected climate data, the previous study was also able to demonstrate effects on crop yield. Modeling outputs for the 21st century indicated that there could be greater nutrient losses from this agriculturally dominated watershed, and that changing conditions could affect future crop yields, with corn yields potentially decreasing by 2%–50% and soybean yields increasing by 20%–60% (Mehan, 2018).

4.2. *WEF nexus tool considerations*

This study included answering the 7-Question (7Q) Guideline to Modeling the Water-Energy-Food Nexus by Daher et al. (2017). Because water quality is a crucial component in water management, the study also assessed the extent to which water quality could be incorporated in FEW nexus modeling. A scenario-based case study was conducted to assess how the chosen tool would perform in representing the interconnections between the FEW sectors including future perspectives, the flexibility in scale through assumptions and inputs and outputs of the framework, and its ability to capture potential trade-offs in various resource allocation strategies.

5. The 7Q guideline: systems of systems analysis

The 7Q Guideline provide a guide to conceptualize the necessary framework for decision-making to quantify interconnections between the sectors of food, energy, and water, as well as to develop scenarios and tradeoffs (Daher et al., 2017). Following is a summary of the responses to the questions, which enabled comprehension of the system within the Matson Ditch Watershed:

- What is the critical question?

How can we assess water resources impacts within the FEW nexus framework, based on varying renewable energy deployment options and sustainable agricultural practices while taking climate change into account?

- Who are the players/stakeholders?

Those interested in long-term projections of water quality and climate change would be considered major stakeholders. These involve local farmers, environmental entities, and academics.

- At what scale?

The scale for this assessment is at the watershed scale.

- How are we defining our systems of systems?

In this case study, the framework is water-centric considering both water quality and quantity. Fig. 2 shows the FEW nexus framework for this analysis. Because the WEF Nexus Tool 2.0 was developed to focus on food production (Daher, 2012), the interconnections represented in this tool focus on the process and dependencies for this goal. Agricultural production is critical to water quality in the food-water portion of the nexus (D'Odorico et al., 2018), thus, including water quality considerations in the analysis introduces an additional interaction where food production affects water by impairing its quality. Water quality is considered at both spatial and temporal scales. Crop location, rotations, and type are included. Additionally, energy requirements and carbon emissions for fertilizer production, tillage, harvesting, and transportation due to crop production are considered. The pilot site, the Matson Ditch Watershed, is a predominantly agricultural research watershed with no competing usage of resources other than the concern of water quality impairment. Because the site is predominantly precipitation-fed, energy for securing water will only be used to demonstrate the energy and carbon emission trade-offs.

- What do we want to assess?

The analysis will include the type of crops being grown, along with their rotations, the sources of energy for agricultural production and securing water, the sources of water, the quality of the water within the watershed, and what climate change projections indicate through the 21st century.

- What data is needed?

Among the data required for the assessment were, water requirement (m^3), spatial-temporal distributions of water resources, the watershed water budget, energy requirement for water (kJ/ m^3), energy requirement for agricultural production (kJ/ha), carbon footprint (ton/kJ), and climate change projection data.

- How do we communicate it? Where do we involve the decision maker in the process?

Through this case study, a holistic assessment of the Matson Ditch Watershed will be provided. Moving forward, it is possible to incorporate more strict constraints and strategies to remove impractical scenarios.

6. FEW nexus framework and assumptions

In order to model the FEW nexus, relationships between the food-energy, energy-water, and water-food sectors needed to be assessed, in addition to inputs and assumptions within each of the respective sectors. The sector and inter-connection assumptions were based upon the equations used in the WEF Nexus Tool 2.0 (Table 2). Because this case study was conducted at the watershed level, the constraints set by Daher (2012) were not incorporated. For assessing outputs of the model, no bounds were included for the equations used. Though the WEF Nexus Tool 2.0 has restraints set for each of the amount of water, land, and energy sources, these were not necessary for the case study since, on an annual basis, the Matson Ditch Watershed receives sufficient rainfall to sustain agricultural production. It was also not necessary to account for importation/exportation of crops, political risks associated with trade, or transportation of the crops being produced, which simplified the modelling.

6.1. *Data development*

Data used in this case study were obtained primarily from Mehan (2018), who used the SWAT model and provided modeling information at both watershed and Hydrologic Response Unit (HRU) levels. HRUs are the smallest modeling unit in SWAT, and are defined as approximately homogenous areas of land use, soil type, and slope (Mehan, 2018). Bias-corrected climate projections from nine different general circulation models (GCMs) and data from two climate change emissions scenarios, (RCP 4.5 and RCP 8.5) were applied to the Matson Ditch Watershed for the 21st century (2006–2099). The climate data through 2099 were separated into three major segments (2006–2019, 2020–2069, 2070–2099) developed using change-point detection algorithms such as the Pruned Exact Linear Time (PELT) algorithm (Killick et al., 2012) to detect points throughout the 21st century where there were inflections in the dataset. The overall analysis was separated into five time periods: 2006–2012; 2006–2019; 2020–2069; 2070–2099; and, 2006–2099. The 2006–2012 period was included to determine hydrologic and nutrient response in the recent past, while the 2006–2099 period was included to determine how the inputs and outputs within individual time periods differed from those of the entire dataset (Mehan, 2018).

For uniformity purposes, the FEW nexus modeling was performed for each of the five time periods outlined in Mehan (2018). Outputs were obtained at the HRU level to provide data based on land use as needed for this study. As the Matson Ditch Watershed is predominantly agricultural, data were extracted for HRUs that had the major crops—corn, soybeans, and winter wheat—and used for evaluations. Nine GCM climate change datasets were applied with two radiative forcing climate scenarios (RCP 4.5 and RCP 8.5). The annual aggregated mean values from the models for precipitation, actual evapotranspiration, nutrient runoff, and crop yields for each of the corn, soybean, and winter wheat HRUs were used.

Fig. 3 shows the integration of the WEF Nexus Tool 2.0 and SWAT for assessment of the Matson Ditch Watershed. In this application, the two are used as stand-alone applications with SWAT model output and watershed representation being used to provide input to WEF Nexus Tool 2.0. The tool

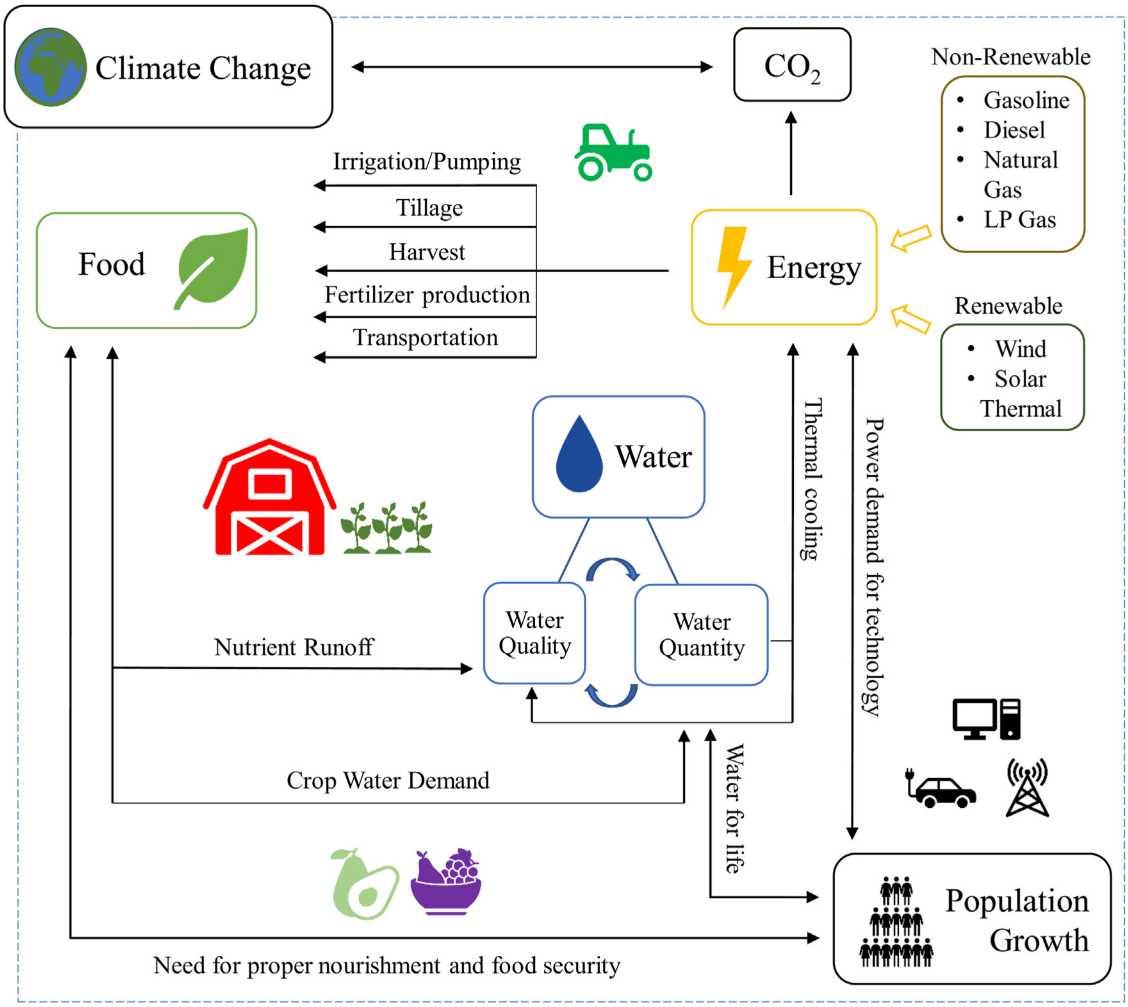

Fig. 2 – Diagram demonstrating the FEW nexus framework.

Table 2 – FEW Nexus Equations and Assumptions (Source: Daher, 2012).

Sector	Equation/assumptions	No.
Food-Energy		
Energy[a,b]	$\text{Energy Total}_t = \sum_{i=1}^{n} E_{1,i,t} + E_{2,i,t}$	(2)
	$E_{1,i,t} = E_{R,i,t} + E_{GW,i,t} + E_{TWW,i,t}$	(3)
	$E_{2,i,t} = E_{till,i,t} + E_{harv,i,t} + E_{fert,i,t}$	(4)
Carbon Emissions[c]	$CO_{2t} = \sum_{i=1}^{n} CO_{21,i,t} + CO_{22,i,t}$	(5)
	$CO_{21,i,t} = CO_{2R,i,t} + CO_{2GW,i,t} + CO_{2TWW,i,t}$	(6)
	$CO_{22,i,t} = CO_{2till,i,t} + CO_{2harv,i,t} + \ + CO_{2fert,i,t}$	(7)

[a] $E_{1,i,t}$ (KJ/year) is the energy needed for either pumping or treating water for irrigation for crop i (KJ/year), and $E_{2,i,t}$ is the energy (KJ/year) needed for tillage (till), harvest (harv), fertilizer production (fert), and local transport (considered negligible and thus not included).

[b] Associated energy values were obtained from Daher (2012), with energy requirements for nitrogen, phosphorus, and potassium/atrazine fertilizers at 78,230, 17,500, and 13,800 (KJ/kg) and the carbon emission was assumed 0.0026 ton/year. Groundwater energy requirement being 4271 KJ/m^3 and treated wastewater requires 1656 KJ/m^3.

[c] Carbon emission from different energy sources for water retrieval were taken into account, including diesel (778 g CO$_2$/kWh), natural gas (443 g CO$_2$/kWh), wind (10 g CO$_2$/kWh), and solar thermal (13 g CO$_2$/kWh.

incorporates water quantity, energy demand and consumption, and overall food production, while quantities such as water demand based on the evapotranspiration, and water quality contaminant values were taken from the calibrated SWAT model. Furthermore, the SWAT model was used to provide climate change projections through the 21st century.

6.2. *Food sector*

The areas for the assumed initial crop production for corn, soybeans, and winter wheat were 1123 ha (2775 acres), 1723 ha (4258 acres), and 238 ha (588 acres), respectively. Land use has not changed much within the region (Sekaluvu et al., 2018), so calculations could be based reliably on the number of hectares

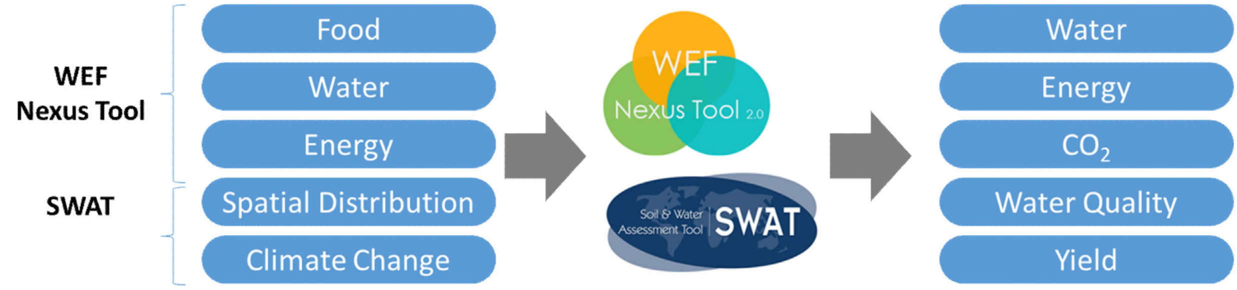

Fig. 3 – Integrating the WEF Nexus Tool 2.0 and SWAT for assessment of the Matson Ditch Watershed.

Table 3 – Yield based on mean yield/ha of watershed crop-based hydrologic response units.

Time period	Corn (ton/ha)	Soybeans (ton/ha)	Wheat (ton/ha)
RCP 4.5			
2006–2012	4.70	4.68	2.95
2006–2019	5.11	4.75	3.87
2020–2069	4.79	4.61	3.53
2070–2099	4.93	4.93	3.86
RCP 8.5			
2006–2012	4.45	4.82	3.05
2006–2019	4.86	4.79	3.83
2020–2069	4.55	4.43	3.56
2070–2099	3.50	3.68	2.87

of current crop production. Thus, the land use was assumed to be consistent throughout the 2006–2099 analysis period. The amount of crops produced on an annual basis for each of the time scales was calculated using Eq. (1).

$$Crop\ Production_{i,\,t} = Yield_{i,t} \cdot Crop\ Area_{i} \quad (1)$$

where production of crop i during time period t is in tons, yield of crop i is in tons/ha (Table 3) for each time period t, and crop area is given in hectares. Historical and future yields for each of the crops were obtained by separating the HRUs for each of the time periods by crop type across the watershed, then taking the average of the yields based on the HRU land use indication. A crop rotation of corn-soybeans-winter wheat (in sequence, one crop per year) was modeled in the analysis conducted by Mehan (2018), and thus these HRU yield values were indicative of the rotational crop production between the years 2006–2099.

6.3. *Energy sector and carbon emissions*

The energy assumptions for this case study were those developed in Daher (2012). Energy requirements within the watershed were determined by Equation 2 (Table 2). The study watershed is a freshwater, primarily rainfed system. Thus, the main water source that was considered was rainfall (energy requirement = 0 KJ/year). Additional analysis was conducted on groundwater and treated wastewater to assess the energy and carbon emission tradeoffs if precipitation was not the primary source of water for the watershed.

In the study area, the primary energy requirements and CO$_2$ emissions for crop production are tied to fertilizer, tillage and harvesting. For tillage and harvesting, it was assumed that only one type of fuel type was used. Energy assumptions for tillage from Daher 2012 were assumed for all the agricultural crops. The fertilizer demands for each of the crops were averaged through all the crop HRUs to take into consideration the crop rotations. Unless otherwise noted, the carbon emissions were based on one energy source. The diesel and natural gas (D + NG) energy source is considered the baseline value for Indiana. According to Dillon and Slaper (2015), Indiana's energy consumption in 2012 was broken down as: 44.7% coming from coal, 24.6% from natural gas, 27.2% from petroleum, and 3.5% from other sources. For simplicity, we assumed that the baseline consumption for Indiana was 75% of the D + NG energy source coming from diesel and 25% from natural gas. The more sustainable combination scenario, consisting of wind and solar thermal (W + S), assumed that energy was coming from renewable resources of wind (50%) and solar thermal (50%). In comparison to nonrenewable sources, wind, solar, and the wind-solar combination have almost minimal carbon emissions. For the Matson Ditch Watershed, wind and solar were considered to be the most probable renewable resources for the region. Carbon emissions were calculated in a similar manner to energy (Eq. (5), Table 2), where total carbon emissions were in tons/year for time period t, $CO_{21,i,t}$ were the carbon emissions from pumping or treating water for irrigation for crop i (tons/year), and $CO_{22,i,t}$ were the carbon emissions from tillage, harvest, fertilizer production, and local transport, all multiplied by the years in time period t. $CO_{21,i,t}$ was calculated using Eq. (6) in Table 2, where the energy was the sum of the amount required to retrieve clean water from rainfall (R), groundwater (GW), and treated wastewater (TWW) to satisfy the crop water demand of crop i during time period t.

The sources of emissions that were considered were those of groundwater and treated wastewater, as rainfall as a water source does not require an extensive energy input. $CO_{22,i,t}$ was calculated using Eq. (7) in Table 3, where the total carbon emissions are the sum of the amount of energy required for tillage (till), harvesting (harv), producing fertilizer (fert), and local transportation (local tr). However, just like for the energy consumption, the transportation CO$_2$ emission component was assumed to be zero. Additionally, the energy and carbon emissions assumptions for the potassium (K) fertilizers, which are not applied in the watershed based on Mehan (2018), were implemented for atrazine for simplification purposes. For these crop production energy sources, the energy sources that were considered were diesel, gasoline, and liquid petroleum fuel, in accordance with the WEF Nexus Tool 2.0. For water retrieval, some of the renewable energy alternatives that were integrated in the WEF Tool 2.0, primarily solar and wind, were maintained in order to incorporate renewable energy initiatives in the region.

6.4. *Water sector*

6.4.1. *Water quantity*

Water quantity and quality values were used from Mehan (2018) for the area. In addition to components of groundwater and waste water, which are included in the WEF Nexus Tool 2.0, this analysis added precipitation as a water source as this is the primary water source in the Matson Ditch Watershed. The application of the WEF Nexus Tool 2.0 in this region, thus, entailed reframing the water component to include precipitation. One of the more simplified methods for estimating crop water demand is through calculating evapotranspiration of the plant. The total actual evapotranspiration (ET_a) values had been calculated per HRU of the watershed and were aggregated based on the crop designation.

6.4.2. *Water quality*

In addition to water quantity, it was critical to consider the water quality status within the Matson Ditch Watershed. For this case study, the total loads of soluble phosphorus from the entire (surface, subsurface) system, as well as the nitrate-nitrogen and soluble phosphorus in subsurface drainage waters from the cropland were calculated using Eq. (9):

$$WQc_{i,t} = WQcY_{i,t} \cdot Crop\ Area_i \tag{9}$$

where $WQc_{i,t}$ is the water quality contaminant coming from cropland i at time period t, $WQcY$ is the water quality contaminant yield (ton/ha) from crop land i at time period t being multiplied by its area (m^2) given the crop rotation. Water quality contaminant values were obtained through a comprehensive modeling effort using SWAT (Mehan, 2018), which included water quality projections through the 21st century.

6.5. *WEF nexus tool outputs*

Throughout the span of 2006–2099, the average annual crop production (tons/year) that was determined is shown in Fig. 4. There was a gradual decline in the average yield for the soybean HRUs, as well as for corn for the RCP 8.5 scenario, with an opposite projection being shown for the soybean HRUs in the RCP 4.5 scenario. The winter wheat HRUs stayed relatively constant throughout the time periods between 2006 and 2099. Though the average values provide an indication of climate impacts, it would be beneficial to be able to also address the extrema of the output to show the full variation from these scenarios.

Table 4 shows the average demand of each of the crops throughout the five time periods in the 21st century for both RCP 4.5 and 8.5. The amount of water required (ET_a) would ensure that the crops are not as stressed throughout the time period on an annual basis. As mentioned before, precipitation is the primary water source in this region; on an annual basis, the amount of rainfall that the watershed receives surpasses the amount of water required to ensure that crops are not stressed. For both scenarios, the corn, soybean, and winter wheat HRUs showed little variation through the 21st century; this was because the SWAT analysis conducted by Mehan (2018) accounted for crop rotations; thus, with expected spatial variation, there was not much difference between the HRU averages. However, it was interesting to note that there were not as large of variations in the water demands, despite the notable changes in the soybean and corn HRU crop yield values throughout the 21st century.

The amount of water that would be required for each of the HRUs could be assessed by multiplying the average crop demand by the area of each crop. There are various methods with which to determine water valuation; for example, Chapagain and Hoekstra (2004) introduced the concept of the water footprint to determine the amount of water that is consumed through the lifetime of a product. An additional step would be to address the source from which the water is being consumed for a product, and the additional inputs and environmental impacts from using one water source over another. For comparison, the energy and carbon emissions of water sources other than precipitation were calculated. Fig. 5 shows the amount of energy that would be required if the water was coming from some source other than precipitation. In the following scenarios, the calculations were done to assess a hypothetical scenario of how to meet this need through groundwater and treated waste water. This was done in order to comprehend the tradeoffs of energy if securing water from an alternative source. Groundwater would be more energy intensive than treated waste water because the average well depth of Indiana ranging from 9.7 to 31 m deep (32–102 ft) (Indiana Department of Natural Resource, IDNR, 2019), is similar to the assumptions made in the WEF Nexus Tool 2.0 model.

Tables 5 and 6 show the amount of carbon emissions based upon the energy source for each of these water source alternatives. This allows for better comparisons of the differences in carbon emissions between conventional energy sources such as diesel and natural gas, and renewable sources such as wind and solar thermal. Out of the four energy sources for water, diesel emitted the most carbon, followed by natural gas. Wind and solar thermal were close in terms of carbon emissions, but wind was the least carbon intensive of the energy sources.

In terms of energy and carbon emissions associated with crop production, we found that fertilizer production required the greatest amount of energy (8.51×10^9, 1.21×10^9, and 1.74×10^9 KJ/year for the corn, soybean, and winter wheat HRUs, respectively). The CO_2 emissions from fertilizer consumption was 393 tons/year for corn HRUs, 589 tons/year for soybean HRUs, and 80 tons/year for wheat HRUs. For tillage, the amount of energy required per crop HRU was 3.45×10^7, 5.18×10^7, and 0.71×10^7 KJ/year for corn, soybean, and wheat, respectively. The carbon emissions for tillage and harvest are outlined in Table 7.

Lastly, water quality was incorporated into the analysis. Fig. 6 shows the annual amount of total soluble phosphorus (Sol P) and nitrate (NO_3) from subsurface drainage from each of the crop areas. The largest annual loads came from soybeans, followed by corn, and finally wheat, largely because values were based on crop area. For soluble phosphorus loads level showed gradual decline through the mid-21st century, with a noticeable increase in the amount of soluble phosphorus output at the end of the 21st century for both the RCP 4.5 and 8.5 scenarios. Soluble phosphorus losses predicted for 2070–2099 under RCP 8.5 were substantially greater than the projected value for RCP 4.5. Based on Mehan (2018), annual soluble phosphorus loads during 2070–2099 could range between a decrease of 45% to an increase of 70% under RCP 4.5, and a decrease of 60% to an increase by 75% under RCP 8.5. The mean value of subsurface NO_3 losses for the crop HRUs demonstrated a decline which is consistent with the overall results of Mehan (2018), in which projected decreases from the baseline based on 9 GCMs ranged between 25–75% for RCP 4.5 and 25–60% for RCP 8.5 during 2070–2099.

7. Discussion

The variety of FEW nexus modeling tools evaluated in this study demonstrate the wide range of applications of FEW

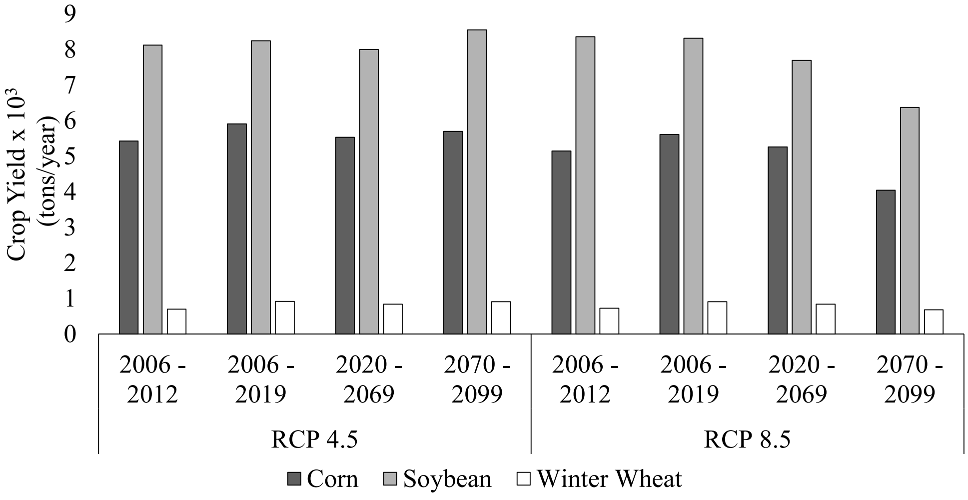

Fig. 4 – Average annual crop production for Crop-Based HRUs in tons/year predicted for time periods between 2006 and 2099.

Table 4 – Average crop water demand for crop-based HRUs in mm/year for time periods between 2006 and 2099.

Scenario and time period	Corn	Soybean crop H_2O demand (mm/yr)	Winter wheat
RCP 4.5			
2006–2012	514.1	486.9	436.2
2006–2019	515.6	490.2	442.2
2020–2069	492.2	496.2	428.9
2070–2099	497.6	493.9	449.9
RCP 8.5			
2006–2012	497.3	484.7	436.6
2006–2019	498.4	496.9	440.1
2020–2069	481.2	481.3	433.4
2070–2099	461.3	466.7	444.1

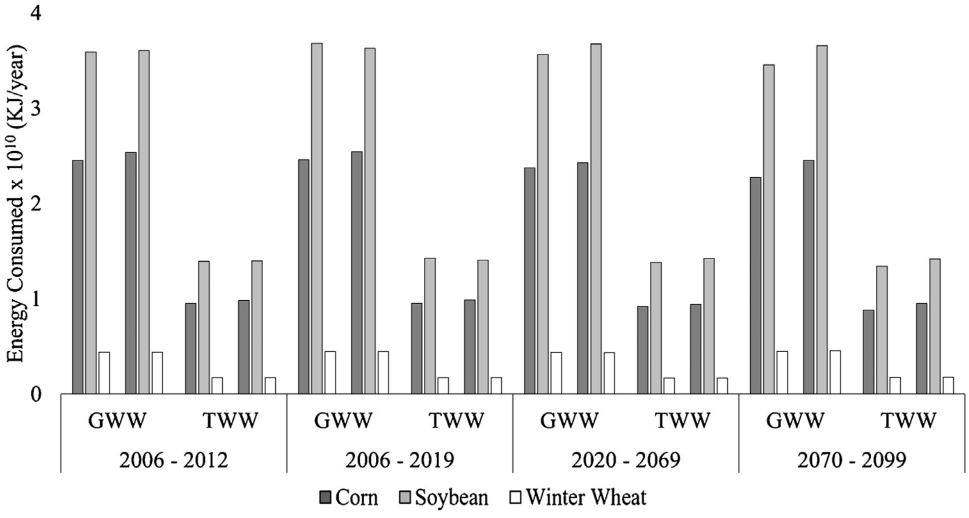

Fig. 5 – Energy that would be required (KJ/year) to meet total water demand for each crop if the primary water sources were ground water (GW) or treated wastewater (TWW); the first set of bars in each of the series are the results of the RCP 4.5 scenario and the second set are the results from the RCP 8.5 scenario.

nexus modeling and how certain sectors may be of more interest than others. Additionally, the varying levels of scale and data requirements indicate a wide breadth of knowledge in terms of accessing data, computing and programming skills, and assumptions that can be made about the system. Dai et al. (2018), Kaddoura and El Khatib (2017), and IRENA et al. (2015) have developed literature reviews of available FEW nexus modeling tools and demonstrated their potential in the integration of a more sustainable future. These reviews give a broad overview of the tools, however our review provided a demonstration of how a user can attempt to assess which tool would be the most implementable given a set of priorities, limitations, and skill set. This study took a water-centric view given the importance of water to both the food and energy sectors. Although there are FEW nexus tools that assess water in terms of both quality and quantity, these are generally missing other portions of the FEW nexus. Nutrient modeling within the FEW nexus is rather limited, even though it plays a critical role in its interconnections (Yao et al., 2018). This, thus, points to the need to enhance and expand existing tools to represent the FEW nexus in a way that is more holistic.

Table 5 – Carbon emissions × 10^{10} (tons CO_2/year) for nonrenewable energy based on alternative water source.

Scenario and time period	Alternative water source	Diesel			Natural gas			D + NG[a]		
		Corn	Soybean	Winter wheat	Corn	Soybean	Winter wheat	Corn	Soybean	Winter wheat
RCP 4.5										
2006–2012	GW	7.83	11.14	1.36	4.46	6.34	0.77	6.99	9.94	1.21
	TWW	3.04	4.32	0.53	1.73	2.46	0.30	2.71	3.85	0.47
2006–2019	GW	7.85	11.21	1.38	4.47	6.38	0.79	7.01	10.01	1.23
	TWW	3.05	4.35	0.53	1.73	2.48	0.30	2.72	3.88	0.48
2020–2069	GW	7.50	11.35	1.34	4.27	6.46	0.76	6.69	10.13	1.19
	TWW	2.91	4.40	0.52	1.66	2.51	0.30	2.59	3.93	0.46
2070–2099	GW	7.58	11.30	1.40	4.32	6.43	0.80	6.76	10.08	1.25
	TWW	2.94	4.38	0.54	1.67	2.49	0.31	2.62	3.91	0.49
RCP 8.5										
2006–2012	GW	7.58	11.09	1.36	4.31	6.31	0.78	6.76	9.89	1.21
	TWW	2.94	4.30	0.53	1.67	2.45	0.30	2.62	3.84	0.47
2006–2019	GW	7.59	11.36	1.37	4.32	6.47	0.78	6.77	10.14	1.22
	TWW	2.94	4.41	0.53	1.68	2.51	0.30	2.63	3.93	0.47
2020–2069	GW	7.33	11.01	1.35	4.17	6.27	0.77	6.54	9.82	1.21
	TWW	2.84	4.27	0.52	1.62	2.43	0.30	2.54	3.81	0.47
2070–2099	GW	7.03	10.67	1.38	4.00	6.08	0.79	6.27	9.53	1.24
	TWW	2.72	4.14	0.54	1.55	2.36	0.31	2.43	3.69	0.48

[a] This was assumed to be the baseline consumption for the state of Indiana, with 75% of energy for the alternative water source coming from diesel and 25% of the energy being retrieved from natural gas.

Table 6 – Carbon emissions × 10^{10} (tons CO_2/year) for renewable energy based on alternative water source.

Scenario and time period	Alternative water source	Wind			Solar thermal			W + S		
		Corn	Soybean	Winter wheat	Corn	Soybean	Winter wheat	Corn	Soybean	Winter wheat
RCP 4.5										
2006–2012	GW	0.10	0.14	0.02	0.13	0.19	0.02	0.12	0.17	0.02
	TWW	0.04	0.06	0.01	0.05	0.07	0.01	0.05	0.06	0.01
2006–2019	GW	0.10	0.14	0.02	0.13	0.19	0.02	0.12	0.17	0.02
	TWW	0.04	0.06	0.01	0.05	0.07	0.01	0.05	0.07	0.01
2020–2069	GW	0.10	0.15	0.02	0.13	0.19	0.02	0.11	0.17	0.02
	TWW	0.04	0.06	0.01	0.05	0.08	0.01	0.04	0.07	0.01
2070–2099	GW	0.10	0.15	0.02	0.13	0.19	0.02	0.11	0.17	0.02
	TWW	0.04	0.06	0.01	0.05	0.08	0.01	0.04	0.07	0.01
RCP 8.5										
2006–2012	GW	0.10	0.14	0.02	0.13	0.19	0.02	0.11	0.17	0.02
	TWW	0.04	0.06	0.01	0.05	0.07	0.01	0.04	0.06	0.01
2006–2019	GW	0.10	0.15	0.02	0.13	0.20	0.02	0.11	0.17	0.02
	TWW	0.04	0.06	0.01	0.05	0.08	0.01	0.04	0.07	0.01
2020–2069	GW	0.09	0.14	0.02	0.13	0.19	0.02	0.11	0.17	0.02
	TWW	0.04	0.05	0.01	0.05	0.07	0.01	0.04	0.06	0.01
2070–2099	GW	0.09	0.14	0.02	0.12	0.18	0.02	0.11	0.16	0.02
	TWW	0.04	0.05	0.01	0.05	0.07	0.01	0.04	0.06	0.01

Table 7 – Tillage and harvest energy requirements and carbon emissions per season.

Crop	Crop production stage	Energy requirement (×10^7 KJ/year)	Carbon emission (ton CO_2/year) energy source		
			Gasoline	Diesel	LP gas
Corn	Tillage	3.45	14.26	11.42	16.59
	Harvest	4.60	16.04	12.85	18.82
Soybean	Tillage	5.18	21.41	17.15	24.91
	Harvest	6.90	24.09	19.29	28.25
Winter wheat	Tillage	0.71	2.92	2.34	3.40
	Harvest	0.94	3.28	2.63	3.85

Tools that are open-access, available online, simple, and user-friendly will generally be used more than those that are not (Kaddoura and El Khatib, 2017; Dargin et al., 2019). Traditionally, software development has focused on defining methods and processes through data specification. Even though design and implementation of user interfaces are recognized to be among the most energy- and time-intensive steps of any software production process, modeling software is not considered to the same extent (Calvary et al., 2007), at times making the software nonintuitive. With the progression of computational technologies, end users have a wider range of data types available (Vogel, 2011). Thus, it is critical that modeling tools have streamlined instructions for data input, ample explanation of input parameters, data visualiza-

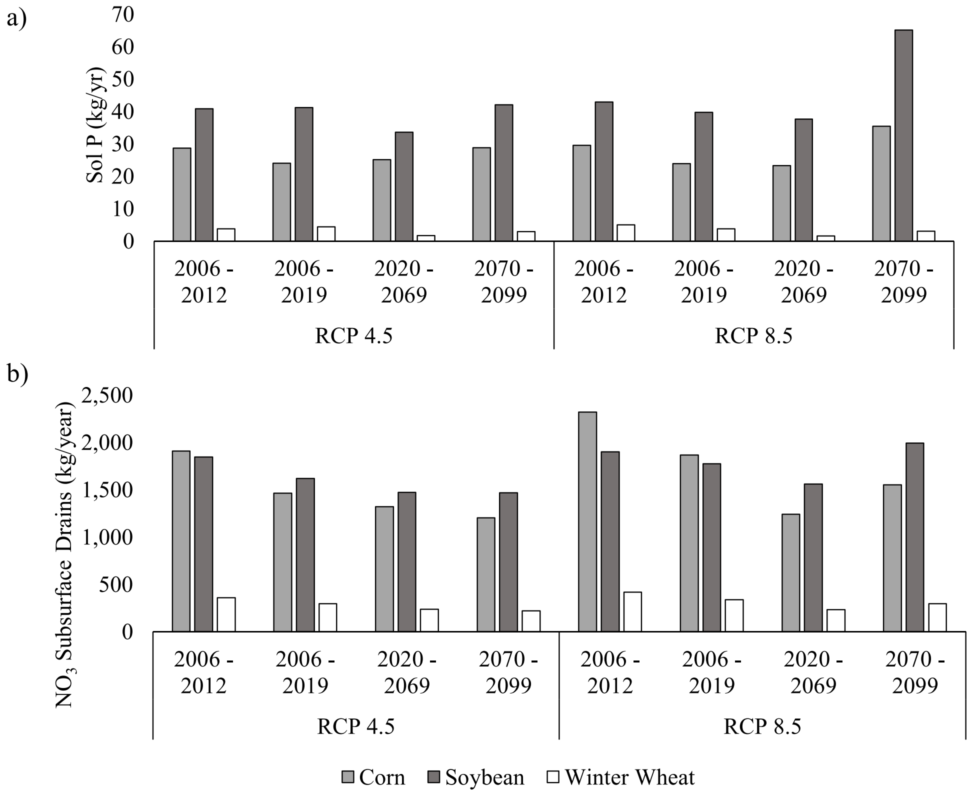

Fig. 6 – Water quality contaminant loads per year from corn, soybean, and wheat crop areas predicted from the Matson Ditch Watershed from 2006 to 2099. (a) Soluble phosphorus (Sol P); (b) nitrate in subsurface drains (NO_3).

tion capabilities, and other analysis techniques that support interactive exploration of data, in addition to an appealing graphical user interface.

The case study presented provides a demonstration of FEW nexus assessment using the WEF Nexus Tool 2.0 based on a watershed (Matson Ditch Watershed) in the Midwestern United States. Results of the assessment demonstrate various trade-offs that can be considered by decision-makers when analyzing scenarios of the FEW nexus (Mohtar and Daher, 2016). For this case study, the average annual values for different time periods were taken into consideration to demonstrate that minimum inputs at a coarse scale can provide a starting point to understand the underlying stressors within the FEW nexus of the system at hand. Focusing on a watershed-scale analysis has benefits; previous studies show that this type of analysis can be conducted using a FEW nexus approach with a similar framework, along with the development of future scenarios (Degirmencioglu et al., 2019). It is important to note, that the Matson Ditch Watershed is a single-use area and interactions and mutual constraints among different sectors are not pronounced. In more complex, multi-use systems, such competition and trade-offs among the sectors would need to be explored in greater depth.

For crop production, the annual average yields from each of the SWAT model HRUs output was based on the mean values from the RCP 4.5 and 8.5 scenarios. Incorporating an average value provides a starting point for assessing how crop production will be affected throughout the 21st century, however, it is necessary to evaluate outputs from several climate realizations in order to get a better indication of the range of crop output that is possible with a changing climate.

For the energy required for crop production, it is important to note that though the average tillage energy and carbon emission values are useful estimations, the WEF Nexus Tool 2.0 could incorporate more specific tillage practices; different tillage systems can affect soil carbon and CO_2 emissions. For example, less intensive tillage systems could reduce CO_2 emissions and improve soil conditions (Al-Kaisi and Yin, 2005). Calculations from West and Marland (2002) show that CO_2 from agricultural operations account for 137 kg CO_2 for no-tillage methods compared to 168 kg CO_2 for conventional tillage. Diversifying the tillage methods simulated would allow for a better estimation of carbon output, better quantify the differences between the tillage and harvest energy requirements, and could demonstrate how agricultural conservation practices affect the FEW nexus. Degirmencioglu et al. (2019) demonstrates how fuel consumption based on tillage practice can be improved upon through a case study in the Gediz Basin in Turkey.

The energy required for alternative water sources was calculated to demonstrate a potential trade-off between precipitation and energy if securing water from an alternative source. The amount of energy was based on the volumetric requirement of water by the crops. Though the WEF Nexus Tool 2.0 can account for desalination, for the Matson Ditch Watershed, only groundwater and treated wastewater were considered based on what is practical for the region. The assumed average depth of a well that could be implemented for groundwater extraction was 30 m (98 ft), with an assumed efficiency of the pump motor at 80%. The energy demand of groundwater pumping in the model was reflective of that within the state of Indiana, where there are more than 300,000 wells (Indiana Geology, 2019), ranging from 9.7 to 31 m deep (32–102 ft) (Indiana Department of Natural Resource, IDNR, 2019). The energy requirement may be greater in areas with lower water tables; for example in California's Central Valley, which is predominantly irrigated agriculture, energy consumed for agricultural practices in 2012 was slightly under

7000 GW hours (2.52×10^{13}) with aquifers of depths up to 61 m (200 ft) (Dale, 2016). For agricultural areas near coastlines, desalination may potentially be a reasonable alternative, especially if precipitation is insufficient to satisfy crop water demand.

Based on Daher (2012), it was assumed that treated wastewater, if used, would be processed using screens and grit removal, with biological treatment of conventional activated sludge and a sequence batch reactor followed by sand filters. The water could then be used for landscape, farms, or ground injection. One of the major concerns with treated wastewater, is health and contamination (Pescod, 1992). However, wastewater is already a common source in countries around the world, such as Pakistan, Vietnam, Ghana, Mexico, Spain, and Greece. Treated waste water totals 1.5% of water withdrawn in the United States (Pedrero et al., 2010). In California, for example, 656 million cubic meters of water are reused annually (Pedrero et al., 2010). In Indiana, there have been two case studies to assess the feasibility of incorporating treated wastewater as a form of irrigation, demonstrating low risk from land application, but mixed responses from farmers (Dare, 2015). A more practical scenario for Indiana farmland is the use of recycled drainage water, which can generally be used without treatment unless the biological quality was of concern.

For treated wastewater, Rao et al. (2017) reported the average energy requirement to treat one cubic meter of water with aerobic sludge treatment and anaerobic sludge digestion was 0. kwh (2160 KJ), with the average in the United States at 0.43 kwh (1548 KJ), consistent with the value assumed by Daher (2012). Additionally, municipal wastewater holds a large amount of energy which could partially be recovered, with a chemical energy content per unit of wastewater of 2.1 kW h/m^3 (7560 KJ/m^3) and 4.7 kW h/m^3 (16,920 KJ/m^3) for domestic and mixed wastewater, respectively. Nitrogen and phosphorus recovery could also be implemented to develop fertilizers (Rao et al., 2017; Yao et al., 2018). This holds potential for further developing FEW nexus tools to capture chemical energy and nutrient recovery. One aspect that was not taken into consideration was the amount of water required for energy supply; water is used in most stages of energy production (Rao et al., 2017), and ensuring that water is being accounted for in the water–energy connection will allow for better assessment of the FEW nexus.

In Daher (2012), the water consumption for crops in the WEF Nexus Tool 2.0 were based on data from the Water Footprint Network and the Agricultural Sector in the Ministry of Environment of Qatar. Due to differences in climate and agricultural production between Qatar and other areas where the tool might be applied, site-specific values of water demand need to be calculated. The Matson Ditch Watershed is a rainfed agricultural region, where on an annual basis the effective rainfall, that is, the rain which is readily available for crop usage, exceeds crop water demand. From Mehan (2018), a baseline value of 819 mm of average annual precipitation was considered at the watershed level, comprising baseline values of actual evapotranspiration (water demand from crops and plants) of 519 mm, surface flow of 161 mm, groundwater flow of 36 mm, subsurface drainage flow of 81 mm, and lateral flow of 22 mm. Evapotranspiration is roughly 63% of the total water available from rainfall. Conventional methods for calculating effective precipitation are on a monthly basis (Brower and Heibloem, 1986). Furthermore, crop water needs vary by crop growth stage. In the study area, for example, excess water due to rainfall and snowmelt in the spring is drained off so as to allow crop production. However, crops may suffer water stress in later growth stages due to insufficient rainfall in summer months—implying that the excess depicted by the annual picture could be deceiving. Thus, in order to fully capture critical aspects of water management in the FEW nexus, the modeling needs to be done on a monthly basis. Using monthly values would allow for finer-scale assessments of the water surpluses and shortages for the crops within the watershed.

Water quality is a critical component that could benefit FEW nexus modeling tools to better address the health of water bodies that impact and are impacted by food and energy production. Without a water quality component, it may not be possible to obtain the full picture of the FEW nexus. Assessment of water quality in a region requires extensive knowledge of the site location, as well as water quality data (Mijares et al., 2019). Though implementing water quality into a model potentially enhances its performance by allowing a more comprehensive assessment of the FEW nexus, the model becomes much more data intensive. Nevertheless, components can be simplified; Yao et al. (2018), for example, developed nutrient flows and stocks in a local FEW nexus system, accounting for inlets and outlets of annual loads of nitrogen, thus, demonstrating the potential of modeling nutrient flows in a simplified FEW nexus system.

It is important that FEW nexus models provide decision-makers the ability to integrate all these components for a single strategy for natural resource management (Mohtar, 2016). One strategy, which is implemented by the WEF Nexus Tool 2.0, is to incorporate a sustainability index, which aggregates the resources through indices that have the potential to be weighted as the stakeholder or decision-maker sees fit (Daher and Mohtar, 2015). Through the incorporation of water quality, an implementation of water quality indices developed for the Western Lake Erie Basin, such as those by Mijares et al. (2019), could be incorporated into a sustainability index to be more reflective of the water resource management in the region.

One aspect that this case study did not mention was the financial obligation for implementing certain scenarios, as these may change with policies based on the type of energy inputs one may use, and with some of the energy markets, such as electricity, as prices are volatile. In the state of Indiana, for example, policies would have to be further developed in order to incentivize solar energy production (Sesmero et al., 2016). Wind, on the other hand, has policies in place that allow it to continue to thrive in Indiana, accounting for $40 million annually (Tegen et al., 2014). In the future, it would be beneficial to make profit or financial projections throughout the 21st century to strengthen the long-term assessments for decision-making. Additionally, trade policies, subsidies, import and export policies, and other unique economic structures may all impact the financial obligations of a scenario (Kaddoura and El Khatib, 2017).

Although it may seem that data are readily available, one of the major limitations in modeling the FEW nexus is extensive data requirements (Kaddoura and El Khatib, 2017). In order to employ the WEF Nexus Tool 2.0, it requires detailed knowledge of the site of interest. Data sources for crop production can be found from sites like the United States Department of Agriculture National Agricultural Statistics Service (USDA-NASS), and the Food and Agriculture Organization (FAO) of the United Nations. However, these databases contain crops that are currently produced on a large scale and data on specialty crops may be not be readily available. Determining tillage, harvest, and fertilizer application methods may be difficult, as this can vary by individual farming facility. Data can be sparse if it is on the local level in terms of crop production, which may require connecting with stakeholders or nongovernmental organizations. The FAO provides various resources for assessing crop growth periods, water demand, and rough yield estimates, which could aid in generating estimates for crop production. National energy and water consumption data may be readily available, but again, may be difficult to downscale. Water quality is spatially dependent and finding long-term reliable data can prove difficult. All of these considerations should be taken into account when assessing FEW nexus modeling tools.

This work provides a starting point for better integrating water management (both quantity and quality) into a FEW nexus framework, and for integrating climate change responses based on climate change projections for the 21st century. While there has been interest in addressing climate change impacts in recent years, the focus in strategic planning has remained “silo-based” or highly sectoral, thereby not addressing the competition among food, energy, and water demands within the nexus (Rasul and Sharma, 2016; Daher and Mohtar, 2015). Without properly addressing the interconnection and interdependence within the FEW nexus, decision-making would not be robust, solutions would not be sustainable, and substantial environmental degradation may result. Analysis on monthly or seasonal basis would allow for finer-scale assessments capturing periods of water surpluses and deficits, and provide deeper insights into nexus responses at different times of the year. A dynamic link between FEW nexus tools and hydrologic and water quality models would help with streamlining the analysis.

8. Conclusion

With various tools for modeling the FEW nexus, it is critical to assess the feasibility of incorporating a model for an area of study. Developing the scope and framework of the food-energy-water nexus may seem daunting, but with the 7-Question Guideline to Modeling the Water-Energy-Food Nexus and available tools, it is possible to integrate a portion, if not all, of a chosen tool’s framework into an assessment The goal of this study was to analyze FEW nexus modeling tools with a specific focus on their potential for addressing water resources management issues at the nexus. Through this work, the framework of the WEF Nexus Tool 2.0 and the SWAT model were implemented in a case study in the Matson Ditch Watershed in Indiana to demonstrate potential growth in modeling the FEW nexus for water resource management while capturing uncertainties due to climate change. Results showed that through the integration of the WEF Nexus Tool 2.0 and a comprehensive watershed model such as SWAT, a more holistic view of the FEW nexus can be developed to improve decision-making. Incorporating futuristic climate data in the analysis demonstrated the potential of FEW nexus tools in assessing future stressors and informing water resource management strategies for the development of robust solutions. Additionally, the analysis showed how spatial, temporal, and water quality components could be integrated in further assessments of sites using a FEW nexus framework approach.

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Conflict of interest

The authors have no conflict of interest to declare.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.fbp.2019.10.011.

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