INFEWS/T1: Sustaining food, energy, and water security in agricultural landscapes of the Upper Mississippi River Basin

1. PROJECT RATIONALE, VISION, AND GOALS

Society depends on Earth's physical and biotic systems for food, energy and water (FEW), yet sustaining FEW in the face of broad-scale change remains a critical challenge. Security in each sector depends on complex linkages and tradeoffs among the three, and such interactions are especially difficult to anticipate in an uncertain future (D'Odorico et al. 2018). Societal needs for FEW are growing as demand for natural resources intensifies; needs must be met in the face of a changing climate and policy arena, and without sacrificing natural ecosystems and ecosystem services (benefits provided to people by nature) (Hoff 2011, Allouche et al. 2014). Drivers of change could compromise FEW security and diminish ecosystem resilience, given unpredictable interactions, feedbacks, and thresholds (Steffen et al. 2018). Understanding how different attributes of FEW systems, with their complex social-environmental interactions, amplify or dampen effects of changing drivers and increased demand is fundamental to FEW security. The proposed research will elucidate biophysical interactions that affect FEW supply and interactions of policies and environmental drivers that will influence FEW security in coming decades.

Understanding FEW interactions is a sustainability research priority in the U.S. (National Research Council 2013) and globally (United Nations 2016), yet knowledge of how to achieve FEW security at regional scales remains scant, particularly because of a lack of integrated modeling assessments that include human/social systems and connections to subsurface processes (Kling et al. 2016; Obersteiner et al. 2016). How varied initiatives – such as new policies, land-use practices, or water management strategies – can mitigate deleterious effects of climate change and land management on FEW security across regions with heterogeneity in soils, land use/land cover, and depth-to-groundwater is currently unknown (Benton et al. 2018, Cai et al. 2018). Further, it is highly uncertain what magnitude of risk or cost it will take for farmers, landowners, and agricultural institutions to change management practices that impede progress towards meeting U.N. sustainable development goals (SDGs). The proposed research directly addresses these societal priorities and research gaps in the critical agricultural landscape of the upper Midwest, where FEW dynamics and security are closely tied to management of agricultural, semi-natural, and natural lands and water resources.

The potential for abrupt changes, i.e. substantial changes in state that occur in a short period of time relative to typical rates of change (Ratajczak et al. 2018) is among the most challenging research frontiers for sustaining FEW in the decades ahead. Abrupt changes are notoriously difficult to diagnose and predict because they can arise from numerous causes. Research on abrupt change, resilience, and collapse has accelerated recently, but surprisingly agriculture receives little attention (but see Kelley et al. 2015, UK Global Food Security Programme 2017). Most studies have focused on theory (Scheffer 2009), empirical detection of past abrupt change (Rocha et al. 2015, Müller et al. 2016, Cumming and Peterson 2017), and development of early warning signals (Scheffer et al. 2015). Many studies are global in scope (e.g., Lenton et al. 2008, Barnosky et al. 2012; Steffen et al. 2015, 2018), and translating concepts associated with feedbacks, tipping points, and sudden change to the scales relevant for regional FEW systems is not straightforward. Thus, answers to many basic questions about FEW security remain elusive (e.g., what sets of biophysical conditions lead to FEW security? where and when will extreme events exceed the capacity of FEW systems to recover? how responsive are individuals and institutions to changing biophysical conditions that affect FEW?). There is a great opportunity and corresponding challenge to apply and extend theory on nonlinear systems and abrupt change to agroecosystems.

We propose integrated modeling research to enhance FEW security in the Upper Mississippi River Basin, a large U.S. region that is a critical component of national FEW supply. We focus our study on studying changes to the year 2050 because uncertainty about future climate change is lower in this timeframe and it is within a time window that society can anticipate and plan for more easily (Carpenter et al. 2015). Finding tenable pathways to FEW security requires substantial research advancements and integrated models aimed at understanding the rates and magnitude of long-term slow (e.g. climate) and abrupt (e.g. extreme weather events; new policy) changes that agricultural landscapes can absorb without experiencing a precipitous decline in FEW supply; identifying where and how different interventions, like land and water management choices, policies and governing systems, can amplify or dampen feedbacks that stabilize or destabilize the FEW system; and avoiding undesirable changes, particularly those that are abrupt, difficult or costly to reverse, or initiate ecosystem collapse. The biophysical system must be modeled interactively with the economic system and representations of policy and governance. External forcings and feedbacks between social and biophysical systems also must be included to manage uncertainty and adapt policies that enhance FEW security (Kling et al. 2016, Rissman and Gillon 2017). Our proposed research addresses these key research needs in the context of our overarching question:

How do FEW systems of the Upper Mississippi River Basin (UMRB) respond to complex social-biophysical interactions, and what policies and practices will sustain FEW security and the environment, reduce risk of abrupt change, and promote ecosystem resilience during the 21st century?

1.1. Specific Research Questions. We will answer research questions related to current conditions and trends in FEW, *top-down* effects of external biophysical and socioeconomic drivers across the entire UMRB region, and *bottom-up* drivers and decisions at finer scales in four diverse representative sub-regions (Fig. 4). We aim to understand how tradeoffs and synergies among FEW are geographically distributed, how local-to-regional policies may improve FEW security under varied climate-change and plausible future scenarios, and how a variety of potential interventions associated with land and water management and mixes of natural and agricultural lands can promote FEW security. Additionally, we will survey farmers and policy actors to understand how they perceive FEW security, tradeoffs, and policy options. We will assess a suite of complimentary quantifiable targets for improving FEW security in the UMRB using the U.N. SDGs as a framework. Our three specific research questions are:

1. ***What is the current status of FEW in the UMRB relative to specific FEW sustainability goals, and how are tradeoffs distributed geographically across the region? (Fig. 4, Q1)*** We begin by quantifying the current status, geographic distribution, and historical trends and tradeoffs of water systems, food and bioenergy production from agroecosystems across the UMRB. This provides the foundation to understand FEW system responses to socio-economic and biophysical drivers, and how it would need to change to meet FEW sustainability goals by 2050. We will assess the current status (baseline) of FEW in the UMRB with numerical modeling grounded in observational data.

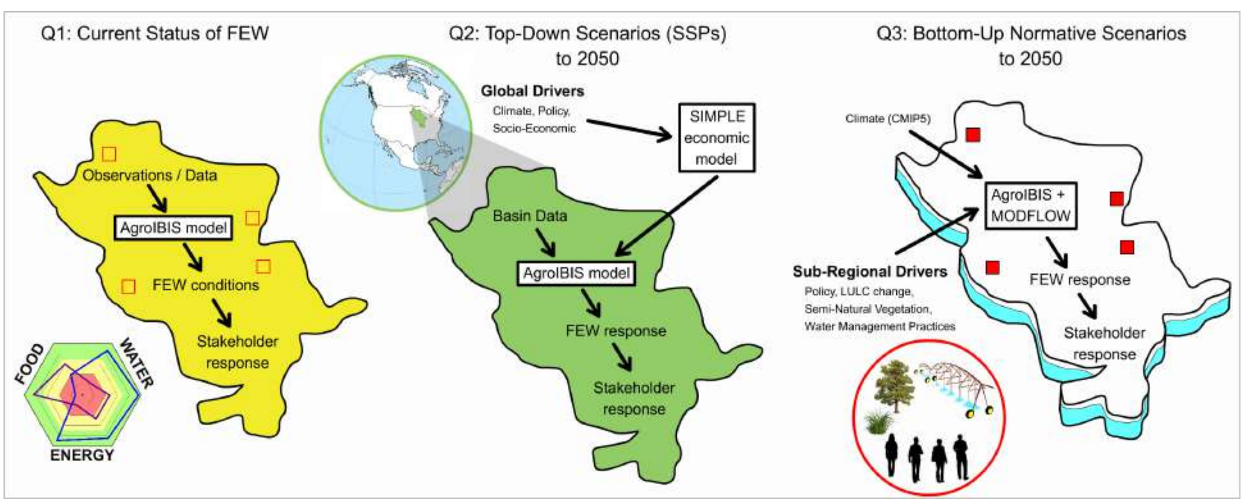

Figure 4. Conceptual figure highlighting our approach to assessing (Q1) current FEW security and future conditions through integrated assessment modeling that uses a (Q2) *top-down* approach to examine impacts of global drivers and regional policies on FEW security across the entire UMRB, and (Q3) a *bottom-up* approach using normative scenarios of land and water management changes and applying an advanced groundwater-agroecological model in four sub-regions.

2. ***How might the introduction of new local-to-global policies alter FEW security and resilience by 2050, and how can the FEW nexus be governed and land/water resources managed to achieve FEW security in the face of rapid environmental change? (Fig. 4, Q2)*** Analyzing the FEW nexus requires understanding of individual and organizational behavior, connections to FEW policy and governance, and effects of globalization. For the whole UMRB, we will use a *top-down* integrated assessment modeling (IAM) approach to examine the effects of plausible policy changes on FEW through 2050. Our IAM framework will incorporate land-use economics and technological change. We will explore scenarios based on shared socioeconomic pathways (SSPs) that include changing climate and atmospheric CO_2 to assess impacts of changing governance on FEW security. Our social-ecological models will explore feedbacks from crop production, economics, land use, and policies that can enhance/reduce our ability to avoid undesirable abrupt changes and meet SDG goals across the UMRB landscape. Our social science work will survey farmers and policy actors to understand their perceptions of FEW security, future scenarios, tradeoffs, and policy options.

3. ***What combinations of conditions could enhance or erode FEW security by 2050, and can undesirable and irreversible changes in FEW components be anticipated and avoided? (Fig. 4, Q3)*** Local conditions and land/water management practices in agricultural landscapes interact with broad-scale drivers to jointly influence FEW supply and trends. We will use a *bottom-up* effort to determine what biophysical conditions are needed to meet SDGs within four representative sub-regions in which competing demands for FEW are distinct and pronounced (Table 1). We will assess how perennial vegetation and specific land/water interventions can mitigate effects of policy shocks and extreme events on FEW, and document stakeholder perceptions. This intensive effort will include direct linkages between subsurface processes and the groundwater system at high spatial resolution (100 m).

1.2 Theoretical Advances

This study will develop and apply new theory about how different combinations of drivers interact in agricultural landscapes in ways that could fundamentally change components of the FEW nexus. We will emphasize three dimensions of abrupt change (Ratajczak et al. 2018) that have strong potential to impact FEW security. First, even if drivers change gradually (e.g., gradual increase in temperature), state variables (e.g., crop yield, biofuel feedstocks, freshwater supply and quality) can change suddenly in response to thresholds, complex interactions among drivers, and internal system dynamics. Thus, a component of achieving FEW security is understanding the mechanisms and feedbacks that can be managed to avoid abrupt collapse (e.g., Cumming and Peterson 2017, Steffen et al. 2018). Second, external drivers can change abruptly (e.g., sudden change in climate, global FEW demand or pricing) and cause an abrupt change in FEW. Inter-annual variation in temperature and precipitation explains up to 60 percent of the variability in crop yield in key agricultural regions, (Ray et al. 2015), and increased variability in the form of extreme droughts, heat waves or floods strongly reduces crop production (Lesk et al. 2016, Tigchelaar et al. 2018). Thus, another component of FEW security is the capacity to sustain FEW supply in the face of abrupt changes in drivers. Third, change in natural and semi-natural elements of agricultural landscapes can affect FEW security if the amount or connectivity of such elements disrupts key ecosystem services (e.g., pollination, pest control, sediment retention). Understanding how such elements function to sustain FEW supply as drivers and demand change is woefully incomplete. We will extend theories of abrupt change to managed agricultural systems and incorporate key mechanisms that can amplify or dampen effects of changing drivers on FEW.

Our work will identify the state-space in which FEW security can be sustained as shocks (drought, extreme heat, flooding, and policy changes) intersect with slowly changing drivers. Drivers act in concert, rather than alone; understanding interactions, nonlinearities, and potential for abrupt change requires conceptual advancements that incorporate key mechanisms. For example, rising temperatures that increase growing season length and potential yield in the cool upper Midwest may be accompanied by abrupt change in the variance of precipitation (Fig. 5a). How these changes affect FEW supply will depend on system state, including management practices. Water management practices (e.g., irrigation, tile drainage) may dampen effects of increased variance in precipitation on food and biofuel production, while croplands that depend on rain are not buffered from annual fluctuations in yield (Fig. 5b). However, other aspects of the FEW system may respond differently. Groundwater security may be sustained in rain-fed systems but eroded if withdrawals for irrigation and losses to drainage are not replenished. In turn, the system may cross thresholds that imperil aquatic ecosystems by reducing stream baseflow (Fig. 5c). We will identify scale- and context-dependent positive and negative feedbacks that act to stabilize FEW supply in the face of change, along with thresholds that cannot be exceeded if FEW security is to be maintained. We also will identify leverage points that can be manipulated to enhance FEW security and describe alternative pathways that can mitigate or avoid abrupt changes in FEW supply.

2. STUDY REGION: THE UMRB FOOD-BIOENERGY-WATER SYSTEM

As a breadbasket, biofuel producer, and water tower, the UMRB is critical to national and global FEW security. The region spans five states, has a wide range of climate, soil types, land cover and crop management, and is home to a variety of political and social structures and decision makers (Fig. 6). The UMRB covers only 6% (489,500 km^2) of the land area in the contiguous U.S. yet it produces 44% of corn grain, 36% of soy, 48% of hogs, 19% of dairy, and 22% of total U.S. agricultural exports (2012 data in USDA-NASS and USDA-ERS, 2017). The UMRB also accounts for 26% and 28% of U.S. nitrogen (N) and phosphorus (P) fertilizer sales, respectively (IPNI, 2016). As a key contributor to global food markets, the region is a critical player in the "*grand challenge*" to feed 9 billion people by 2050 in ways that ensure the long-term sustainability of our planet's natural resources. The UMRB is also a critical hub of renewable energy production and ongoing research that has significant ramifications for the global crop production, exports, and trading; ~40% of corn grain goes towards biofuel production (USDA-ERS, 2017), first generation ethanol plants dot the Midwest landscape, and research on advanced cellulosic biofuels has a strong foundation in the UMRB (Slater et al. 2015). The nation's reliance on the UMRB underscores the importance of determining how FEW security can be achieved in an uncertain future in which drivers of change are already jeopardizing environmental sustainability.

Unfortunately, reliance on the UMRB landscape to produce large amounts of food and biofuel has led to myriad current and potential future tradeoffs that jeopardize elements of the FEW system and also make national and global food supplies particularly vulnerable to anthropogenic change. UMRB soils are impacted by legacy P from manure and fertilizers (Sharpley et al. 2013, Motew et al. 2017), and an increased frequency of extreme rainfall events–associated with climate change –has amplified negative impacts from agrochemicals and manure, contributing to abrupt changes in nutrient transport to aquatic systems and substantially reducing water quality (Jarvie et al. 2015, Hein and Leemans 2012, Gillon et al. 2015, Pace and Gephart 2017). Reliance on inorganic N fertilizer has

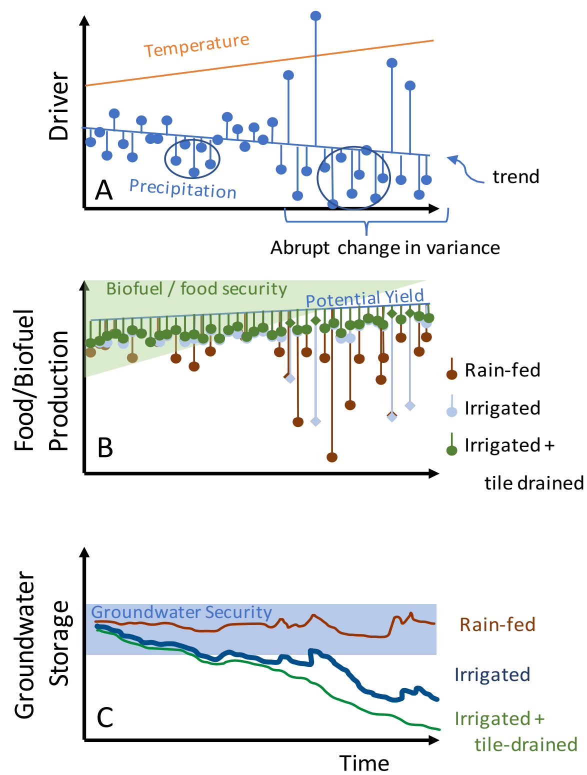

Figure 5. Gradual changes in temperature an precipitation interact with an abrupt change in interannual variability in precipitation (A) to alter the ability to maintain food, energy (B), and water (C) security. While both tile drainage and irrigation close the yield gap through smart water management, neither completely achieive food and energy security in the face of increase variability and reduce the resilience of the groundwater system to multi year droughts (indicated with elipses).

compromised groundwater quality, with nitrate levels often above the EPA safe drinking water limit, while N transport to the Gulf of Mexico contributes to a large hypoxic zone (Rabalais et al. 2002, White et al. 2014, Scavia et al. 2017). Following a rapid increase in demand for corn ethanol in 2007-08, cropland expanded into lands not previously devoted to agriculture and to lands less suitable for cultivation (Lark et al. 2015). Increased crop production on marginal soils has also been accompanied by increased irrigation, groundwater depletion (Kraft et al. 2012), and increased tile drainage.

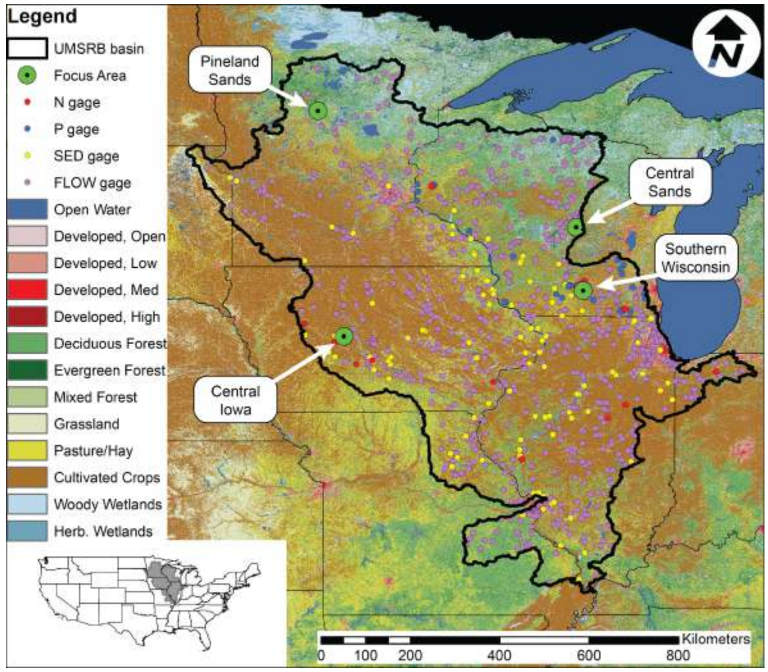

Figure 6. Land cover (2011) of the Upper Mississippi River Basin (UMRB) with streamflow and nutrient gages, and locations of four sub-regions targeted for nested modeling studies with MODFLOW-AgroIBIS.

The long-term consequences of rapidly changing water management practices are not well understood and are currently debated by scientists, producers, and lawmakers. Expanded irrigation, freshwater degradation, and forest conversion are fueling current water-rights controversies in the Central Sands region of WI and the Pineland Sands of Minnesota (Kraft et al. 2012). Tile drainage, one of the most direct and widespread hydrologic interventions across the UMRB, causes groundwater to be short-circuited from the soil hydrologic cycle and discharged to ditches and streams, altering hydrologic and ecologic functions. FEW governance is also changing as diverse agencies and organizations implement multiple approaches to protect natural resources (or roll back regulations) while enhancing economic growth (Rissman and Carpenter 2015, Garnache et al. 2016). These shifting drivers are manifest throughout the UMRB and challenging the capacity of existing land-use patterns and practices to sustain FEW. Yet, these issues–and the attention they garner–also present opportunities for increasing ecosystem resilience and averting abrupt change, improving environmental, agricultural, and economic security, and enhancing stakeholder engagement. Within the large UMRB region, we identified four focal sub-regions for intensive study in which different dimensions of these issues are especially pronounced (Fig. 6, Table 1). These sub-regions differ significantly in their dominant cropping systems and land use, soil types, and water management.

Table 1. Four focal sub-regions within the UMRB illustrate representative but contrasting FEW conditions. Collectively, these represent dominant aspects of FEW within the region.

Sub-region name and location	Dominant crops and land uses	Dominant soil type	Water Management
Southern Wisconsin (Yahara River watershed)	Dairy (corn, alfalfa, soy); biofuel; urban; wetlands	Silty Loam	Rain-fed; limited tile-drainage
Wisconsin Central Sands (Wisconsin River watershed)	Vegetables (potatoes, snap beans, peas); dairy; biofuel; lakes	Loamy Sand	Irrigated
Minnesota Pineland Sands (Crow Wing watershed)	Vegetables (potatoes, dry edible beans); forests; biofuel; lakes	Sandy Loam	Irrigated
Central Iowa (Raccoon/Upper Des Moines River watersheds)	Commodity grain (corn, soy); hog and egg; biofuel	Clay Loam	Rain-fed; extensive tile-drainage

3. FEW INDICATORS AND MODEL OVERVIEW

We will focus on indicators of food production, bioenergy production, improved water quality, adequate water supply while minimizing flood risk, and habitat for biodiversity (Table 2) to address all three of our research questions. For each indicator, we have identified specific quantitative goals (Table 2) that are hypothesized to increase FEW security in the UMRB by the year 2050. These targets include thresholds already specified by federal agencies (e.g., EPA 10 ppm nitrate in drinking water), measures of long-term improvements in ecological systems (e.g., reduced P yield), and translations of broad SDGs to the focal region (e.g., reduced land in monoculture). Implicit in these goals is the desire to create positive directional change in FEW security and ecosystem health in the UMRB. Our integrated assessment model (IAM)–which we describe next–aligns directly with the specific FEW goals (Table 2) and allows us to assess the likelihood of success for each target under different scenarios. Our experienced, interdisciplinary research team is ideally suited to conduct this study with a long history of productive collaboration (see *Results of Prior Support*). Together, our team brings together expertise in terrestrial ecology, agroecology, atmospheric sciences, biogeochemical cycling, ecohydrology, ecosystem engineering, and social systems and human behavior. We will draw on our integrated and proven biophysical and hydrologic modeling portfolio and incorporate a new component of economic land use modeling that fills a crucial research gap in exploring future FEW security with IAMs.

Table 2. FEW categories, FEW indicators, and specific quantitative goals for assessing FEW security in the UMRB.

FEW Category	FEW Indicators	Quantitative FEW goals in the UMRB
Food Production *SDG: Increase food production*	Corn production Soybean production Human food energy production	Increase agricultural production 2% yr^{-1} Limit inter-annual variability of yields to 20% of average values
Energy Production *SDG: Affordable and clean energy* *SDG: increase biodiversity*	Corn production for bioethanol Soybean production for biodiesel Corn stover for cellulosic bioethanol Grasses – production for cellulosic bioethanol Bioenergy production Proportion of landscape in native vegetation vs. row crops	Increase biofuel feedstock production by 25% Limit inter-annual variability of biofuel biomass/yield production to 20% of average values Increase pollinator and grassland bird habitat by 25%
Water Quality *SDG: Clean water and sanitation*	Phosphorus yield Stream phosphorus load/concentration Nitrate leaching to subsurface Stream nitrate load/concentration Soil phosphorus accumulation rate	Reduce P yield by 50%. Maintain concentration of NO_3-N leaching past the root zone to levels below 10 ppm.
Water Quantity *SDG: Clean water and sanitation*	Drainage Streamflow export from UMRB # of days below low-flow threshold # of days above flood threshold	Improve crop water use efficiency by 25% Maintain current streamflow and seasonality.

3.1 Integrated Assessment Modeling

Our state-of-the-art, spatially explicit modeling framework will link terrestrial ecosystem processes, traditional cropping systems (corn, soy, wheat), and bioenergy crops (Agro-IBIS; Kucharik, 2003, Vanloocke et al. 2010, 2012) with hydrologic transport (THMB) at 4-km x 4-km spatial resolution throughout the UMRB (see *Results of Prior Support* for more detail on our modeling approaches & Fig. 2). In the four sub-watersheds (Table 1) that represent diverse ecoregions, we also will implement MODFLOW-AgroIBIS (Zipper et al. 2017), our coupled model of the land surface and groundwater system. We will leverage these models and enhance the realism of our investigations of future conditions by using land use and land management information (which are hereafter referred to as part of "boundary conditions") provided by the SIMPLE economic model of land use, created by Baldos and Hertel (2013; *see Facilities statement and letter of collaboration from Prof. Thomas Hertel, Purdue University*). These model linkages represent a major and needed advance and address a significant gap in current integrated modeling approaches on FEW security (Kling et al. 2016). This suite of models will allow us to investigate the impacts of global economics and alternative land-use policies to the region's biophysical systems by 2050.

We will incorporate a partial equilibrium model of agricultural trade called SIMPLE (or A Simplified International Model of crop Prices Land use and the Environment) into our biophysical (Agro-IBIS and THMB) modeling framework (Fig. 7). As stated by Baldos and Hertel (2013), ***scientists who use biophysical crop modeling tools to project changes in future productivity, but ignore changes in crop prices due to global supply and demand will likely understate changes in crop production.*** This is an important reason for integrating SIMPLE with our Agro-IBIS model. The SIMPLE model is used in scenario analysis to evaluate the effects of policy and technological change on food supply and demand, trade, and food security outcomes. It allows for investigation of connections between globalization and food-energy-water systems. For our future scenarios, it will provide land use and land management information, which we will refer to as land use/land management boundary conditions (crop production, cropland extent, land equipped for irrigation, livestock consumption of feedstocks, and fertilizer applied to cropland) to our agroecosystem model (Agro-IBIS).

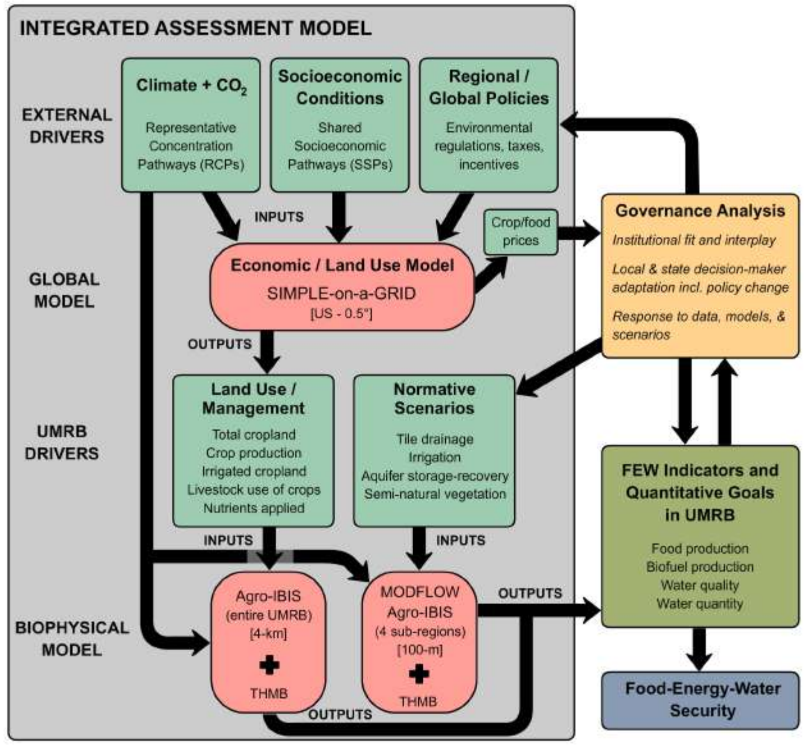

Figure 7. Diagram of linkages between future scenarios, biophysical modeling, economic and land use modeling, and governance analysis.

SIMPLE description. In SIMPLE, the world is conceptualized as sixteen economic regions, requiring a combination of both land and non-land (fertilizers, farm labor, and machinery) inputs. Global demand for cropland output is divided among inputs for processed food production, direct consumption by households, biofuel feedstocks, and livestock feed (Baldos and Hertel, 2013, Hertel 2016). Demand for food is a function of regional population, commodity prices, and per capita income (Baldos and Hertel, 2013). To support intensive crop and livestock production, crop inputs are required, and the demand for those can be altered with technological advances (e.g., increased nitrogen use efficiency in crops, more land area equipped for irrigation, or more feed efficient livestock). Future growth in agricultural production is supported by investments in agricultural research and development, fertilizers and water inputs, policy changes, and some changes in climate (Baldos and Hertel 2013, Hertel and Baldos 2016). Land pricing influences the amount of the landscape devoted to cropping systems. In our applications, a new version of SIMPLE, called SIMPLE-on-a-GRID will be used by disaggregating U.S. crop production at a 0.5º x 0.5º grid-cell resolution. SIMPLE-on-a-GRID is an extension of SIMPLE that has been applied to study long-term sustainability issues in agriculture (Baldos and Hertel 2014). Population, per capita income, biofuel mandates (exogenous in the model), and prices (endogenous to the model) drive regional demand. SIMPLE-on-a-GRID extends SIMPLE by disaggregating rain-fed and irrigated production at the individual grid-cell level. Agro-IBIS will use SIMPLE-on-a-GRID boundary conditions at 0.5º resolution to simulate impacts of changing policy and land use/management on FEW indicators.

Integrated Scenarios for 2050. ***We will implement a new framework for integrated scenarios to support integrated assessment modeling*** (Fig. 7). As discussed in van Vuuren et al. (2013) and O'Neill et al. (2014), this framework combines three pathways of future change: (1) climate model projections, (2) socioeconomic conditions, and (3) assumptions about climate policies. We will establish a set of baseline scenarios that combine varied climate model projections with future pathways of socioeconomic conditions, and study how alternative regional policies in the UMRB change FEW systems and associated ecosystems services. These pathways will be used as inputs to the SIMPLE model. Three baseline scenarios of future conditions in 2050 will be created using CMIP-5 model output for Representative Concentration Pathways (RCP) 2.6, 4.5, and 8.5 (i.e., atmospheric CO_2 in 2050 is approximately 450, 530, and 625 ppm, respectively, in each RCP) in combination with available Shared Socioeconomic Pathways that have been developed (SSPs; Keywan et al. 2017) and are already being used to drive SIMPLE. An SSP represents alternative trends in society and natural systems, consisting of a storyline and quantitative measures of development, and serves as a reference pathway that is absent of climate change or climate policies. This is done intentionally so SSPs can be studied in combination with the other components of the IAM framework (O'Neill et al. 2014). Preliminary proof-of-concept modeling (Fig. 8) with Prof. Thomas Hertel's group at Purdue Univ. demonstrates new scientific advances when linking economic and biophysical models. We simulated a new scenario using SIMPLE-on-a-GRID predicted land use (total irrigated and rain-fed cropland) for 2050 in the Yahara watershed of southern WI using Agro-IBIS, and compared it to three scenarios offline that do not include economic feedbacks. Crop production, lake P loading, and drainage varied across scenarios (Fig. 8), and when globally-driven land-use changes were considered using SIMPLE, the outcomes (particularly crop production) were different compared to the original scenarios (NW, CC and AR in Fig. 8). ***This preliminary work shows that global drivers of land-use change & economics are a necessary component to studying FEW security.***

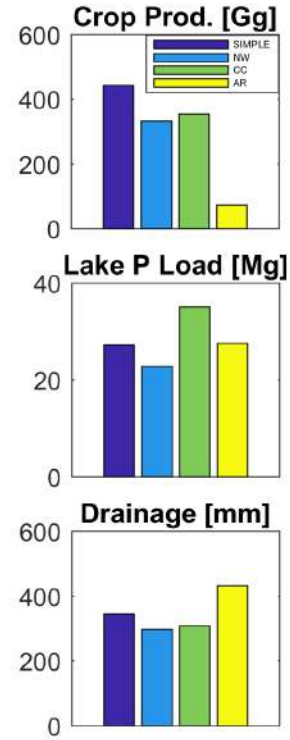

Figure 8. Agro-IBIS simulated total crop production, lake P load, and average drainage for three scenarios of change to 2050 for the entire Yahara watershed of southern Wisconsin (NW – Nested Watershed, CC – Connected Communities, AR – Abandonment and Renewal, Booth et al. 2016) compared with values generated using boundary conditions of total irrigated and rainfed crop area in 2050 provided by the SIMPLE-on-a-GRID economic land use model using RCP 8.5 and SSP2 pathways.

4. RESEARCH QUESTIONS AND APPROACH

Q1. What is the current status of FEW in the UMRB relative to specific FEW sustainability goals, and how are tradeoffs distributed geographically across the region?

We will use our Agro-IBIS and THMB modeling suite (Fig. 2 is found in *Results of Prior Support*) and extensive empirical datasets to quantify the FEW indicators relevant to food and bioenergy production and water quantity and quality in the contemporary landscape. Models will first be calibrated and validated across the entire region. We will then use the models to assess tradeoffs and synergies in FEW across the UMRB, quantify how they respond to extreme weather events, and assess how dominant water diversion practices – including irrigation and tile drainage – currently affect dimensions of FEW.

While our modeling tools (Fig. 2, *Results of Prior Support*) have been previously subjected to extensive calibration and validation across the Midwest US (Kucharik 2003, Kucharik and Brye 2003, Donner and Kucharik 2008, Twine and Kucharik 2008, Motew et al. 2013, Motew et al. 2017), we will re-evaluate our models across the entire UMRB for the most recent 12-year time period. We will use datasets on county-level crop production (USDA-NASS) and streamflow and water quality (P, N, and sediment) from USGS stream gages (shown in Fig. 6) to evaluate model simulations of changing FEW conditions from 2007 to 2018. Climate data inputs will be created using spatially continuous datasets from University of Idaho GRIDMET (Abatzoglou, 2013) (air temperature, relative humidity, wind speed, solar radiation) and NOAA's National Stage IV QPE Product (precipitation, Nelson et al. 2016). Gridded soils data originate from the STATSGO2 dataset from USGS. Elevation data will be obtained from the USGS 3D Elevation Program (https://nationalmap.gov/3DEP/), stream network characteristics from the National Hydrography Dataset (https://nhd.usgs.gov/), and land-use/land-cover data from the USDA-NASS Cropland Data Layer (USDA 2016). Fertilizer and manure application rates will be determined based on the approach from Booth et al. (2016), using crop type, published recommendations, and county-scale fertilizer sales (IPNI, 2016) and manure production estimates (Gronberg and Arnold, 2017).

Sub-question 1.1. How do biophysical drivers and extreme weather events affect current FEW status and tradeoffs among FEW dimensions across the UMRB? We will combine model output and new analyses of observational data to assess current FEW status. First, indicators of FEW sustainability and resilience (Table 2) will be quantified using our Agro-IBIS and THMB modeling tools for each year from 2007 to 2018. Besides using the model outputs of FEW indicators, we will calculate human food energy, bioethanol, and biodiesel production using a method similar to Cassidy et al. (2013), which uses FAO crop allocation data to separate crops produced for feed, food, and fuel. Tradeoffs and synergies among food and bioenergy production and the quantity and quality of water will be quantified using methods from our previous work (Qiu and Turner 2013). Outcomes will be summarized and plotted using radar diagrams, maps, and spatial analyses to establish current baseline conditions for multiple dimensions of FEW within the UMRB. Extreme weather affects all FEW categories in the UMRB. We will also assess effects of droughts and floods, which can have catastrophic consequences for crop production at field to regional scales (Zipper et al. 2016). Extreme precipitation events can trigger large fluxes of sediment and nutrients into rivers, lakes, and reservoirs and degrade water quality (Carpenter et al. 2014, Gonzalez-Hidalgo et al. 2013). We will assess the status, trends, and spatial patterns of droughts and floods in the UMRB by analyzing records of precipitation from the National Climatic Data Center, NOAA-QPE, and GRIDMET, and river discharge data (Fig. 6).

Sub-question 1.2. How do current dominant water management practices (irrigation, tile drainage) in the UMRB affect food and biofuel production and water quantity and quality? Understanding and anticipating water management is crucial for FEW security in the UMRB. Currently, significant conflicts over water use exist in sandy regions of the UMRB. As the density of high-capacity wells used for irrigation has increased to support potato and vegetable agriculture, stream and lake levels have declined (Kraft et al. 2012). We will perform model simulations to quantify effects of **current** irrigation practices on FEW in Wisconsin's Central Sands and Minnesota's Pineland Sands region, as well as effects of tile drainage in Central Iowa (Fig. 6). These regions are exemplars of heavily irrigated and tile-drained regions of the UMRB. However, the effects of tile drainage are typically neglected from regional scale hydrologic models and land surface models. We will evaluate the extent to which tile drainage and irrigation has already changed water, food, and ecosystem outcomes, and how it will change them under future scenarios. ***To accomplish this, we will add a tile-drainage module to MODFLOW-AgroIBIS,*** which will act as head-dependent sink term in the groundwater model that will be proportional to the height of the water table above the tile drain. This water and its nutrients will be routed directly to THMB, our hydrologic transport model. Model experiments for our historical time period (2007-2018) will use two sets of simulations in each of these three sub-regions and compare current conditions with the absence of tile drainage or irrigation. For the two sand regions (Fig. 6; Table 1; ~1000 km^2 each), we will use our coupled ecosystem-groundwater (MODFLOW-AgroIBIS) model at high spatial resolution (~100-m pixels) to understand the impacts of typical plant-available water thresholds (e.g., 80-90%) that trigger irrigation events and N fertilizer applications on water use, crop and biofuel feedstock (corn, *Miscanthus*, switchgrass) productivity, and leaching of N to groundwater. In the Central Iowa region, we will use MODFLOW-AgroIBIS to investigate the consequences of using tile-drainage on water budgets, crop productivity, and N flux to groundwater and

N discharge out of these watersheds. We will also quantify synergies/tradeoffs among flood vulnerability, nutrient loading to surface waters, and ecosystem support as indicated by lake levels and baseflow, by feeding outputs from MODFLOW-AgroIBIS to THMB.

Q2. How might the introduction of new local-to-global policies alter FEW sustainability and resilience by 2050, and how can the FEW nexus be governed and landscapes and water resources managed to achieve FEW security in the face of rapid environmental change?

Analyzing the FEW nexus requires a deeper understanding of individual and organizational behavior and the connections to FEW policy and governance (Al-Saidi and Elagib 2017). As the FEW system is shocked by abrupt changes and strained by slow trends, decision makers such as farmers and state governments are tasked with responding and making sometimes-difficult tradeoffs. ***Understanding what factors contribute to decision-makers' adaptation responses is an important developing research field which addresses questions like: How much change – and in what drivers – does it take for farmers or organizations to change their behavior to meet SDGs?*** These decisions can then be linked to other FEW system dynamics through scenarios and integrated modeling. We will use our IAM to explore how changes in land-use policy (e.g. taxes on water for irrigation, fertilizer, and manure use), varied socioeconomic pathways, and climate change impact future FEW sustainability and resilience (Fig. 7).

Scientific data, models, and scenarios play important roles in supporting decision-maker adaptation, but many questions remain about how FEW research can become usable science (Lemos et al. 2012). Flows of information from the global / U.S. economic and land-use models (e.g., food/crop prices) along with output from our biophysical models will offer a variety of new data and potential future conditions to elicit stakeholder responses (Fig. 7). A participatory modeling approach to incorporate stakeholder input in model development will be supported by a dedicated project outreach specialist at the University of Wisconsin Extension. As part of work in sub-questions 2.3 and 2.4, we will interface with critical stakeholder groups, particularly the multistate Southern Extension and Research Activities Committee 46 (SERA-46) and the Gulf of Mexico Hypoxia Task Force. Model output data will be coupled with mixed-methods studies of governance that assess how decision makers use information to learn and adapt.

Sub-question 2.1. How are indicators of FEW security impacted by changes in climate, atmospheric CO_2, and changing social systems and economics by the year 2050? In order to answer this question, we will use three global business-as-usual scenarios modeled to 2050, implementing the "Middle of the Road" SSP2 in combination with three RCPs (2.6, 4.5, and 8.5) and the corresponding CMIP-5 climate data. These simulations will provide insight on future conditions and changes in FEW before the impacts of new regional policies are quantified in Q2.2 (see below). Model output will be quantified based on analysis methods used in previous scenarios work (Qiu et al. 2018). These outcomes will be summarized to assist in communicating the future status of FEW and SDG goals to stakeholders.

Sub-question 2.2. How are indicators of FEW sustainability and resilience impacted by new regional policies for (a) water withdrawals for irrigation of agricultural crops, (b) N and P fertilizer applied to croplands, and (c) manure applied to croplands? Baselines of future conditions for 2050 (Q2.1) will be compared with additional scenarios that represent the potential impacts on FEW, ecosystem services, and SDG indicators of alternative land use/environmental policies. A key issue in the UMRB is the tradeoff of crop productivity and water quality, due to loss of N and P applied as inorganic fertilizer or in manure to the system (Fig. 9). Excess groundwater withdrawals for irrigation or excess application of fertilizer / manure will be subject to taxation and an increase or decrease of regulations in model experiments. This exercise will allow us to investigate the impacts of varied policies for water, fertilizer, and manure on farmer decision-making, and on the security of FEW in comparison to today's conditions as well as the business-as-usual baselines in Q2.1. For instance, we will impose levels of tax applied to each liter of excess water used or excess N or P applied to the landscape within SIMPLE-on-a-GRID. In turn, Agro-IBIS will be run with new boundary conditions for 2050 that will allow us to compare the policy impacts to the baseline scenarios in Question 2.1. For these policy scenarios, we will also use three RCP pathways (2.6, 4.5, and

8.5) and SSP2, which will be the baselines for Question 2.1. Increased taxation or restriction of management decisions pertaining to water and nutrients will effectively increase the costs of managing agricultural lands with these practices.

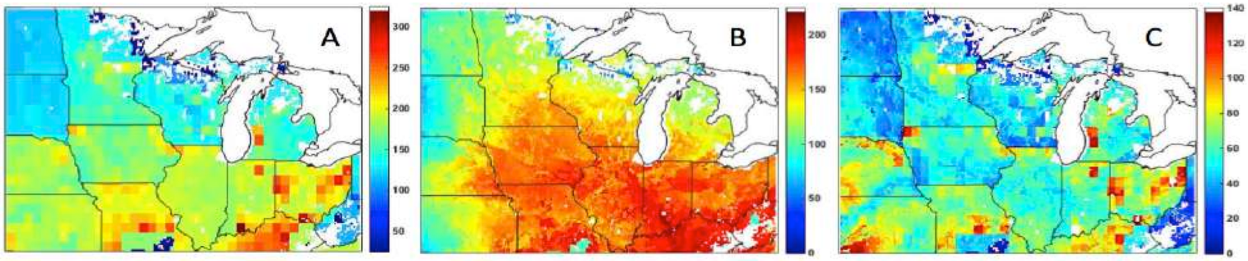

Figure 9. Midwest US tradeoffs for food/bioenergy from corn grain, and water quality: **(A)** Average annual fertilizer and manure applications of N (kg ha^{-1}) circa year 2000 and Agro-IBIS simulated annual average **(B)** rainfed corn yield (bu ac^{-1}), and **(C)** potential NO_3-N leaching (kg NO_3-N ha^{-1} yr^{-1}) past the root zone in the Midwest US.

Sub-question 2.3. How do farmers and policy actors perceive FEW sector security, tradeoffs, policy options, and future scenarios? ***Empirical social research will be used to modify policy inputs and scenarios in our modeling approach*** (Fig. 7). We will begin with online focus groups of key regional stakeholders to understand their perceptions of FEW security, reaction to FEW goals (Table 2), perceived tradeoffs, and responses to slow and abrupt change (Daw et al. 2015). To co-produce models with key decision-makers, we will conduct annual workshops with a group of stakeholders operating across the region, drawing from SERA-46, the Gulf Hypoxia Task Force, and other food and bioenergy stakeholders. Participatory modeling between scientists and stakeholders can increase learning and perceived legitimacy (Röckmann 2012). Participants will provide input on model assumptions, decision rules, and preferred policy options. Participant perspectives will be captured through pre- and post-workshop surveys, observation during workshops, and a follow-up interview.

To better understand heterogeneity in farmer and policy actor decision-making, we will develop a mail survey of farmers and a mixed-mode survey of policy actors in the UMRB to examine perceptions of FEW security and tradeoffs among food production, bioenergy production, and water quality and quantity. We will ask about support or opposition to policy options modeled under Q2.2. We will embed an experiment in both surveys in which respondents will receive historical (sub-questions 1.1, 1.2) vs. predictive scientific information (sub-questions 2.1 and 2.2) related to behavioral, normative, and control beliefs about FEW sustainability (Wiest et al. 2015). For the farmer survey, we will also ask about adoption of FEW-relevant practices, such as fertilizer use, manure spreading, and tile drainage. Based on the Theory of Planned Behavior (TPB) (Azjen 1991, Lynne et al. 1995), we propose to relate attitudes, norms, perceived behavioral control, behavioral intent, and biophysical and structural controls to adoption with mediation models. We will ask about changes in these behaviors in response to slow changes (e.g. rising winter temperatures) and abrupt changes (e.g. recent floods or market shifts). We propose to stratify the farmer sample to include areas with high modeled nutrient runoff. We will conduct a four-wave survey of 2100 farmers, expected response 800-1000 (Dillman et al. 2014). For the policy actor survey, we will include staff of county, state, and federal governments; agricultural, bioenergy, and water-dependent businesses; and FEW nongovernmental organizations identified through meeting attendance records, key stakeholder interviews, and web searches. We will survey ~2000 respondents (expected response ~1000) with advance paper mailing, four waves of email surveys, and paper survey follow-up. Select questions on policy options, adaptation, and perceptions of FEW tradeoffs will be compared between farmer and policy actor surveys. Survey results will inform case scenarios and models under Q.3.

Sub-question 2.4. How do FEW governance networks influence decision-making under slow and abrupt change? Governance networks play critical roles in resource sustainability and adaptation to environmental change (Villamayor-Tomas 2015) yet "nexus governance is the missing link" in FEW research (Al-Saidi and Elagib 2017). Drawing on the Institutional Analysis and Development framework (Ostrom 1999), and the theory of Ecology of Games (Lubell 2013), we will characterize networks of adjacent FEW action situations (McGinnis 2011) in responses to slow and abrupt biophysical change. Action situations involve individual and organizational decisions, institutions, and functional connections among FEW sectors. We propose to connect network analysis to socio-ecological institutional fit and interplay (Young 2002) to understand leverage points for improving institutional fit and reducing tradeoffs (Moss 2003). One of the stakeholder workshops will examine feedbacks and thresholds in response to abrupt change.

Q3. What combinations of conditions could enhance or erode FEW security by 2050, and can undesirable and irreversible changes in FEW components be anticipated or avoided?

In the face of changing drivers, FEW security may be achieved through varied land uses, patterns of land covers, and management interventions that enable society to meet its needs and recover from extreme events. Alternative portfolios have different sets of benefits and costs that are poorly understood, and how the effectiveness of different interventions for reducing vulnerability to interacting changing drivers varies with landscape context is not well known. Here, we focus our modeling at the finer scales that align with local *bottom-up* choices within four sub-regions (Fig. 6, Table 1) that are broadly representative of the patchwork of agroecosystems and natural vegetation in the UMRB. We will implement our coupled MODFLOW-AgroIBIS modeling approach and use normative scenarios of land use and water management changes to assess FEW security using the specific quantitative goals in Table 2.

Sub-question 3.1. Where, when, and how can natural/semi-natural vegetation enhance and buffer FEW systems and SDGs from abrupt change as environmental drivers change? Natural ecosystems contribute to FEW security in working landscapes (Bennett 2017, Schulte et al. 2017), but the ecosystem diversity needed to achieve SDGs and where leverage or tipping points lie are poorly understood (e.g., Grêt-Regamey et al. 2015, Qiu and Turner 2015). Perennial vegetation can serve as "keystone landscape elements" that have greater influence on FEW than suggested by their abundance. These elements enhance crop production (via pollination and pest control, Garibaldi et al. 2013), hydrologic services (Brauman et al. 2007), and produce biomass for bioenergy (Blank et al. 2014, 2016). Re-designing agricultural landscapes by augmenting areas of perennial vegetation has been suggested for enhancing FEW security (e.g., Werling et al. 2014, Schulte et al. 2017). However, planning for changing environmental drivers (e.g., more frequent high-intensity precipitation or drought) is a challenge (Tscharntke et al. 2012; Lawler et al. 2014). The "insurance hypothesis" (Tscharntke et al. 2005) suggests that maintaining natural elements will become increasingly important for sustaining FEW as drivers change. ***We will quantify the degree to which semi-natural habitats can enhance FEW security by 2050, buffering watersheds from undesirable changes; and the amounts and locations of semi-natural habitats that are well-suited for sustaining FEW and preventing an ecosystem services debt, i.e., delayed loss of ecosystem services associated with FEW as landscapes change over time and semi-natural habitats are reduced or altered.***

We will use a two-pronged approach. First, spatial analyses will quantify relationships between <u>current</u> LULC patterns and FEW in the sub-watersheds of the UMRB. We will use

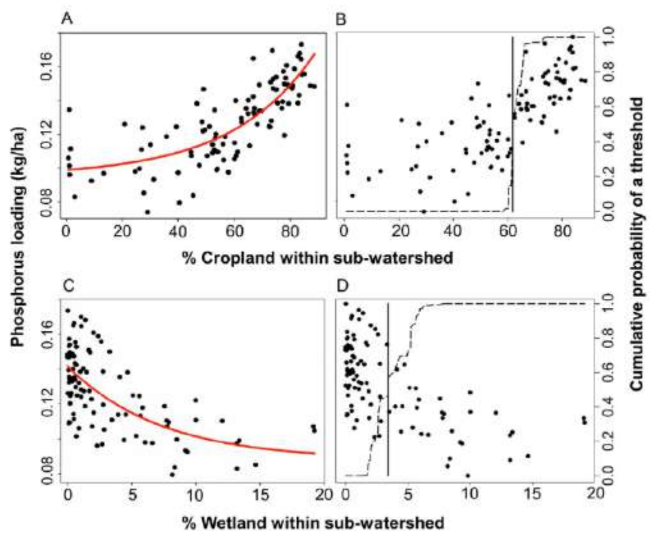

Figure 10. Nonlinear response of surface-water quality to percent cropland and wetland in the Yahara Watershed, WI: (A) scatterplot of average P loading vs. percent cropland within each subwatershed; (B) nonparametric deviance reduction result suggested a change-point of 62% cropland for surface-water quality; (C) scatterplot of average P loading vs. percent wetland within each subwatershed; (D) nonparametric deviance reduction result suggested a change-point of 3% wetland for surface-water quality. From Qiu and Turner (2015).

landscape metrics (Turner and Gardner 2015) to quantify LULC composition and configuration in each sub-watershed and assess our FEW indicators in each sub-watershed. Statistical analysis will identify the relative importance of semi-natural vegetation in explaining variance in FEW and determine whether threshold relationships between landscape patterns and FEW are suggested (Fig. 10). Second, we will use our models with normative scenarios of change to 2050 to explore the capacity of LULC to mitigate abrupt changes in FEW and achieve our targets (Table 2) given changing climate and feedback from farmer and policy actor surveys in Q2.3. Normative scenarios are used to identify alternative pathways to our specified UMRB goals (Table 2; Nassauer and Corry 2004; Alcamo 2008; Houet et al. 2010). We will explore potential reconfigurations of LULC then simulate these with a wide range of future environmental conditions. We will identify thresholds in the proportion of natural area associated with declines or sudden collapse in FEW supply and determine the amounts and arrangements of natural areas that sustain FEW under different levels, frequencies, and sequences of environmental drivers, including extreme events. We will identify hotspots & coldspots where LULC or management have substantial or little influence on FEW (Qiu and Turner 2013). Results will determine when and where adverse impacts may occur, and how perennial landscape elements can mitigate FEW tradeoffs and enhance synergies.

Sub-question 3.2. How can modified water management practices (such as irrigation, tile drainage, and aquifer storage and recovery) improve water, food, and ecosystem outcomes, and do such practices enhance or erode FEW security and ecosystem resilience as environmental drivers change? Local, even field-scale, water management practices such as irrigation and tile drainage are intended to improve agricultural production. However, current use of these practices may not be optimized and may improve or degrade downstream water, food, and ecosystem outcomes through their influence on the hydrologic cycle. For example, tile drainage is the most direct and widespread hydrologic intervention across agricultural lands of the UMRB. By lowering the water table it minimizes waterlogging/ oxygen stress in crops (Hiler et al., 1971, Kemper et al., 2012) and improves field trafficability, particularly during the wet planting season. However, under some conditions, shallow groundwater has positive impacts on yield (Follett et al. 1974, Ragab and Amer, 1986, Nosetto et al., 2009, Gowing et al. 2009, Karimov et al. 2014, Wu et al. 2015). In addition to affecting crop yield, tile drainage alters myriad other hydrologic and ecologic functions by short-circuiting water flowpaths and changing subsurface residence times. Tile drainage is leading to increases in baseflow and leaching of nitrate (Schilling and Helmers, 2008), but the effects on flooding and biogeochemical processing are less clear and representation of the process is woefully lacking in regional hydrologic and land surface models. We propose to evaluate the extent to which both irrigation and tile drainage can improve FEW security and ecosystem outcomes and resilience. In our four sub-regions with exemplars of heavily irrigated and tile-drained regions (Table 1), we will use the improved MODFLOW-AgroIBIS (tile drainage added and assessment of *current* conditions as part of Question 1) – applied at 100-m pixel resolution – to simulate agricultural production, hydrologic response, and water quality outcomes associated with scenarios that implement varying intensity of irrigation and drainage. We will quantify synergies and tradeoffs among flood vulnerability, food production, nutrient loading to surface waters, carbon storage, and ecosystem support as indicated by lake levels and baseflow. Furthermore, we will evaluate ecosystem resilience by investigating how the provisioning of these ecosystem services recover in response to extreme droughts and precipitation events across scenarios. We hypothesize that controlled tile drainage (NRCS standard 554) offers a means by which synergies among increased productivity, decreased nutrient loading, increased carbon storage, and ecosystem support can be strengthened and outcomes improved. Controlled tile drainage allows both the drainage level and timing to be actively managed at subfield levels by opening and closing drain outlets to release or retain shallow groundwater. We will simulate strategies by which 1) water is retained at various levels with release triggers and on different timing schedules so that groundwater may subsidize crop growth during dry periods, but still allow for drainage at times when oxygen stress limits productivity (Zipper et al. 2015, Soylu et al. 2014) and 2) drainage is delayed for various time periods (1, 2, 3 days) such that discharge from tile drainage is separated from peak discharge from the watershed to reduce flood risk. These and other strategies will be evaluated in terms of their ability to meet our specific FEW goals for the region and more broadly their ability to enhance crop production, reduce nutrient loading, reduce flood risk, increase carbon storage in soils through reduced soil respiration, and support ecosystems dependent on lake water levels and baseflow.

Larger scale water management interventions such as aquifer storage and recovery (ASR) also provide a tool to enhance the security and resilience of coupled food, water, energy, and ecologic systems (Khan et al. 2008, Ringleb et al. 2016), but their implementation is sparse in the UMRB. In the Central Sands region of WI where irrigation has resulted in groundwater depletion (Kraft et al. 2012) causing lower lake levels and streams to run dry, the nearby Wisconsin River typically has high flows during the spring snowmelt that contribute to downstream flooding. We will simulate the system effects of diverting a portion of peak flows to artificially recharge aquifers by surface spreading prior to planting. We will evaluate the feasibility of ASR in the study regions and the extent to which this minimizes groundwater depletion, reduces downstream flood risk, increases baseflow, and increases in lake levels.

5. BROADER IMPACTS. The place-based, integrated biophysical and social-ecological research we propose will generate the systems-level understanding of FEW dynamics needed to foster a sustainability transition in national and global FEW systems. Our work would help enable society to become better stewards of our collective resources to meet the grand challenge of adapting human use of FEW for the benefit of people and ecosystems. We will connect our scientific research with students, educators, stakeholders, policy actors, and the public through specific efforts described in detail below that will foster discussions of FEW security in classrooms, boardrooms, and town halls.

Increase usability of integrated modeling output on FEW security across the US. We will build a front end graphical user interface for our models for use as a teaching and research tool by other researchers and students at other institutions. We envision that an end user could pick watersheds of their choice in the US and perform specific land use/land cover and climate change studies to generate new model output. Our computing systems analyst (*Dr. Pavel Pinkas*) will lead this effort. Computing support for this effort would come via the UW-Madison Center for High Throughput Computing.

Organize symposia on FEW systems at high-impact meetings. We will organize a symposium at the AGU annual meeting in year 3 and the AAAS annual meeting in year 5. The focus of the AGU symposium would likely be on capacity building, advances in modeling, and improving integrated modeling tools to study FEW systems. At AAAS, we would likely focus on comparing results among other INFEWS investigators (and beyond) to establish a state-of-the-science in FEW modeling, likely culminating in a synthetic collaborative peer-reviewed publication that chronicles the progress of FEW research over the past 5-10 years. Speaker invitations will prioritize other NSF funded INFEWS PIs in the modeling track. Graduate students and post-doctoral scientists will be encouraged to submit abstracts.

Train the next generation of scientists in FEW systems and sustainability science. We will provide opportunities for ***undergraduate students*** in UW-Madison's two-semester Introductory Biology course to gain mentored research experience. Training ***graduate students*** is a central goal of this project, and the proposed research will contribute to training four doctoral students. The 5-year length of this proposal allows for graduate students to have continuity through their studies which benefits them as well as the project. We will reach more students by offering two new graduate courses at UW-Madison focused on *ecosystem modeling* and *FEW* systems. These courses will be led by the PIs and offered two times during this grant cycle, during years three and five. Kucharik will develop new modules related to FEW systems and modeling for his graduate course, *Agroecosystems and Global Change.* We will reach graduate students from across the country by participating in the **CUAHSI Virtual University supported by NSF (***see letter of collaboration***)**. In this initiative in collaborative graduate training, a faculty member from each participating university offers a specialized online hydrology module of nominally 1 unit of semester credit and students enroll in a 3-cr class at their home institution. Each student individually selects three modules in highly focused research niches offered by national experts using synchronous online teaching methods. We will offer a module on *"Resiliency in food, energy, and water systems"* and work with CUAHSI and other INFEWS PIs to develop a subset of INFEWS-related modules to facilitate exchange of research innovations across the INFEWS network. This collaborative effort open to all US universities dramatically increases hydrologic course offerings at participating institutions and accelerates the rate at which research findings are incorporated into graduate courses.

Connection with key actors in the UMRB. Engaging with key actors is imperative to ensuring our research is translational and informative to decision making in the UMRB. As such, we will work to engage with key actors that will enable direct two-way communication about models and information needs of a broad community concerned with FEW security in the larger Mississippi River Basin. We will connect with agricultural producers, crop advisors, soil and water conservation professionals, legislators, and other decision makers with direct influence on land and water health. ***To reach these groups, we will build on existing relationships with state chapters of the Soil and Water Conservation Society, the North Central Region Water Network, SERA-46, the Gulf Hypoxia Task Force, and state-based biofuel associations, led by UW-Extension and Rebecca Power (see sub-award).*** Through these relationships, we will co-generate resources and learning opportunities to exchange knowledge and encourage behavior change that will serve to meet food and energy needs while also lessening water impacts in the UMRB.

Advance public engagement through dedicated use of social media and outreach materials. We will create a broad-reaching online presence and portfolio of outreach tools to advance public engagement with FEW issues in the UMRB. The dedicated outreach specialist will work with project PIs to plan and implement a foundational brand identity for the project including development of a project webpage, edit project blog posts; assist faculty and students with research briefs, facilitate the development of project reports, and assist with press releases. The outreach specialist will also work with the Univ. of Wisconsin Environmental Resources Center (ERC) Marketing and Communications unit on web development and graphic design needs for the previously mentioned products. We will also engage in social media platforms and maintain a listserv for research updates to extend our reach.

6. INTELLECTUAL MERIT. The UMRB is a linchpin for US FEW security and a model for similar regions worldwide**.** Our approach is synthetic and uses state-of-the-art models and methods for projecting dynamics of FEW over space and time. The future conditions we consider are broadly relevant, including baseline scenarios of changing climate and socioeconomic pathways; local-to-regional policies that affect extraction of water, deposition of fertilizers and manure; and distribution of land use and management practices in agricultural landscapes. We address key shortcomings identified in previous and current integrated assessment modeling of the FEW nexus by including global economics as well as subsurface processes and the groundwater system. Our integrated project will identify the magnitude and rate of long-term slow (e.g. climate) and abrupt (e.g. extreme weather events; new policy) changes on agricultural landscapes that can be absorbed without experiencing precipitous declines in FEW supply by the year 2050. We will evaluate changes in seven FEW components: cellulosic biofuel from grasses, biofuel from crops, water quality and quantity, crop production, human food calories, and indicators of ecosystem biodiversity. We will assess a suite of complementary quantifiable targets for improving FEW security in the UMRB using the U.N. SDGs as a framework. Our research will address three research questions related to current conditions and trends in FEW, *top-down* effects of external biophysical and socioeconomic drivers across the entire UMRB region, and impacts of *bottom-up* drivers and decisions at finer scales in four diverse representative sub-regions of the UMRB. Our work will identify where and how different interventions, like land and water management choices, and policies and governing systems, can amplify or dampen feedbacks that stabilize or destabilize the FEW systems. Our work will develop and apply new theory about how different combinations of drivers interact in agricultural landscapes in ways that could fundamentally change components of the FEW nexus. Furthermore, we will identify the state-space in which FEW security can be sustained as shocks (drought, extreme heat, flooding, and policy changes) intersect with slowly changing drivers. We will integrate biophysical and economic land use modeling with mixed-methods studies of governance that assess how decision makers use information from models and scenarios to learn and adapt. The place-based, integrated biophysical and social-ecological research we propose will generate the systems-level understanding of FEW dynamics that will be needed to foster a sustainability transition in global FEW systems.