

COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

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LTER: The Ecology of Row Crop Ecosystems and Landscapes at the KBS LTER Site

Project Summary

Overview: KBS LTER probes key ecological relationships in intensive row-crop ecosystems and landscapes of the US Upper Midwest. The project aims to understand the fundamental ecological underpinnings of row-crop ecosystems and reveal ways that ecological knowledge can enhance the long-term sustainability of production agriculture.

Since 1988 the project has examined the global hypothesis that agronomic management based on ecological knowledge can better provide ecosystem services, including yield, than can management based on synthetic chemicals. Follow-on hypotheses related to the patterns and processes that drive ecosystem productivity and environmental performance are addressed with observations and experiments at field and landscape scales, including a major field experiment comprised of 11 different cropping systems and unmanaged communities.

This proposal builds on past work to launch an effort to better understand the long-term stability of key ecosystem services afforded by agriculture, with an emphasis on three major drivers: climate change, changes in agronomic management, and invasive species. Two overarching questions motivate research:

- 1) How do changing environmental drivers affect the delivery of key ecosystem services, and
- 2) To what extent can ecological knowledge strengthen the robust delivery of these services?

Key ecosystem services include yield (net primary production) but also extend more broadly to climate stabilization (greenhouse gas emissions), water quality (eutrophication), pest suppression (insect herbivory and predation), and soil fertility (plant-microbe-soil interactions). Structural equation modeling is used to quantify a conceptual framework that includes for each major research area submodels expressed as metamodels. Knowledge gaps identified from research to date are addressed with new research lines that include rainfall manipulation experiments, watershed observations, and examinations of rapid evolution of plant-microorganism associations, predator-prey dynamics newly influenced by invasive species and novel pesticides, and long-term changes in farmer attitudes and behaviors.

Intellectual Merit: The application of ecological theory to develop sustainable agricultural systems remains a recognized grand challenge for environmental science. KBS LTER research is unique in its long-term and systems approach to understanding interacting taxa and processes at both local and broader scales. That results are published in ecological, environmental, and agronomic journals underscores the breadth of research at the site and, as well, broad scientific interest in fundamental ecological research in agricultural systems.

Broader Impacts: Agriculture is the dominant land use in the Midwest and is one of the biggest agents of global environmental change, with far-reaching impacts on human welfare and the environment. Proposed research bears directly on agricultural and environmental management and policies at scales ranging from local to global. Training graduate students and postdocs is an important outcome, as is providing research experiences for undergraduates. Work with K12 science teachers continues an established partnership with 11 nearby school districts. Outreach and extension activities reach a broad community of stakeholders, and will include a new emphasis on farmers and those who influence farmer decisions.

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1.0 Results of Prior Support

1.1 Overview

Agriculture is the dominant land use in the US Midwest and is one of the biggest agents of global environmental change, with far-reaching impacts on human welfare and the environment. The need to better understand how ecosystem services are provided in agricultural landscapes and how they may respond to future conditions is crucial, especially in light of changing environmental conditions, the introduction of new technologies, trade globalization, and increasing demands for agricultural intensification to feed a burgeoning and more affluent global population (Tilman and Clark 2014).

Research at the Kellogg Biological Station LTER site (herein, KBS), located in the agricultural heartland of the US (Fig. 1), represents a long-term integrative effort to examine key ecological interactions in intensively managed row-crop ecosystems and landscapes. We aim to test and apply ecological theory to better understand the fundamental ecological underpinnings of these systems. A multi-decadal sampling program reveals long-term trends, and both short- and long-term experiments allow us to test hypotheses about the drivers and consequences of these trends. Key findings to date are summarized in our recent site synthesis volume (Hamilton et al. 2015a), available online at the KBS LTER website.

KBS LTER has grown into a complex transdisciplinary research program. At the outset of the project in 1987 we focused on a limited number of ecological processes in individual cropping systems and successional fields. In 1992 we added more unmanaged ecosystems, and in 1998 expanded to landscapes with the addition of watershed biogeochemistry (Hamilton 2015) and insect predator-prey dynamics (Landis and Gage 2015). In 2004 we added an economic component with a focus on the valuation of ecosystem services (Swinton et al. 2015a), further expanded in 2010 in a socio-ecological model (Robertson and Hamilton 2015) that has allowed us to examine how alternative cropping systems provide different ecosystem services and how farmers make decisions to adopt practices to promote those services.

In this proposal we expand efforts to understand the long-term stability and resilience of ecosystem services afforded by agriculture, with an emphasis on three major drivers of change: climate, agronomic management, and invasive species (in particular pests and their predators). Our new

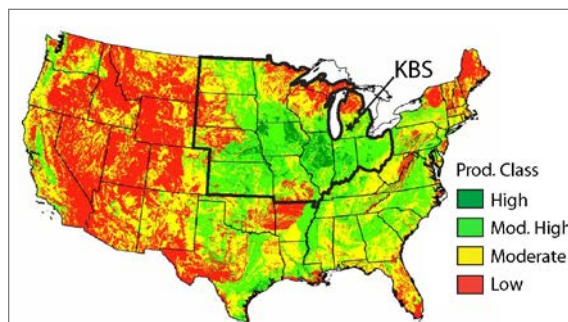


Fig. 1. Location of KBS in the US corn belt (outline). Base productivity map from Nizeyimana et al. (2001).

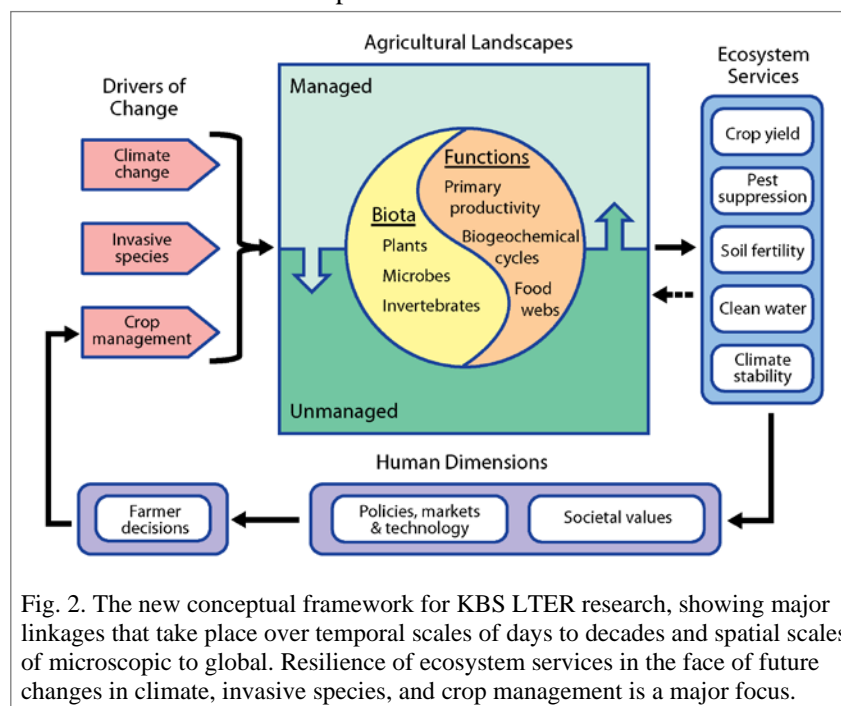


Fig. 2. The new conceptual framework for KBS LTER research, showing major linkages that take place over temporal scales of days to decades and spatial scales of microscopic to global. Resilience of ecosystem services in the face of future changes in climate, invasive species, and crop management is a major focus.

research framework (Fig. 2) embodies an interlinked set of quantifiable conceptual models that lay the groundwork for understanding the indirect relationships and feedbacks that most affect the delivery of key services. Knowledge gaps identified from our prior research are addressed in this renewal with new approaches that include ecosystem responses to changing rainfall patterns, the role of agriculture in the eutrophication of downstream rivers and reservoirs, rapid evolution of plant-microbial associations, indirect effects of novel pesticides on trophic relationships, and long-term change in farmer attitudes and decision-making.

Our global hypothesis, a consistent theme of KBS research, is that agronomic management based on ecological knowledge can better deliver ecosystem services, including yield, than can management based on synthetic chemicals. Much of our research has been conducted in the context of our Main Cropping System Experiment (MCSE): replicated systems spanning a gradient of management intensities that includes four annual cropping systems (corn-soybean-wheat rotations under conventional, no-till, reduced input, and biologically based managements), two perennial cropping systems (alfalfa and hybrid poplar), and a set of early to late-successional unmanaged plant communities (Figs. 3, 4). The power of this design lies in its range of differently managed, experimental communities with long-term measurements of organisms and processes, complemented by short- and long-term experiments to test mechanistic hypotheses. Management of these systems change slowly in step with regional farming practices as farmers adopt new genetic and other technologies. This approach allows us to research systems, not practices per se.

To test hypotheses at the landscape scale we sample surface waters within the broader watershed to address questions related to water movement and quality, and we sample multiple terrestrial habitats to address questions related to the movement of crop pests and predators. Our economic analyses—informed by farmer focus groups and mail surveys—are conducted at regional scales.

Other long-term experiments that allow us to examine specific mechanisms include the Resource Gradient Experiment (est. 1999), where nitrogen (N) and water additions allow us to examine interactions between two crucial constraints on primary productivity, and the Biodiversity Gradient Experiment (est. 2000), where 21 crop diversity treatments ranging from continuous monocultures to rotations with cover crops provide an opportunity to examine the impact of plant diversity on other taxa and ecosystem processes. In addition, a Biofuels Cropping System Experiment (est. 2008) includes 10 different bioenergy cropping systems ranging from continuous corn to restored prairie, providing opportunities to examine how ecosystem functions and resilience relate to plant community diversity.

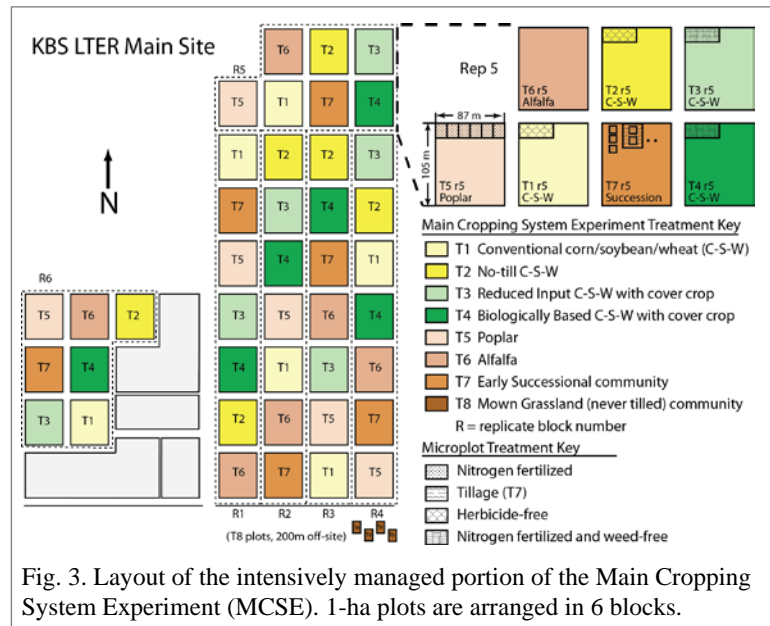


Fig. 3. Layout of the intensively managed portion of the Main Cropping System Experiment (MCSE). 1-ha plots are arranged in 6 blocks.



Fig. 4. Locations of the Mid-successional (SF) and Coniferous (CF) and Deciduous (DF) Forest systems. Other MCSE systems are in the Main Site, upper right outline.

1.2 Progress in Specific Areas of Research

We describe below selected areas of recent progress in four research dimensions—Productivity, Biogeochemistry, Biodiversity, and Human Decision-making—showing how they relate to long-term trends and interact to influence the suite of ecosystem services provided by row-crops and landscapes.

Productivity – To what extent can ecological knowledge substitute for chemical subsidies to maintain crop yields? Crop productivity is central to the study of agricultural systems—the primary service delivered by agriculture is yield. Crop yields in our conventionally managed system have been consistently close to yields for non-irrigated row crops in both Kalamazoo County and the 12-state North Central Region (Robertson and Hamilton 2015). Productivity in our alternative systems (Fig. 5) has differed in significant ways. Relative to conventional management, over a 24-year period the no-till system has provided a 10-20% yield benefit. The reduced input system, which receives 1/3 of the synthetic chemicals applied to the conventional system, has had equivalent total yields; and the biologically based system has had equivalent soybean but lower corn (80% of conventional) and much lower wheat (60%) yields, largely owing to insufficient N acquisition: Both the reduced input and biologically based systems rely on winter cover crops for most (reduced input) or all (biologically based) of their added N. The finding that long-term yields follow the pattern no-till > conventional = reduced input > biologically based is support for our original global hypothesis (Robertson et al. 2014a).

The higher performance of the no-till system appears due to enhanced soil fertility, an important supporting service. Soils in the no-till system contain ~20% more carbon (C) than do those in the conventional system (Syswerda et al. 2011), which increases water-holding capacity.

In most years this appears valuable during late summer droughts common at KBS, when stored soil water can provide a small productivity benefit to crops. In drier years this benefit becomes especially valuable: e.g., a severe Midwest drought in 2012 (6 weeks without summer rainfall) suppressed conventional yields by 50% but no-till yields by only 25%. Soil water content measurements show that there was more water stored in no-till soils at the drought's beginning, which likely mitigated the rainfall deficit (Robertson et al. 2014a).

Crop yields from our recently completed Scale-up Experiment highlight the importance of water availability and the vulnerability of these systems to the increased precipitation variability that will occur under climate change (Pryor et al. 2014). This experiment included our conventional, reduced input, and biologically based systems on 27 farm fields at KBS and was established to determine the extent to which results from our small plot (1 ha) experiments are relevant at farm scales. Each rotation phase (corn, soybean, or wheat) of each system was replicated on three commercial fields, providing 18 crop years over the six years of the experiment. In general, yields scaled well except in the biologically based system, where labor constraints at the farm scale made timely weed control and cover crop establishment difficult (Snapp et al. 2016). This exception, however, was mainly in high rainfall years (Fig. 6), especially for corn (Fig. 6A), likely due to greater weed competition for N in favorable rainfall years—an important interaction of climate change and N availability in agriculture (Robertson et al. 2013).

Biogeochemistry – What is the ecological basis for the provision of key biogeochemical services in agricultural landscapes? In this past cycle we focused on understanding the long-term movement and

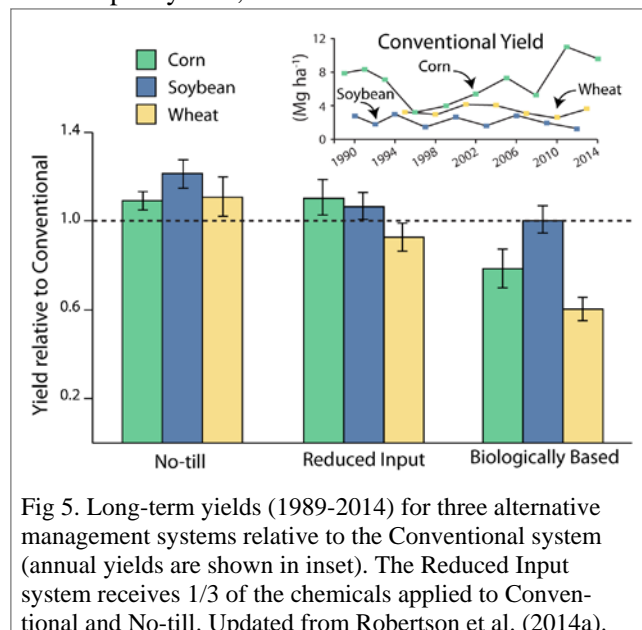


Fig 5. Long-term yields (1989-2014) for three alternative management systems relative to the Conventional system (annual yields are shown in inset). The Reduced Input system receives 1/3 of the chemicals applied to Conventional and No-till. Updated from Robertson et al. (2014a).

transformations of key elements in agricultural systems with two main areas of emphasis: greenhouse gas (GHG) exchange with the atmosphere and the movement of water and nutrients through surface water systems, with particular emphasis on shallow aquatic ecosystems.

Greenhouse gas exchange. Globally, agriculture not including land use conversion is responsible for 8-14% of GHG emissions (IPCC 2014, Robertson 2014). All three GHGs affected by agriculture are biogenic and thus their management relies on fundamental knowledge of the organism-environment interactions responsible for their emissions. We have measured nitrous oxide (N_2O) and methane (CH_4) fluxes in all MCSE systems biweekly (except winter) since 1992. This is one of the longest continuous records of GHG fluxes in any ecosystem, and it reveals patterns and controls on long-term fluxes in response to agricultural management and climate variability. We have also measured changes in net CO_2 exchange, best detected over decadal time scales via soil C change. While soil C is accumulating in our no-till, cover-cropped, perennial, and successional systems (Syswerda et al. 2011), careful geospatial sampling shows net C loss from our conventionally tilled system, thought to have equilibrated decades ago. This seems to be newly occurring perhaps as a result of recent wintertime warming (Senthilkumar et al. 2009, Ruan and Robertson 2016). We have also learned how quickly accumulated soil C can be lost; in a first-of-its-kind experiment, a single tillage of a 20-year-old Conservation Reserve Program field at KBS obliterated >8 years of C gain (Ruan and Robertson 2013).

We have also learned that the best predictor of long-term N_2O loss is soil N availability (Gelfand and Robertson 2015) rather than applied fertilizer N. Nevertheless, fertilizer N has an overwhelming impact on N_2O loss where fertilizer is applied, and the relationship to emissions is not linear (as assumed by IPCC methodologies) but exponentially increasing (Hoben et al. 2011, Shcherbak et al. 2014). This observation has had significant policy implications (Millar et al. 2010, Ogle et al. 2014), and appears mostly related to competition between microorganisms and plants for available N, although shifts in microbial community composition may be involved as well (Cavigelli and Robertson 2001, Schmidt and Waldron 2015). Recent work has also shown that a reduced suite of methanotrophic taxa appears to explain the markedly lower rates of CH_4 oxidation following agricultural conversion and its slow recovery following abandonment; both methanotroph diversity and CH_4 uptake change monotonically across our successional gradient (Levine et al. 2011).

Our long-term GHG measurements in the MCSE allowed the first full-cost GHG accounting for intensive agriculture (Robertson et al. 2000). More recent insights from continued measurements include three major findings: 1) over time, cover crops can create soil C sinks equal to no-till management (Syswerda et al. 2011, Ladoni et al. 2016), likely from effects on plant-derived microbial metabolites rather than additional plant biomass (Kallenbach et al. 2015, Tiemann et al. 2015); 2) agricultural lime, added to soils to counteract pH declines caused by accelerated nitrification, is a much weaker source of emitted CO_2 than originally thought (Hamilton et al. 2007, Gelfand and Robertson 2015), especially under irrigation (McGill and Hamilton 2015); and 3) cellulosic biofuels can provide substantial climate change mitigation when conversion to these crops minimizes soil C and N_2O losses (Gelfand et al. 2011, 2013).

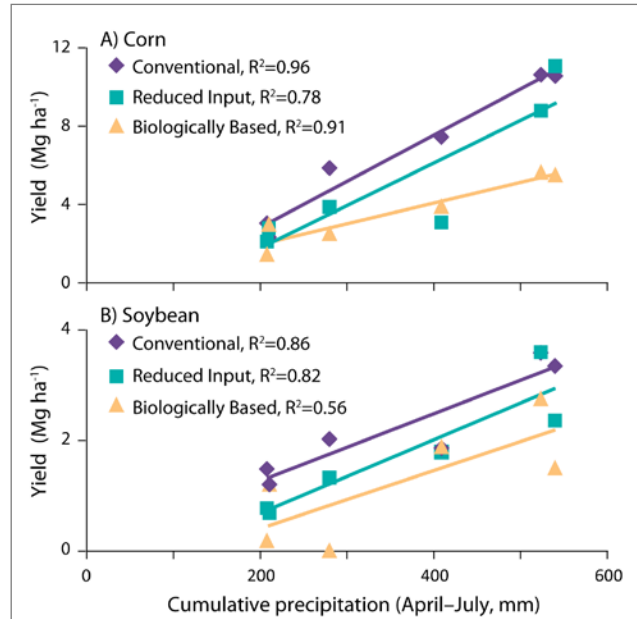


Fig. 6. Corn (A) and soybean (B) yields in conventional, reduced input, and biologically based systems in 27 Scale-up fields in relation to precipitation (Snapp et al. 2016).

Movement of water and nutrients through agricultural landscapes. Environments within landscapes are connected through surface and subsurface fluxes of water, and provision of high-quality water is an important ecosystem service. Since 1999 we have measured major solutes and nutrients at key points along hydrologic flow paths at KBS, including infiltrating soil water, ground waters, streams, wetlands, and lakes (Hamilton 2015). Recent investigations have focused on interactions among nutrient cycles in shallow waters (O'Brien et al. 2012a,b; Bruesewitz et al. 2012, Hamilton 2012, Burgin et al. 2012, Kinsman-Costello et al. 2014, 2015). In addition, since 2010 we have built a new line of research on watershed hydrology, which we highlight here.

Interactions between surface waters and groundwater are especially important in the postglacial landscape around KBS, where most precipitation infiltrates soils (Syswerda et al. 2012) and most surface waters are sustained by groundwater discharge (Thobaben and Hamilton 2014, Hamilton 2015). The terrestrial water balance—how precipitation is partitioned into evapotranspiration (ET), overland runoff, and groundwater recharge—is strongly influenced by vegetation water demand, which returns about 60% of annual precipitation to the atmosphere at KBS.

Recent work on water balances at KBS has yielded surprising results, suggesting that mesic vegetation uses most available water regardless of species composition, growth forms, and water use efficiency. For example, we determined long-term, landscape-scale water balances for Augusta Creek, a 3rd-order watershed at KBS that drains a mixture of cropland, successional fields, and forest into the Kalamazoo River. Since 1960 about 37% of the watershed has been abandoned from annual row crops to successional vegetation, with very little residential development. Combining fifty years of precipitation with stream discharge records (Fig. 7) shows no discernible long-term trend in ET, despite replacement of annual crops with perennial vegetation (Hamilton et al. 2016).

Field measurements support this observation. Mass-balance accounting of water based on continuously measured soil water profiles under annual crops (corn, soybean), perennial herbaceous communities (switchgrass, miscanthus, native grasses, restored prairie), and perennial woody ecosystems (poplars, native forest) show remarkably similar ET rates (Hamilton et al. 2015b). Eddy covariance measurements of water vapor fluxes in corn, switchgrass, and restored prairie across four years provide independent whole-field ET estimates that further corroborate our findings (Abraha et al. 2015).

These results have implications for models of climate change and bioenergy-related land use. Although current climate change models assume mesic landscapes will return more available water to the atmosphere in a warmer climate, our results suggest that during the growing season, water return in the KBS landscape is largely insensitive to climate variability—plants use all available water, such that there

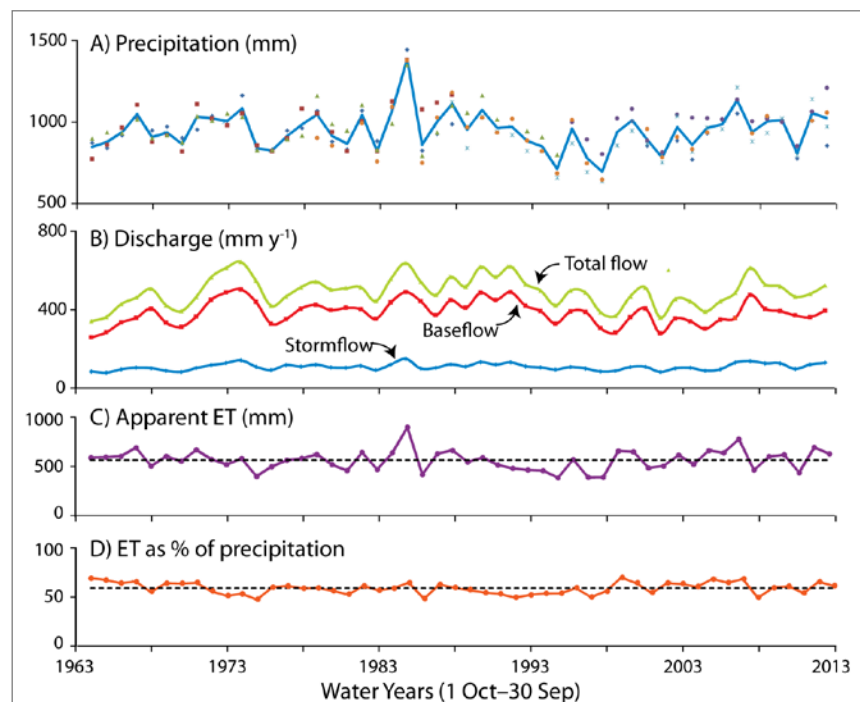


Fig. 7. Augusta Creek hydrological record. A) precipitation; B) stream discharge; C) apparent ET (precipitation less baseflow discharge); and D) apparent ET as a % of precipitation (mean, 59%). Runoff is minimal (Hamilton et al. 2016).

may be little change to precipitation-driven groundwater recharge and surface water flows during the growing season in a warmer climate. Irrigation withdrawals, increasing rapidly in the Midwest, may be the larger threat to ground and surface water resources and the biodiversity services they support. This also means that if, as expected, the demand for perennial herbaceous bioenergy feedstocks grows substantially in the next decades, there will not be a significant effect on groundwater recharge and streams compared to annual crops.

Biodiversity – How can we manage biotic communities and interactions to strengthen ecosystem services in agricultural landscapes? Biodiversity research at KBS LTER targets three taxa of importance to ecosystem functions in both natural and managed ecosystems: insects, microorganisms, and plants. We investigate key interactions hypothesized to significantly contribute to the delivery of ecosystem services: arthropods as they suppress other insect pests; microorganisms as they decompose plant inputs, recycle nutrients, and produce GHGs; and plants as they interact with microorganisms to acquire nutrients. All three lines of research have brought new insights to the function and importance of these complex interrelationships in agroecosystems.

Insects. At the landscape scale, we have explored the role of biodiversity and landscape structure in regulating insect pest suppression in row crops using as a model system the invasive soybean aphid *Aphis glycines* and its top-down control by natural predators (coccinellid ladybeetles) (Costamagna and Landis 2011, Ragsdale et al. 2011). We have tested the hypothesis that mosaics of agricultural and unmanaged lands are important to pest suppression and investigated how the spatial configuration of mosaics matters. We have shown that adding floral strips to the margins of fields consistently increases coccinellid abundance, but with little effect on pest suppression in adjacent fields. Overall aphid suppression is instead primarily related to landscape complexity as it affects coccinellid immigration and abundance (Gardiner et al. 2009, Woltz et al. 2012). Further, by manipulating coccinellid immigration rates in soybean fields, we determined that landscapes that support the early-season arrival of only 2-3 beetles m⁻² week⁻¹ are sufficient to suppress aphid population growth (Woltz and Landis 2013). We also found similar results (Safarzoda et al. 2014) in wheat with the oat aphid (*Rhopalosiphum padi*). Collectively, these studies have helped to define the role of landscape structure in moderating biodiversity patterns and processes in agricultural landscapes (Tscharntke et al. 2012).

The composition of coccinellid communities at KBS continues to change due to species invasions and regional changes in pesticide use. Over the past 24 years we have documented the arrival of three new exotic coccinellids into our study site, with the coincident decline of natives. Competitive interactions and habitat compression best explain the natives' decline (Bahlai et al. 2015a). However, overall pest suppression by coccinellids is not changed by these invasions, suggesting that exotics can provide the same level of pest suppression as the native species they replace (Fig. 8; Bahlai et al. 2013a). More recently, we have discovered changes in the abundance of the invasive multi-colored Asian ladybeetle (*Harmonia axyridis*) driven by a combination of new prey resources (invasive aphids)

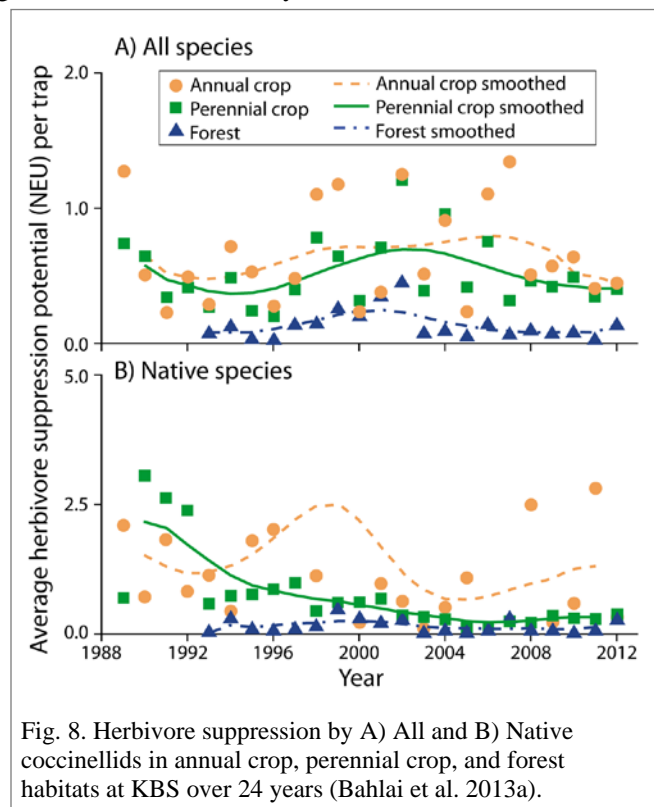


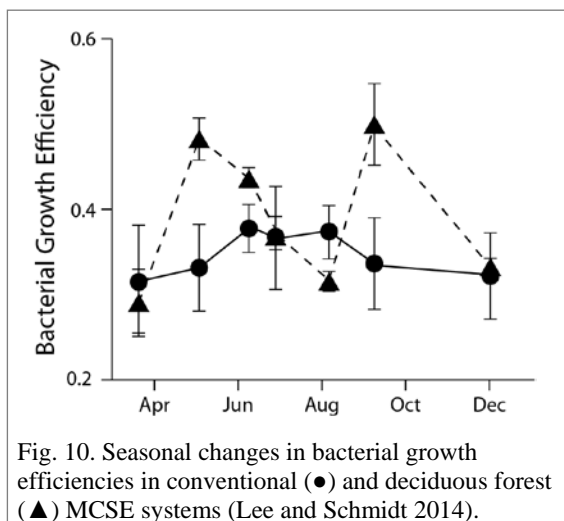
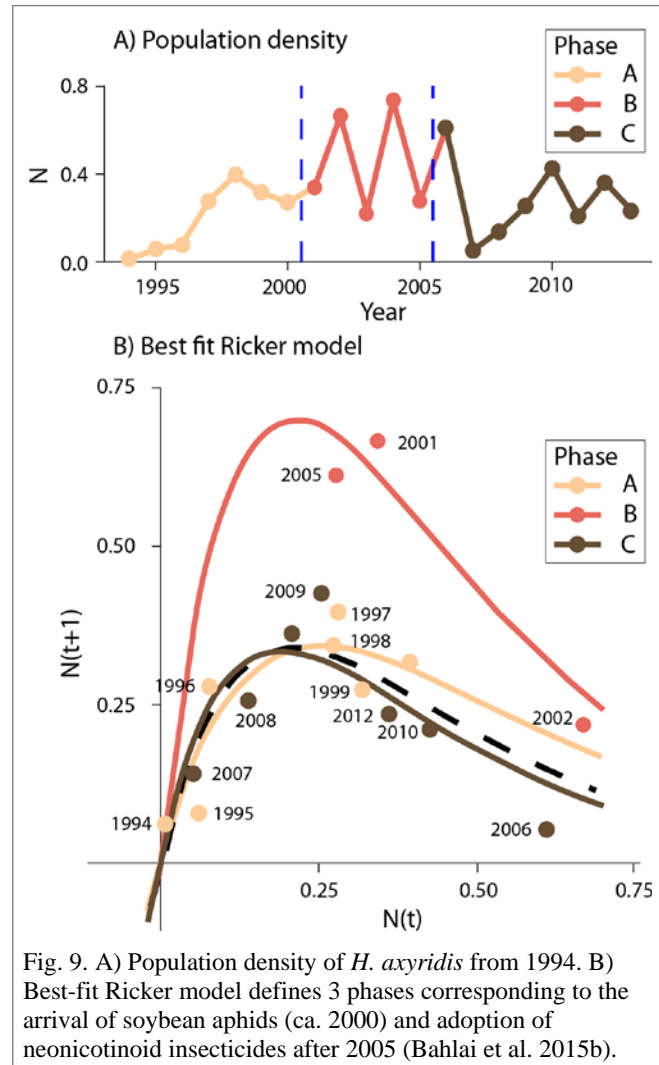
Fig. 8. Herbivore suppression by A) All and B) Native coccinellids in annual crop, perennial crop, and forest habitats at KBS over 24 years (Bahlai et al. 2013a).

and shifting farmer practices (primarily adoption of neonicotinoid seed treatments) (Bahlai et al. 2015b). Following the initial invasion of soybean aphids in 2000, *H. axyridis* populations increased dramatically, which led to an alternate year predator-prey cycle (Fig. 9A). The decline in *H. axyridis* abundance and a return to pre-2000 aphid population dynamics (Fig. 9B) followed the widespread adoption of neonicotinoids in 2005 (Bahlai et al. 2015b). Such findings underscore the need to understand not only landscape habitat abundance and proximity for providing pest-suppression services but also changes in pest-predator interactions as new technologies such as neonicotinoid pesticides emerge and interact.

Microorganisms. Microorganisms are key regulators of ecosystem services related to soil fertility, nutrient cycling, and GHG fluxes and intimately interact with all other taxa. Recent advances to characterize the composition of microbial communities, together with measurements of microbial activity, have expanded our understanding of connections between the structure and function of these complex communities. Since 2010 we have focused on how microbial composition affects rates and stability of C turnover, and specifically how natural selection can maintain communities that convert resources into biomass at different efficiencies (Roller and Schmidt 2015). Bacterial growth efficiencies (the % of C consumed that becomes cell biomass) varies greatly among MCSE treatments, ranging from 23–63%, and some treatments such as the conventional system strongly vary seasonally (Fig. 10; Lee and Schmidt 2014).

Variation in bacterial growth efficiencies has important implications for modeling C accumulation in soils because widely used models such as DAYCENT assume static growth efficiencies. For example, differences in growth efficiencies among treatments and seasons at KBS resulted in >20% differences in model estimates of the actively turning-over C fraction (Lee and Schmidt 2014). Seasonal variation in bacterial growth efficiencies in cropping systems implies that climate change, specifically longer warm seasons and more extreme rain events, may accelerate soil C consumption (Fig. 10).

In further pursuit of a mechanistic understanding of factors influencing the fate of C in agricultural soils, we found support for the hypothesis that oligotrophic bacteria, defined as those with few operons encoding



ribosomal RNAs (rrn), used C more efficiently than faster growing heterotrophic bacteria (higher rrn copy number). This suggests that the composition of soil bacterial communities influences the relative amount of C that is sequestered in microbial biomass vs. respired to CO₂ (Roller and Schmidt 2016). We now have a comprehensive database of rrn to facilitate further studies (Stoddard et al. 2015).

We have also expanded the examination of microbial communities in soil to include both saprophytic and mycorrhizal fungi, a gap identified in our mid-term site review. As expected, land management significantly influences soil fungal communities, with lignolytic gene sequences reflecting plant litter composition (Wright 2016). Arbuscular mycorrhizal fungi (AMF) play critical roles in agricultural systems as well, including plant acquisition of P and N. Agricultural legacy effects are visible in the composition of AMF across the MCSE; in the conventionally managed and no-till MCSE systems, which receive N fertilizer, less beneficial and potentially more parasitic AMF species are common (Gottshall and Emery 2014).

Plants. Our work on plant communities at KBS has focused on how resource enrichment affects 1) productivity, species composition, and successional dynamics in successional communities, and 2) resource mutualisms between host plants and their associated rhizobium and AMF populations. Through cross-site syntheses with the national Productivity Diversity Trait Network (PDTNet), we have continued to explore how grassland communities will respond to predicted changes in climate, particularly precipitation (Cleland et al. 2013, Hallett et al. 2014), and how this relates to species composition and diversity. A recent 20-year analysis of long-term impacts of fertilization in the MCSE Early Successional community revealed that 14 years were required for plant species richness to significantly decline in N fertilized plots, despite a much earlier increase in aboveground production (Fig. 11; Dickson and Gross 2013). An increase in the abundance of a specific functional group—tall species with long-distance (runner) clonality—was strongly correlated with changes in richness in fertilized plots. These results confirmed observations from the PDTNet cross-site synthesis that found that tall-runner species typically respond strongly to fertilization in grasslands, reducing species richness (Gough et al. 2012).

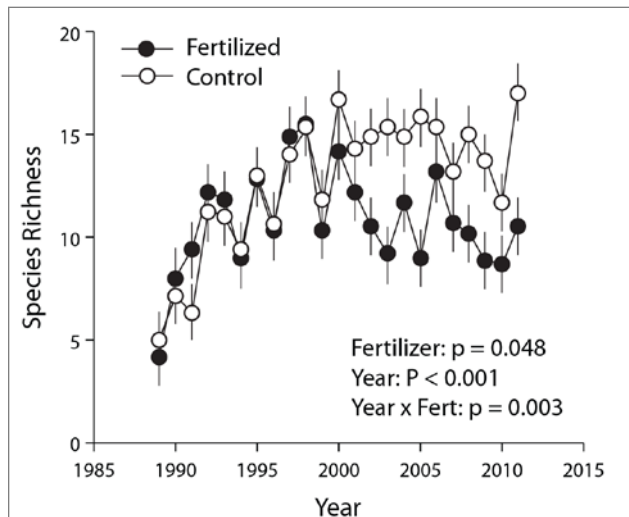


Fig. 11. Long-term effect of added N on plant species richness in the MCSE Early Successional system (Dickson and Gross 2013).

Long-term fertilization experiments in the MCSE Early Successional system have provided the opportunity to focus on the ecological and evolutionary impacts of N fertilization on plant-microorganism interactions. We have documented that these interactions might contribute to observed plant responses to long-term N additions. By studying 20 legume species that varied dramatically in their responses to N across the LTER network, we found that legumes that are better able to control resource allocation to rhizobia and that benefit from rhizobia, even under low light and high nitrogen conditions, were less impaired by N addition in the field. In addition, we discovered that chronic N fertilization results in rapid (< 20 years) micro-evolutionary reductions in rhizobium quality (Weese et al. 2015), and that both horizontal gene transfer (Gordon et al. 2016) and point mutations at known symbiosis genes contribute to the observed reduced cooperation (Klinger et al. 2016). These studies are some of the first to use long-term field experiments to study rapid evolution.

Human decision-making: What motivates farmers to provide ecosystem services? Agricultural systems produce multiple row-crop services that emerge from specific sets of practices including crop rotation, cover crops, tillage, and chemical use. Because farmers have heterogeneous preferences, oppor-

tunities, and farm resources, the cost of changing agricultural practices varies from one farm to another. Our research with farmers shows that certain shifts in management practices can increase certain ecosystem services at low cost (Ma et al. 2012), while others may be quite costly. For example, many surveyed corn and soybean farmers indicated a willingness to add cover crops to a corn-soybean rotation that would reduce GHG emissions and nitrate leaching in exchange for an average payment of \$18-19 per acre (Ma 2011), while Michigan residents were willing to pay six times this amount to abate eutrophication of lakes (via cropping practices that reduce nutrient loss from farm fields), but less for climate change mitigation (Chen 2010, Ma 2011, Ma and Swinton 2011). We have also used bioeconomic modeling to infer the implied value of predator control of soybean aphids based on the insect biodiversity studies described above (Zhang et al. 2010, Zhang and Swinton 2012) and to predict the positive impact of planting perennial bio-energy crops on the delivery of ecosystem services from watersheds under different economic scenarios (Egbenewe-Mondzozo et al. 2013, 2015). Overall, this research indicates which kinds of incentives and payments to enhance ecosystem services would be most effective, politically palatable to taxpayers, and attractive to farmers, who vary in their costs to participate due to differences in their farms and personal preferences.

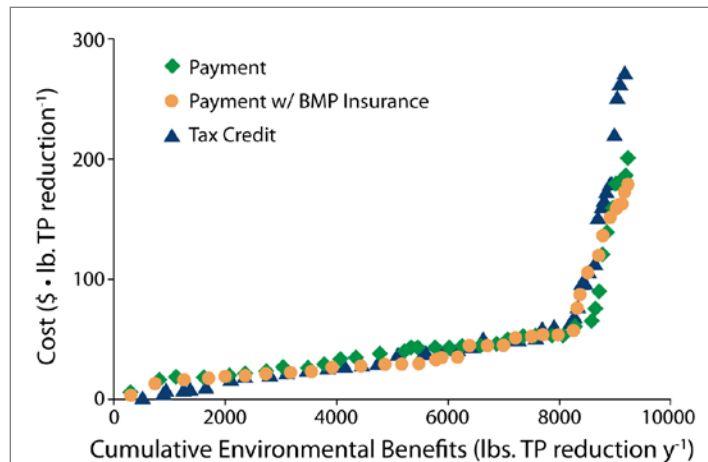


Fig. 12. Costs of incentives required by farmers to adopt practices that reduce P runoff in experimental auctions (Palm-Forster et al. 2016).

Many of the most important ecosystem services are delivered at landscape scales, however, requiring participation of many farmers. Should particular farmers or landowners be targeted in programs to enhance ecosystem services? In payment-for-ecosystem services programs, one goal is to identify who can deliver ecosystem services at lowest cost. We used experimental conservation auctions to elicit the lowest payment that farmers would willingly accept to adopt cover crops, conservation tillage, and filter strips. By simulating associated P movement into waterways using the Soil and Water Analysis Tool (SWAT), we estimated the payment cost per unit of reduced P runoff. The auctions were conducted with farmers in the Western Lake Erie Basin (200 km east of KBS), where farmers use cropping systems similar to those at KBS and harmful algal blooms linked to P are recurrent. A supply curve for P reduction from these practices (Fig. 12) indicates that 80% of P abatement could be achieved for $< \$130 \text{ kg}^{-1} \text{ P}$, but that the remaining 20% would become very costly. Practices that required cooperation with other farmers or dealing with crop insurance programs substantially increased payment costs (Palm-Forster et al. 2016a). When we scaled up the research from pilot auctions to all landowners in two watersheds, these perceived participation costs impeded both individual and joint bidding, substantially reducing the cost-effectiveness of the auction program (Palm-Forster et al. 2016b, 2016c). These results suggest that ecologically targeted fixed payments can reduce unit costs of P abatement better than auction-based payment-for-ecosystem-service policies.

Our social dimensions work thus far has elucidated opportunities and barriers to motivating farmers to practice increased ecological management (and thereby enhance ecosystem services) compared with today's conventional management. As noted below, this knowledge provides the foundation on which we can now ask novel long-term questions about how changing technologies and attitudes influence farmer decision making.

1.3 Top 10 Papers since 2010 (full author lists found in *Section 3.0 References Cited*).

Bahlai et al. 2015a. The role of exotic ladybeetles in the decline of native ladybeetle populations: Evidence from long-term monitoring. *Biol. Invasions* 17:1005-1024.

Beaulieu et al. Nitrous oxide emission from denitrification in stream and river networks. *PNAS* 108:214-219.

Dickson and Gross 2013. Plant community responses to long-term fertilization: changes in functional group abundance drive changes in species richness. *Oecologia* 173:1513-1520.

Gelfand et al. 2011. Carbon debt of Conservation Reserve Program (CRP) grasslands converted to bioenergy production. *PNAS* 108:13864-13869.

Hamilton et al. 2015b. Comparative water use by maize, perennial crops, restored prairie, and poplar trees in the US Midwest. *Environ Res Let* 10:064015.

Levine et al. 2011. Agriculture's impact on microbial diversity and associated fluxes of carbon dioxide and methane. *ISME J* 5:1683-1691.

Ma, S. et al. 2012. Farmers' willingness to participate in payment-for-environmental-services programmes. *J Agric Econ* 63:604-626.

Robertson et al. 2014a. Farming for ecosystem services: an ecological approach to production agriculture. *BioScience* 64:404-415.

Ruan and Robertson. 2013. Initial N₂O, CO₂, and CH₄ costs of converting Conservation Reserve Program grassland to row crops under no-till vs. conventional tillage. *Global Change Biol* 19:2478-2489.

Weese et al. 2015. Long-term nitrogen addition causes the evolution of less-cooperative mutualists. *Evolution* 69:631-642.

1.4 Broader Impacts Summary

Our research bears directly on agricultural management and policies from local (e.g., soil and water conservation) to global (e.g., climate stabilization) scales. We disseminate our research broadly in national and international scientific venues and directly have had many opportunities to influence policymaking, but at the same time we communicate our science to citizens, students, teachers, journalists, farmers and others. Since 2010 over 5,000 people have visited the site.

K-12 Educators. The KBS-K12 Partnership for Science Literacy, supported since 1996 with Schoolyard LTER (sLTER) funds, annually provides ~130 science teachers from 16 school districts around KBS in-depth exposure to ecological science, including two full-day schoolyear workshops plus a 3-day summer science institute, and since 2010 we supported (with mostly non-LTER funds) ~35 RET teachers to participate in research on site. During this period we leveraged sLTER funds for a cross-site NSF Math and Science Partnership (2008–2013, with SBC, SGS, and BES) and GK-12 (2010–2015), DRK-12 (2010-2015), and STEM+C (2014-2019) awards led by LTER scientists and teacher educators. A highlight of the GK-12 award is the Data Nuggets project developed by GK-12 fellows with LTER and other data. Data Nuggets help K-16 students learn quantitative interpretation skills and promote evidence-based science discussions; to date they have been used by over 9,000 teachers in 50 US states and 130 countries (Schultheis and Kjelson 2015). The Data Nuggets project has been featured in National Institute for Mathematical and Biological Synthesis (NIMBioS) events and data workshops across the country.

University Students. Several university classes use the LTER site for formal teaching activities, and we also host REU and other undergraduate interns on site with support from LTER, DOE, and other sources; this includes 43 REU students since 2010, including many in underrepresented groups. We actively encourage graduate students to participate in all aspects of LTER research and outreach. In the current award period 30 students working on site have received degrees and currently 50 are site-affiliated.

Agricultural Professionals and Industry. Extension educators, crop advisors, and agency personnel participate in site-based workshops we sponsor with MSU Extension, NRCS, and other organizations that deliver continuing education to working professionals. We have also partnered with industry to develop a C credit protocol for agricultural N management to allow farmers to participate in voluntary C credit markets. This protocol, the first for N, compensates farmers for more precisely applying N fertilizer to reduce N₂O emissions (Millar et al. 2010, 2013). Development was supported by seven electric utilities

coordinated by the Electric Power Research Institute, and protocols are now provided by the American Carbon Registry and the Verified Carbon Standard; the first credits were sold in 2014 by a Michigan farmer to The Climate Trust, who then retired them. We continue to develop climate change and agriculture programming for extension educators in Michigan, in partnership with MSU Extension, and in the upper Midwest in partnership with USDA-SARE, EPA, and NOAA.

Public. We reach the public by sponsoring educational booths at local, state, and university science fairs and expos and have established blog posts about our research (many are written by LTER REU students and graduate students). We continue to expand our use of social media (e.g., Facebook and Twitter) to communicate and promote recent findings from LTER research. We have established two LTER walking trails at KBS in collaboration with teachers, and have developed a teacher's resource and curriculum guide that highlights LTER research and supports NGSS and other science curriculum standards.

Journalists and Policy Makers. We partnered with MSU's Knight Center for Environmental Journalism and the Society of Environmental Journalists to host two climate change communication workshops at KBS for journalists and scientists from around the Great Lakes (2012) and the US (2013), including scientists from other LTER sites. Additionally KBS research received considerable press for papers published in *PNAS*, *Bioscience*, *Evolution*, *Nature* and elsewhere, and has been highlighted in many media outlets including National Public Radio, Detroit Public Television, Scientific American, ClimateWire, and Bloomberg.

1.5 Results of Supplemental Support

Since 2010 we have received six supplements to our base award. In 2011 we received \$30,000 to enhance KBS participation in Network Information System (NIS) activities: programming support for data submissions and participation in sensor and spatial activities. We additionally received \$20,000 in ROA support to fund an investigator from UW-Oshkosh to conduct mycorrhizal research, and \$16,000 to support a high school intern (RAHSS) and teacher (RET). A \$25,000 equipment award helped to meet sample archiving plus information management (IM) and lab hardware needs. In 2012 a \$90,000 supplement included IM support for aerial imagery and database programming, and support for an ROA investigator and an RET teacher to study rapid evolution in plant-microbial interactions. In 2015 we received an equipment supplement (\$50,000) to replace a field truck and meet other field needs. Also in 2015 we received a major supplement (\$386,000) to expand our watershed hydrology efforts as part of the SEES: Food-Water-Energy Nexus program, bringing to KBS LTER expertise in landscape hydrology and new research on the long-term implications of rapidly expanding irrigation in the region using remote sensing and landscape-level modeling. In 2016 we received supplements to support two RET teachers and ROA support for an early career investigator to conduct work on evolutionary biology at the site.

1.6 Resolution of Mid-term Review Issues

Our 2013 mid-term review commended our significant progress in areas flagged for improvement by the 2010 panel: updated and expanded microbial ecology research, better incorporation of long-term data in synthesis efforts, and a leadership succession plan. Areas for improvement newly identified at the mid-term review were the need for: 1) better integration across research areas (as opposed to collaboration and synthesis, identified as strengths); 2) a comprehensive and quantifiable conceptual model that allows for co-development of research questions focused on the basic ecological mechanisms responsible for ecosystem services; and 3) better strategies to define integrative questions, guide the addition and termination of new projects, and attract new co-PIs. Data management issues are discussed in Section 8.1.

Since the review we have addressed these concerns. First, our new conceptual framework (Fig. 2) and the research proposed in the next phase address the first two points above, better integrating the ecological, evolutionary, and socioeconomic mechanisms that interact to deliver key ecosystem services in agricultural landscapes. This work is strengthened by the addition of structural equation modeling to provide quantitative analysis. Second, we strategically considered our current assemblage of experiments and sharpened our focus on those crucial for addressing core hypotheses and expanding on current

findings in novel ways (e.g., we retired the Scale-up Experiment and the Biofuels Experiment will be simplified in 2017). Third, we recruited three new co-PIs in the areas of plant evolutionary ecology (Lau), microbial ecology (Evans), and sociology and structural equation modeling (Marquart-Pyatt). Three current co-PIs have rotated out (Gross, Schmidt, and Snapp), and we will search for an additional senior co-PI to potentially become next lead-PI during the coming funding cycle (see Section 5.4).

2.0 Proposed Research

Since its inception in 1987 the KBS LTER has developed a comprehensive understanding of the interacting ecological processes that sustain crop productivity, maintain biodiversity, and drive productivity and ecosystem functions in agronomic and unmanaged systems of upper Midwest agricultural landscapes (Hamilton et al. 2015a). This fundamental research provides the scientific basis for alternative management practices that reduce dependence on intensive chemical inputs, while informing basic ecological theory related to biodiversity, ecosystem function, and ecological and evolutionary responses to global environmental changes such as species introductions and climate change.

Through field experimentation and comparisons with nearby managed and unmanaged sites, we have documented the short- and longer-term environmental consequences of different agronomic management strategies. Our results reveal that row-crop ecosystems, despite low diversity and high disturbance, are ecologically complex. We have also demonstrated ways that biologically based management can – to a point (Fig. 5) – replace chemical inputs without sacrificing yields, and have identified environmental and economic trade-offs.

For this next phase of research we will continue our focus on long-term ecological interactions in agricultural landscapes, while developing complementary experiments that both diversify our research and provide a better mechanistic understanding of how ecological interactions support the delivery of ecosystem services. The global question that motivates our research is:

In what ways can new and existing ecological knowledge improve the long-term delivery of ecosystem services from agricultural systems and landscapes?

Two overarching questions follow and guide the upcoming phase of research:

- 1) How do changing environmental drivers affect the delivery of key ecosystem services, and
- 2) To what extent can ecological insights strengthen the robust delivery of these services?

Key ecosystem services include the fundamental purpose of agriculture—the production of food, fuel and fiber— but there is potential for agriculture to also promote services related to water, biodiversity, climate stabilization, soil fertility, and pest suppression, as well as cultural services ranging from recreation to aesthetics (Robertson and Swinton 2005). Our research focuses on developing and integrating the fundamental knowledge needed to provide such services, and to minimize agriculture’s disservices (Swinton et al. 2006, 2007). In particular, we seek to understand the factors that underpin the long-term stability of these services in the face of climate change, changing management, and emerging biotic stressors such as invasive pests.

Resilience in the face of environmental changes, both predictable and unpredictable, is critical to sustaining services in the long term (OECD 2014). And understanding resilience demands a long-term perspective not only to encompass a range of environmental variability, but also because some ecological changes and ecosystem services are initially slow to respond to management changes yet ultimately will become critically important. Documenting evolutionary responses to agricultural management also requires a long-term perspective—many responses that are considered rapid evolution (e.g., Weese 2015) can still take decades to become evident. Likewise, long-term observations of arthropod populations at KBS have revealed cycles and their drivers that would not have been detectable in a decade or less (e.g., Bahlai et al. 2015a), and soil C and stream chemistry changes driven by groundwater flow paths can also take decades to reflect land management changes (Hamilton 2012).

Our new conceptual framework (Fig. 2) incorporates a growing understanding of key drivers in agricultural systems and interactions with the broader landscape. In this renewal, we focus efforts on ecosystem services that are affected by biotic interactions occurring within and among managed and unmanaged portions of the landscape, and how they are influenced by changing external drivers, principally climate change, invasive pests and their predators, and agronomic management. Management is a human enterprise so an understanding of human behavior and decision-making remains an important part of our framework: Work to date has identified the complex factors that drive farmer decisions about biologically based practices; with this proposal we initiate a long-term study of changing influences.

In the coming LTER phase we propose research that allows us to examine the delivery of specific services chosen for their societal and agronomic importance, their relevance to row crops, their reliance on complex ecological interactions, and their interdependencies. Continuing and newly proposed theory, observations and experiments will inform structural equation models (SEMs) with internally consistent and interlocking frameworks that we expect will provide a better understanding of the causal relationships within our systems (Grace et al. 2012, Marquart-Pyatt et al. 2015). SEMs are increasingly employed in multidisciplinary research projects to provide statistical and visual expressions of complex hypotheses involving indirect effects, reciprocal relations, and feedback loops. Here we use the term metamodel to refer to a preliminary graphical representation of the hypothesized causal relationships, the first step towards eventual quantitative SEMs. The metamodel provides a framework for hypothesis development, grounded in ecological theory, as well as for identification of data needs prior to testing the hypotheses with the full SEM.

As noted later (Section 2.2), once the quantitative SEM models are formulated for specific research areas (greenhouse gas exchange, eutrophication, plant-microorganism interactions, herbivory, and farmer decision-making), the specific SEMs will be incorporated as submodels in a combined SEM model that elucidates feedbacks and synergies and permits iterative hypothesis testing. We expect this understanding as a long-term outcome, with shorter-term insights emerging sooner as we quantify the specific SEM submodels. Thus over the coming phase of LTER research we will progress from specific metamodels to specific SEMs, gathering new data as needed, and then build the combined SEM once the specific SEMs are complete; we anticipate that this process will take as long as six years depending on new data requirements in each area. More detail on our SEM approach is provided in Section 2.2.

We recognize that there are challenges in adopting SEM as a modeling framework. Of particular importance are the data needs and assumptions for this type of analysis; we may find some metamodels or portions more amenable to SEM than others given differences in data availability. Also, while we have taken pains to identify the constructs most important in each metamodel, and to harmonize constructs among metamodels, some variables or paths may be detected only as we develop these analyses and link them with one another. As a result, we may find that our models require adjustment or re-specification to be informative across relevant spatial and temporal scales and across relevant social and ecological gradients, and as we gather more data (Grace and Bollen 2008, Grace et al. 2010, 2012, 2015). Despite these potential challenges, we are convinced that SEM is an appropriate tool for quantifying our conceptual framework and that the benefits could be substantial, and we believe that with sufficient planning and flexibility in modeling these risks can be mitigated. In fact, any or all of these outcomes will inform a path forward and allow us to better understand the forces and feedbacks that affect ecosystem service outcomes. In order to successfully employ this new framework, we have recruited a new co-PI to the project with expertise in SEM, and budgeted for a postdoc with modeling expertise to provide modeling assistance to the PIs.

We have organized our proposed research efforts into two major integrated focal areas—biogeochemistry and biotic interactions among plants, microorganisms and insects—both affected by human decision making. In each of these sections we briefly describe the new research we will develop and an initial SEM metamodel that will guide our evaluation of the hypotheses proposed. In a final section, we describe how integration of these research lines will derive from commonalities among the models. In addition to

this new research, we will maintain our long-term observations of productivity and yield in our MCSE treatments, furthering our understanding of how the cropping systems compare in their stability and resilience in the face of inter-annual variability and trends in the drivers of change noted in Fig. 2.

2.1 Major Focal Areas

Biogeochemical Interactions (Hamilton, Robertson, Evans). Biogeochemical processes drive nutrient and GHG fluxes central to several ecosystem services, including soil fertility, clean water, and climate stability. We propose to build on our longstanding emphasis on soil and aquatic biogeochemistry, including long-term data collection from the MCSE, with new work focusing on the implications of climate change. A particular emphasis will be on changes related to warmer winters and more variable precipitation. Warmer winters (Fig. 13) mean less persistent snow cover, which increases the frequency of freeze-thaw cycles (Ruan and Robertson 2016). Increased precipitation variability means less frequent but more intense rainfall, an ecologically more important change (Fig. 14) than the small increase in precipitation projected and seen so far. Model projections indicate that we can expect to see more mid-winter thaws and rain-on-snow events and during the growing season longer intervals between rainfalls (Pryor et al. 2014).

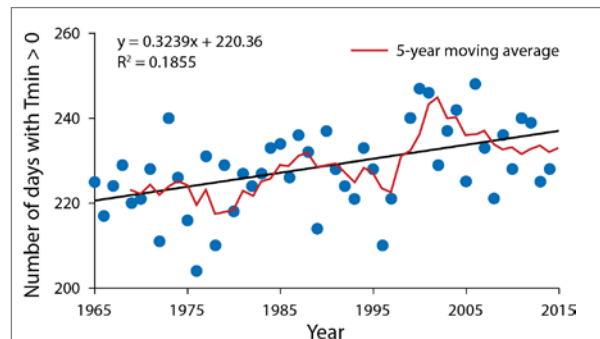


Fig 13. Winter warming at KBS (number of days per year with minimum air temperature $>0^{\circ}\text{C}$ from 1965).

Soil freeze-thaw and wet-dry cycles control soil biogeochemical processes, GHG exchanges with the atmosphere, and the movement of water and nutrients downward to groundwater (Robertson et al. 2013). These dynamics may in turn alter the magnitude and stability of various ecosystem services, including yield, soil fertility, clean water, and climate stabilization. Farmers are responding to climatic changes by installing more irrigation, which has significant implications for soil biogeochemistry, GHG exchange, and landscape water movement.

We propose to address three questions to better understand the interacting biogeochemical responses to these changes and their ecological implications. The first two examine the effects of precipitation variability and winter thaws on biogeochemical cycles at the field and landscape scales, respectively. A third examines the implications of irrigation, which on the one hand attenuates rainfall variability and on the other hand can exacerbate leaching and runoff when rain falls on recently irrigated soils. We have developed two SEM metamodels to evaluate 1) GHG exchange and N leaching and 2) surface water eutrophication, with links to each other and as well to the biotic and farmer decision metamodels described later.

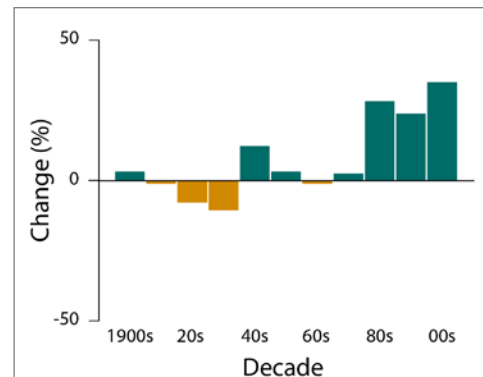


Fig. 14. Decadal changes in heavy rainfalls (heaviest 1% of all daily events) in the Midwest from 1900 (Pryor et al. 2014).

Q2.1 How do increased precipitation variability and more frequent winter thaws affect long-term soil C storage and N_2O emissions?

We anticipate that changes in winter thaw cycles (more frequent thaws as a result of less snow cover and warmer air temperatures) will reduce soil C storage via warmer soils and especially changes in aggregate stability that reduce physical protection, making soil C more available for oxidation later in the spring under drier conditions. Earlier work (Senthilkumar et al. 2009), based on precise geospatially constrained comparisons of contemporary vs. initial soil C, suggests that soil C in the MCSE conventionally managed system declined as much as 4.5 Mg ha^{-1} over the first 15 years of the experiment. This is remarkable

because soils conventionally tilled for >125 years are usually close to equilibrium C levels (Paul et al. 2015), and no MCSE management changes can explain a change in this direction (Syswerda et al. 2011). Senthilkumar et al. (2009) noted that this loss corresponded to a 16 day increase since 1965 in the number of days per year with minimum daily temperatures above freezing (Fig. 13), but this association has not been tested through experimentation.

Soil aggregates are important to long-term C sequestration at KBS as elsewhere (Grandy and Robertson 2007, Paul et al. 2015) and are sensitive to freeze-thaw events. In a three-year snowfall removal experiment conducted at KBS that doubled the number of wintertime thaw events, Ruan and Robertson (2016) found a 40% loss in the number of macroaggregates accompanied by a 56% increase in microaggregates as compared to ambient snowfall; remarkably, by the following winter the aggregate size distribution had completely recovered, but with unknown changes in soil C.

We will examine the potential for changes in C storage that result from increasing winter thaw frequencies by establishing a Snow Reduction Experiment (using the rain-out shelters described below) within which we can follow short-term changes in soil aggregate stability and annual CO₂ fluxes using automated chambers. Our prediction (embodied in the metamodel shown in Fig. 15) is that warming will increase intra-annual aggregate turnover and thus accelerate the decomposition of soil C that might otherwise remain protected within the aggregates.

There may be concomitant changes in microbial communities (Q2.4 below). While we do not expect freeze-thaw frequency to greatly alter the functional capacity of the heterotroph community, we hypothesize that denitrification will increase in response to more frequent soil moisture and redox oscillations. Thus the expression of denitrification genes *nirK* and *nosZ* will be significantly enhanced, accompanied by an increase in N₂ production, in addition to the already-documented N₂O increase (Ruan and Robertson 2016). We will test for enhanced N₂ production by using short-term denitrification enzyme assays in the laboratory, and in the field will infer the proportion of N₂O that is denitrifier derived using isotopomer analysis (Ostrom et al. 2010) with a Los Gatos Research Isotopic N₂O Analyzer.

We also hypothesize that changes in growing season precipitation patterns will affect CO₂ and especially N₂O fluxes. More specifically, we hypothesize that more intense summer rainfalls occurring between longer dry intervals will affect N₂O fluxes through a) shorter persistence of N₂O reductase over longer dry intervals, and b) changes in the soil microbial community to favor nitrification over denitrification as the dominant source of N₂O due to nitrification's becoming more dominated by bacteria (AOB) than archaea (AOA) following episodic rewetting. Most denitrifiers are facultative, producing denitrifying enzymes only when conditions warrant (Robertson and Groffman 2015). Because these enzymes are induced in a sequential fashion there can be a significant lag between the time that N₂O is produced by NO reductase and its consumption by N₂O reductase. With longer dry intervals, then, there will be less N₂O reductase remaining in soil just prior to rewetting, allowing more N₂O to be emitted after wetting before its further reduction to N₂ (Bergsma et al. 2002, Evans and Burke 2013).

Changes in rainfall patterns are also likely to affect the relative importance of AOB vs. AOA nitrifiers because of changes in N mineralization rates, with consequences for N₂O fluxes. AOA tend to dominate where soil ammonium levels are low, including arable soils prior to fertilization (Taylor et al. 2012), so if episodic rainfall results in a large pulse of N mineralization or fertilizer leaching then AOB may quickly respond. Although data are sparse, early evidence suggests that AOB may be responsible for most nitrifier-derived N₂O in fertilized soils—such that a nitrifier N₂O pulse may further exacerbate our hypothesized denitrifier pulse. Together these processes may result in substantially increased N₂O fluxes from soils exposed to longer dry intervals, as has been observed in drier ecosystems (Evans and Burke 2013).

We additionally hypothesize that more intense precipitation and mid-winter thaws will result in more leaching of soluble nutrients such as nitrate from the root zone (Hess et al. 2015), and this will ultimately lead to more nitrate in groundwater and groundwater-dependent surface waters. However this

groundwater nitrate will take years to fully affect the river systems (Hamilton 2012). We will also examine P leaching; while P is often not considered a soluble element lost through leaching, new evidence from the Lake Erie watershed suggests that a soluble component dominates P transport to streams and rivers (Daloglu et al. 2012).

We will test hypotheses related to changing rainfall patterns in a Rainfall Manipulation Experiment using rainout shelters newly tested at KBS. Paired shelters (3×4 m to 2.5-m high; movable to allow farming) will be installed in four replicate plots of five MCSE systems (Conventional, No-till, Reduced Input, Biologically Based, and Early Successional). Under one member of each pair, an average amount of rainfall collected elsewhere at KBS is applied at 2-wk intervals by overhead sprinklers. Under the other member equivalent rainfall is added at ~3-day intervals, the average (30-y mean) KBS growing season rainfall interval. A variant of this system worked well for a 2-y nitrate leaching study in the conventional and no-till MCSE treatments (Hess et al. 2015). We will measure gas fluxes and, as described later, microbial community dynamics. We will test the nutrient leaching hypothesis by expanding our soil leachate sampling in the MCSE and Resource Gradient experiments to include mid-winter thaws and rain events, and in the Rainfall Manipulation Experiment. Tension lysimeters are installed just beneath the root zone (1.2 m depth) in the MCSE and Resource Gradient experiments as well as under the rainout shelters. Our experience has shown that a number of years of leaching observations are required because of the inherently high spatiotemporal variability of soil water samples, but over time patterns emerge.

We articulate in a preliminary metamodel the ways in which management decisions and climate change will interact with each other and the soil microbial community to affect GHG emissions and N leaching (Fig. 15). Multiple pathways lead to soil N₂O and CO₂ emissions. Climate change as evidenced in rainfall events, warming and freeze-thaw cycles will affect episodic soil saturation and soil aggregation. Soil

saturation and aggregation will affect C availability, nitrification, and denitrification (also influenced by the Plant-microorganism SEM), which will then affect the emissions of CO₂ and N₂O. Changing crop management through crop choice and chemical inputs like N will affect N₂O emissions through soil nitrification and denitrification. Methane consumption by soil methanotrophs is subject to suppression by N fertilization. This metamodel ties in directly with the farmer decisions, plant-microorganism, and eutrophication metamodels as indicated in Fig. 15. It is also a subset of a GHG mitigation metamodel (not shown) for which

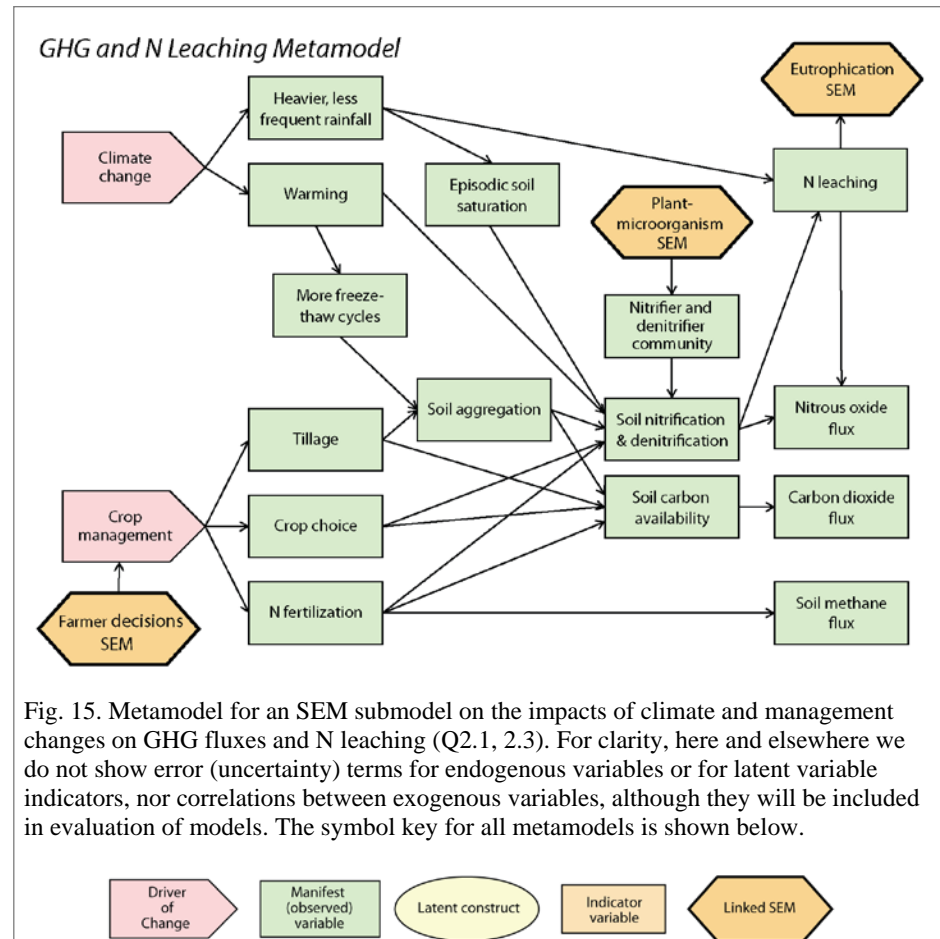


Fig. 15. Metamodel for an SEM submodel on the impacts of climate and management changes on GHG fluxes and N leaching (Q2.1, 2.3). For clarity, here and elsewhere we do not show error (uncertainty) terms for endogenous variables or for latent variable indicators, nor correlations between exogenous variables, although they will be included in evaluation of models. The symbol key for all metamodels is shown below.

N_2O , CO_2 , and CH_4 fluxes are driving variables together with the CO_2e costs of agronomic inputs and operations (Gelfand and Robertson 2015).

Q2.2 How will more intense rainfall and runoff change the amount of N and P transported from agricultural sources to surface waters, thereby affecting downstream eutrophication?

A major concern for intensive agriculture is the export of nutrients from fields to aquifers and waterways, degrading aquatic habitats by eutrophication and compromising human uses of water for drinking and recreation. In agricultural landscapes with cities and towns, nutrient pollution of river systems stems from agricultural, urban, and suburban sources. Eutrophication of downstream reservoirs and lakes and the role of agricultural nutrient sources is a new line of KBS LTER research.

Stream discharge records reveal that in many parts of the US more intense rainfall and runoff events are leading to a greater frequency of flood flows (e.g., Kaushal et al. 2014, Bettez et al. 2015). We have detected this at KBS in streams such as Augusta Creek, a 3rd order stream draining the KBS LTER site (Fig. 16). Augusta Creek receives little runoff from built-up areas, and summer discharge is normally supported largely by groundwater inputs. As noted earlier, land cover change over the past 50 years (fewer row crops and more forest) has had surprisingly little effect on the watershed water balance at annual scales (Hamilton et al. 2016; Fig. 7), suggesting that increased flashiness likely reflects the intensity of rainfall through its direct capture by lakes and wetlands along the stream course, as well as some overland flow from lands close to the stream channels. This flashiness can have major implications for downstream rivers. Water level records for the Kalamazoo River, which drains Augusta Creek, from 1937–2000 show only three summertime floodplain inundation events; however, since 2000 there have been 17 such events. The transport of agricultural nutrients to sensitive downstream water bodies such as reservoirs and lakes is thus likely to be increased under this new flow regime.

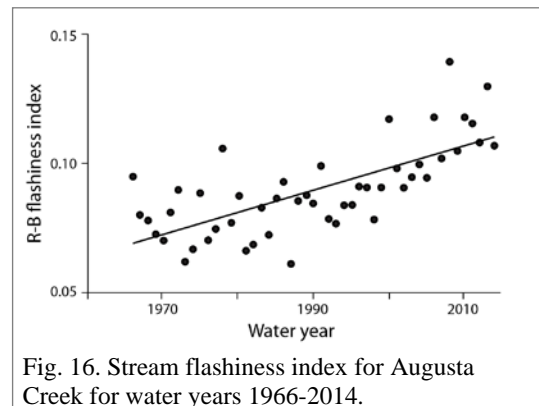


Fig. 16. Stream flashiness index for Augusta Creek for water years 1966–2014.

Increased frequency and intensity of runoff events are one of the hypothesized reasons for the re-eutrophication of western Lake Erie, which has been linked to increased dissolved P movement from agricultural lands into tributaries to the lake (Daloglu et al. 2012, Michalak et al. 2013). Additionally, high discharge events may allow nutrients to escape retention and removal in headwater streams and wetlands where these processes are most efficient (Mulholland et al. 2008), delivering the nutrients instead to downstream lakes and reservoirs at a time of year most likely to result in eutrophication.

These observations at KBS and in other watersheds, combined with our data on increased variation in summer rainfall and runoff, lead us to hypothesize that episodic inputs of nutrients into streams, rivers, reservoirs, and lakes in the KBS watershed are likely to increase. To test this hypothesis we will establish a new sampling effort in two reservoirs on the Kalamazoo River downstream of KBS, Morrow Lake and Lake Allegan. These reservoirs are ideal for studying the interplay between river discharge and eutrophication because 1) they are run-of-river reservoirs with no direct inflows from tributaries and no point-source inputs, facilitating direct comparisons of inflow to outflow; 2) they are on the same river, but Morrow Lake receives about half the P loading of Lake Allegan due to the influence of urban discharge as well as a P-rich tributary draining agricultural lands; and 3) they have been monitored monthly in the summer since 1998 by the state because Lake Allegan has a Total Maximum Daily Load for P. We have sampled the inflows and outflows at these reservoirs and compiled data on a wide set of variables that influence or indicate eutrophication; Reid and Hamilton (2007) analyzed data up to 2006 from these systems and found evidence for seasonal shifts in the most limiting factor for summer phytoplankton growth between P, N, and silica (the latter important for the diatoms that dominate this systems in summer), but no evidence that any of these were limiting during much of the rest of the year when

hydraulic residence times were too short for much algal growth. This interplay among potential limiting factors is likely to change with increasing frequency of intense storm events, which will increase nutrient loading but decrease reservoir water residence time.

We will initiate a high-frequency sampling program at the inflow and outflow of Morrow Lake that will capture episodic high-flow events and the successive falling limbs of the discharge hydrograph when

algal responses (measured as chlorophyll and oxygen saturation) are most likely. Monthly monitoring by the state since 1998 has not been able to capture these dynamics. This will allow us to understand how changing patterns of discharge and nutrient transport by streams interact to affect the eutrophication of sensitive downstream reservoirs.

Our SEM metamodel for reservoir eutrophication (Fig. 17) incorporates both existing long-term data as well as new data we will collect, and also incorporates the GHG and farmer decision metamodels.

Eutrophication is a higher-order (latent) construct comprised of four main indicators used by regional reservoir managers. Both agricultural and urban sources of N and P loads to inflowing waters need to be considered, as do the roles of water residence time and internal loading (sediment P release) within the reservoir.

Q2.3 What are the hydrological and biogeochemical implications of irrigation on intensively managed crops in mesic landscapes?

The increasing frequency of long dry spells (especially in mid-summer) has led to a tremendous increase in the use of irrigation in Michigan (Fig. 18). Locally, irrigated crop acreage has increased >50% over the past 20 yrs. This trend will likely continue and will have important biotic and biogeochemical implications—in particular for biodiversity as groundwater withdrawals divert water to crop evapotranspiration that otherwise would have discharged to first-order streams and fen wetlands of conservation interest. It may also affect soil C and GHG fluxes as irrigation causes higher productivity and more constant soil moisture that will stimulate greater and more consistent microbial activity.

We hypothesize first that properly managed irrigation not only produces higher crop yields, but by enabling crops to more efficiently utilize fertilizer N in years of water stress irrigation will also reduce excess nitrate in soils and consequently nitrate leaching to groundwater and indirect (downstream) N₂O fluxes (Beaulieu et al. 2010). Lower soil nitrate will decrease direct N₂O fluxes (Gelfand and Robertson 2015), as will more constant soil moisture owing to the greater persistence of N₂O reductase in frequently irrigated soils (see Q2.1). On the other hand, rates of denitrification (which includes N₂) and possibly methanogenesis may increase with irrigation if it results in more water filled pore space and consequently more anaerobic microsites in soil. Irrigation may also increase soil C availability due to higher

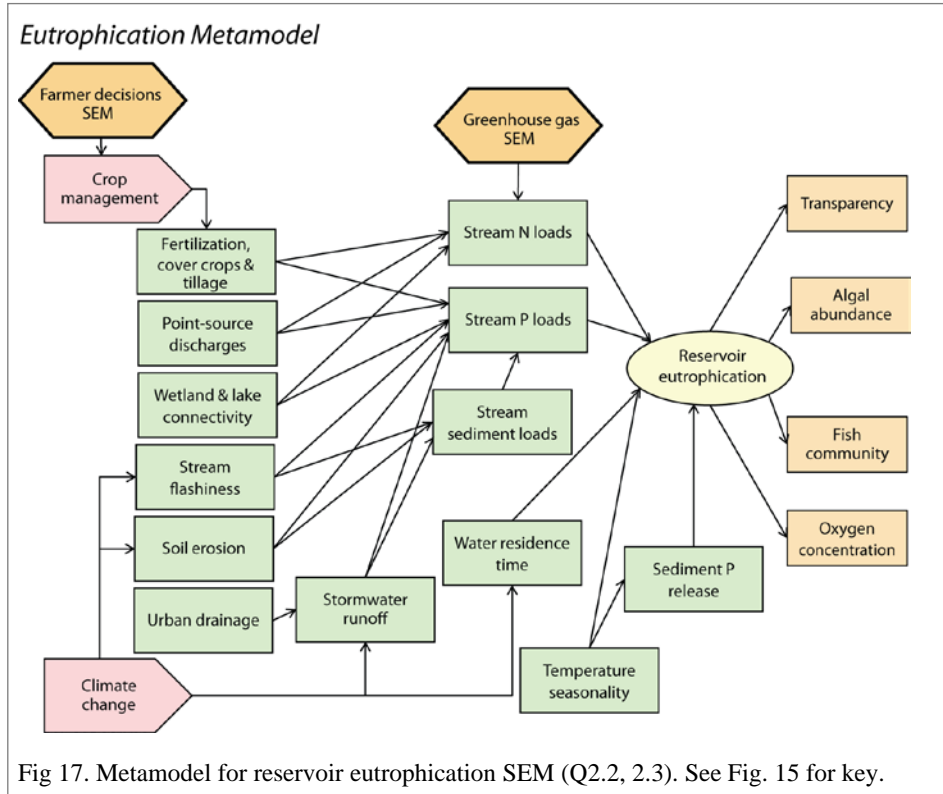


Fig 17. Metamodel for reservoir eutrophication SEM (Q2.2, 2.3). See Fig. 15 for key.

productivity, but soil C may not change if higher crop productivity is offset by greater microbial activity (cf. Liska et al. 2014, Robertson et al. 2014b). In addition to water, irrigation can also deliver groundwater nitrate (our site has concentrations of 10–20 mg N L⁻¹) and bicarbonate (McGill and Hamilton 2015), which has the potential to offset some N fertilizer and agricultural lime needs—or to create additional N₂O and CO₂ emissions (Hamilton et al. 2007). Overall, if not accompanied by increased fertilization, we expect irrigation to attenuate N leaching and N₂O production, but perhaps increase denitrification and CH₄ production. We therefore hypothesize that the net global warming impact (GWI) of irrigation will depend mainly on whether N₂O savings are sufficient to offset the CO₂ associated with electric groundwater pumps, and whether the soil C balance (organic and inorganic) changes. And an unknown driver is the interaction of irrigation with increasing heavy rainfalls, which may promote leaching (and denitrification N₂ loss) because rain will fall on already irrigated soil.

We will test this hypothesis using data from the LTER Resource Gradient Experiment (Section 1.1). Crop rotations and management in this experiment are identical to the MCSE no-till system but include nine N fertilizer rates (0–300 kg N ha⁻¹ to corn) with and without irrigation. We recently initiated a soil water sampling program there with analysis of all major solutes, and already have several years of data on GHG exchanges (but none with irrigation). We will add measurements of denitrification (both lab and field, using highly enriched ¹⁵N fertilizer) and the microbial communities noted in Q2.1 to this sampling so we can determine the reasons for presumed N₂O flux differences, assess denitrification N losses, and further inform Q2.1 hypotheses.

Where irrigation is practiced on a significant fraction of a watershed it may reduce summer stream flow and water levels in groundwater-fed streams, wetlands, and lakes. This effect is well known for drier climates but has not been documented for more mesic regions like KBS. A recently funded FEW supplement (Section 1.5) has allowed us to begin to test this hypothesis in a new collaboration with MSU geoscientists. The research entails remote sensing imagery analysis (Brown and Pervez 2014) and landscape-level crop and hydrological modeling (Basso et al. 2015, Hyndman et al. 2007) supported and validated by field data collection and experiments. The supplement is allowing us to refine methods in several test watersheds near KBS. The soil and watershed impacts of irrigation (the converse of less frequent but heavier rainfall) are embedded in the GHG (Fig. 15) and eutrophication (Fig. 17) metamodels, respectively.

Biotic Interactions (Lau, Evans, Landis)

Understanding biotic interactions is fundamental to understanding ecosystem services provided by agriculture, and here we focus on two broad areas: plant-microorganism interactions and plant-insect interactions. Our overarching question regarding biotic interactions is: How do management and environmental changes influence biodiversity, ecological, and evolutionary outcomes of species interactions and the resulting ecosystem services?

Long-term experiments offer a unique opportunity to test theoretical predictions regarding how management and environmental changes influence biotic relationships. Longstanding ecological and evolutionary theories (e.g., Hutchinson 1959) highlight the key role temporal variation plays in maintaining biodiversity at both intra- and interspecific levels, yet there are few empirical tests of these

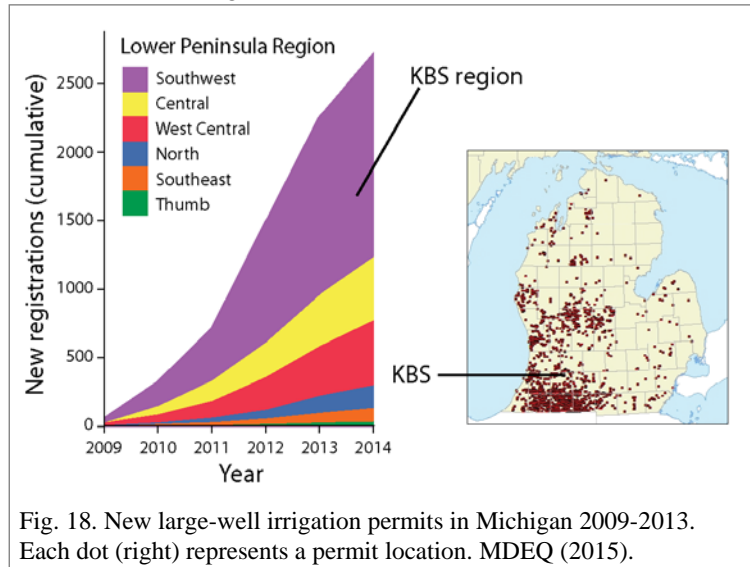


Fig. 18. New large-well irrigation permits in Michigan 2009-2013. Each dot (right) represents a permit location. MDEQ (2015).

theories, and even fewer experimental manipulations of temporal variability over long time scales. Long-term observational data can document temporal changes in biotic interactions that may reflect phenological mismatches resulting from species-specific responses to climate change (Parmesan and Yohe 2003, Cleland et al. 2007); such mismatches may have important implications for the ecosystem services underpinned by biotic interactions.

We have developed four specific questions regarding plant-microbial mutualisms and predator control of prey populations that benefit from long-term experiments, and that give us the ability to consider processes that occur over longer time-scales (e.g., evolution and ecological indirect effects). We are also able to couple results from experimental manipulations of temporal variability with long-term observational datasets that span natural variation in environmental conditions. This gives us the power to elucidate the effects of phenological asynchronies and species introductions that may only be apparent over decadal time scales.

Q2.4 How do changing environmental conditions influence N supply to crops through effects on plant and microbial diversity (both species and genetic) and life history evolution?

Prior KBS research has shown how environmental drivers affect plant and microbial diversity and community composition (Gross et al. 2015, Schmidt and Waldron 2015), and these drivers are subject to change over time. Classic ecological theory posits that temporal variation in environmental conditions contributes to the maintenance of biodiversity both at the species (Hutchinson 1959) and genetic (Turelli et al. 2001) levels. However, tests of this theory are biased towards studies of plants and animals, and the degree to which this theory applies to soil microorganisms—and thus to plant-microorganism interactions—remains relatively unexplored.

Here we ask how temporal variability caused by crop management and climate change influences plant and microbial communities and their interactions. Direct effects of increased temporal variability on microbial communities may include increases in genetic and species diversity, a larger proportion of taxa that exhibit dormancy, and greater resilience in the face of stressful environmental fluctuations. If microorganisms respond rapidly to temporal variation in the environment, they may buffer plant responses to environmental variation. Direct effects of increased temporal variability will also affect plants, including perhaps C allocation to roots and exudation, which will in turn influence microbial communities.

An SEM metamodel describes how temporal variability in environmental conditions affects microbial communities and their interactions with plants (Fig. 19). This general model includes latent (higher-order) constructs for the soil microbial community and plant-microorganism interactions, which are proposed to be reciprocally related, and can be customized to apply to a particular microbial group or plant-microorganism interaction, as for the legume-rhizobium metamodel presented later (Fig. 20). Climate change will have an indirect effect on the soil microbial community, working through soil moisture and soil aggregation. Changing crop management will affect plant-microorganism interactions indirectly through substrate and nutrient variability as well as via soil aggregation and the soil microbial community. This model ties in with the farmer decisions and greenhouse gas metamodels and shows examples of implications for ecosystem services as latent variable indicators.

We hypothesize that temporal variability, whether imposed by climate (e.g., increased soil water variability) or crop management (e.g., variation in substrates and nutrients) will enhance both species and genetic biodiversity in microorganisms, and alter life history evolution and/or community composition, because bet-hedging strategies (dormancy, phenotypic plasticity) will be favored. We will test this hypothesis by examining the responses of plants, microorganisms, and plant-microorganism interactions across a gradient of crop rotational diversities (Biodiversity Gradient Experiment, Section 1.1), and by measuring soil microbial community responses to altered rainfall patterns (using the Rainfall Manipulation Experiment, Q2.1).

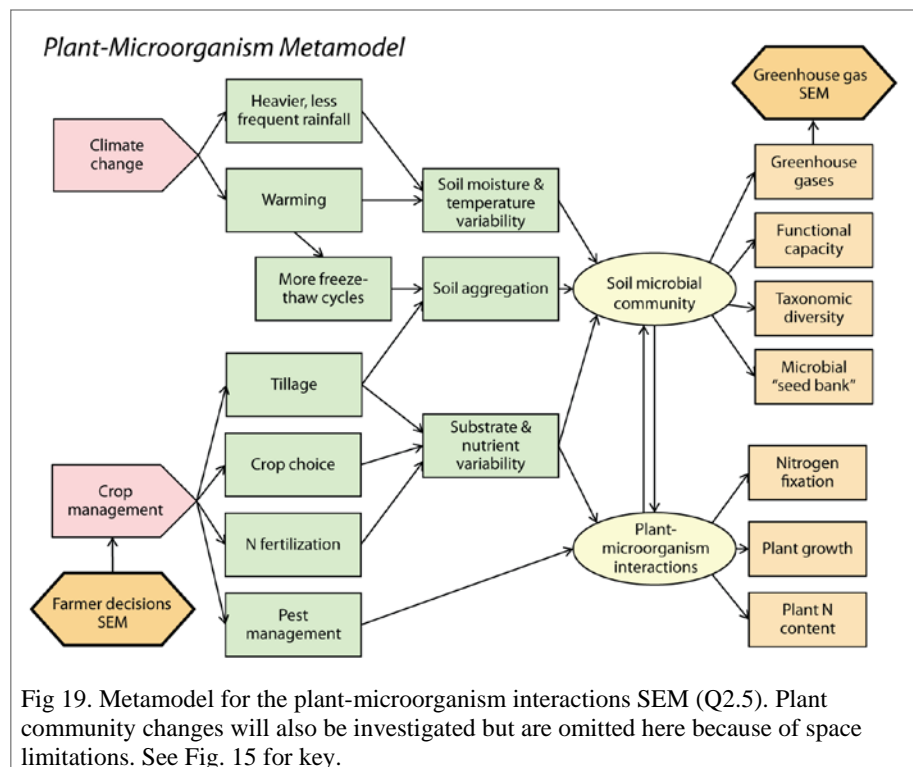
The Biodiversity Gradient Experiment is well suited to test these questions because treatments include

continuously planted corn, soybean, and wheat as well as these crops in rotations with every rotation entry point represented in every year, without the complicating effect of external nutrient inputs. These treatments create contrasting environments such that in continuous rotations populations experience relatively consistent organic matter inputs and disturbances, and as a result experience relatively consistent selective pressures, whereas in rotations populations experience greater temporal variability. For example, wheat fields sown in fall and harvested in late summer allow for a long growing season and an extended phenology for weed populations. In contrast, soybean and corn plots are tilled in early spring, planted in late spring, and experience periodic mechanical weed control, resulting in very short intervals between disturbance events for weed populations to complete their life cycles.

We will re-examine existing datasets and annually sample plant community composition in these treatments to investigate weed diversity and life history traits in constant vs. more temporally variable environments. We will also collect seeds from two abundant species found across all cropping treatments: *Arabidopsis thaliana* and *Capsella bursa-pastoris*. These species have very different seed longevities: *Arabidopsis* is short-lived in the seed bank while *Capsella* is long-lived. Preliminary work on an initial *Arabidopsis* seed collection from 2010 suggests that seeds collected from wheat treatments tended to germinate later than those from soybean or corn treatments, a potentially adaptive trait given the longer growing season in wheat systems, and that populations from continuous cropping treatments tended to have a higher germination rate than those from rotations, suggesting the evolution of dormancy in rotational systems. Further common garden experiments using the collected seeds together with sequencing of *Arabidopsis* may identify potential genetic differences in continuous vs. rotational systems.

Differences among microbial communities across cropping systems in the biodiversity gradient will reveal microbial responses to temporal change. Tiemann et al. (2015) found greater microbial activity and diversity in rotation treatments, which had higher soil organic C, while Lee and Schmidt (2014) found that bacterial growth efficiencies were lower in rotations compared to continuous soybeans. We predict that increased rotational diversity will increase C sequestration by increasing the diversity of organic substrates, microbial life history strategies, and resource use efficiencies. We will measure microbial species diversity with conserved marker genes (16S, 18S), microbial respiration, enzyme activities, and the composition of actively growing communities using bromodeoxyuridine (BrdU) labeling of DNA (Evans et al. 2014). We will examine growth efficiencies of individual microorganisms and of the whole community to characterize shifts in life history strategies and assess the proportion of dormant (zero growth) taxa. Sampling over multiple years will allow us to separate the effect of variability *per se* from the effect of the crop at the year of sampling.

The Rainfall Manipulation Experiment is ideal for examining plant and soil microbial community responses to climatic



variation, which affects biogeochemical fluxes and resultant ecosystem services. Although some studies have reported a change in microbial community composition under altered rainfall timing (e.g., Evans and Wallenstein 2012), others find community composition highly resistant to this stress (Cruz-Martinez et al. 2009), likely because microorganisms can adapt to greater temporal variability by way of evolution or physiological shifts, which in turn induce functional shifts. Evans and Wallenstein (2014) showed how both responses contribute to changes in function in prairie soils; 80% of the changes in life history strategies induced by altered rainfall timing were due to shifts in community composition, but the remaining changes were due to individual taxa shifting strategies, either via physiological plasticity, evolution, or horizontal gene transfer.

We predict that increased variability of soil moisture will first increase physiological plasticity in plant-associated microbial communities (change in life history strategies but not species composition). Greater plasticity will increase survivorship but reduce overall functional potential because of physiological tradeoffs. As new taxa eventually colonize, community composition will shift, increasing overall functional capacity. Investigating a subsample of these communities using shotgun metagenomics, in addition to targeted amplicon sequencing, will allow us to test whether changes in non-conserved regions of the genome are sensitive to changes in rainfall timing. Previous work by our group in simplified greenhouse mesocosms showed how these changes to microbial communities may feed back to influence plant drought responses (Lau and Lennon 2011, 2012); to test whether these findings apply to the more complex communities found in nature we will study plant and microbial responses in the Rainfall Manipulation Experiment.

Q2.5 How do changing environmental conditions influence ecological and evolutionary outcomes of plant-microorganism interactions that underpin plant nutrient acquisition and production?

To date, plant productivity in the MCSE systems has largely been considered separately from the associated microbial communities, yet they are strongly interdependent. We propose to complement our continued observations of plant and microbial communities with new experimental and synthetic approaches that explicitly study their linkages and overall function as an integrated plant microbiome. The responses of the plant microbiome to changing environmental conditions may be ecological, such as plastic changes in plant traits or changes in belowground microbial community composition, or they may entail rapid evolutionary change. Furthermore, changes in agricultural management and climate may drive rapid changes in the plant microbiome that can be beneficial (e.g., improved nutrient acquisition by crops) or harmful (e.g., greater pest, pathogen, and weed pressure).

Nitrogen is the most limiting nutrient for the growth of plants, including crops, in many terrestrial ecosystems including those around KBS (Gross et al. 2015). The mutualistic association of rhizobia with legume crops offers a well-understood system to study rapid evolution of the plant microbiome in the face of environmental change and variability, with applications to similar mutualisms in other plant species.

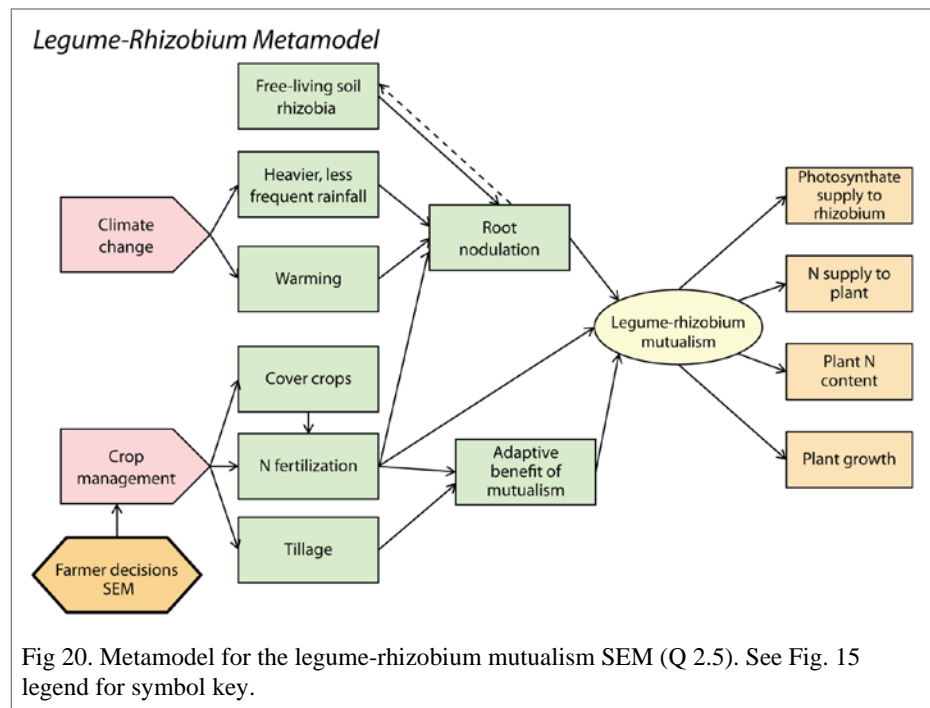
We will focus on how N availability influences plant N fixation in the context of changing management and climate. We hypothesize that increasing N availability destabilizes the mutualistic relationship between plants and N-fixing symbionts, reducing rates of N fixation both through ecological responses and longer-term evolutionary changes in both plants and microorganisms.

Extensive theoretical work on resource mutualisms predicts that the availability of traded resources has large effects on their ecological and evolutionary stability (Johnson et al. 1997, Schwartz and Hoeksema 1998). Prior work at KBS showed that N addition causes the evolution of less cooperative rhizobium mutualists: *Trifolium* plants inoculated with *Rhizobium* strains isolated from MCSE plots N-fertilized since 1988 result in plants that produce ~20% less biomass than those inoculated with *Rhizobium* strains isolated from adjacent control plots (Weese et al. 2015). These evolutionary shifts in *Rhizobium* quality appear due to both horizontal gene transfer (Gordon et al. 2016) and point mutations at genes related to the symbiosis (Klinger et al. 2016). Notably, these shifts appear to be driven by selection favoring lower quality (less mutualistic) rhizobium strains in N-addition plots, as evidenced both by reduced nucleotide

diversity at known symbiosis genes in high N plots (Klinger et al. 2016) and by quantitative genetic experiments using single strain inoculations in controlled greenhouse conditions (Lau et al., in prep). These evolutionary shifts also appear to have ecological consequences; preliminary data from recent REU projects using greenhouse experiments suggest that *Trifolium* inoculated with high quality rhizobia are preferred by herbivores, more attractive to pollinators, and result in higher soil N concentrations.

Although we have shown that N-addition causes the evolution of less mutualistic rhizobia, we have not yet considered evolutionary change in the legume hosts: theory predicts legume abandonment of the mutualism in high N conditions. In addition, our work suggesting that low quality *Rhizobium* strains are favored by natural selection in high N environments may indicate that *Rhizobium* quality is likely to decline further in the future. In the next phase of LTER we will: 1) re-isolate *Rhizobium* strains to determine whether N-addition causes further declines in *Rhizobium* quality; 2) explicitly quantify N fixation in mesocosms simulating the MCSE Early Successional system to determine whether reduced N fixation may offset the effects of synthetic N-fertilization on plant community dynamics; 3) use common garden experiments including *Trifolium* seeds collected from N-addition and adjacent control plots to test for evolutionary changes in the legume hosts; 4) expand our work to soybean-*Bradyrhizobium* interactions; and 5) examine these interactions in the Rainfall Manipulation Experiment. These experiments will reveal temporal dynamics of evolution in this system, explicitly link evolution to ecosystem services (nutrient availability) in less managed and agronomic systems, potentially link our *Trifolium*-rhizobium findings to observed shifts in legume abundance previously documented in the Early Successional system, and investigate how changing precipitation patterns alter this interaction and the important ecosystem services it provides.

We have developed an SEM metamodel to depict the mechanisms by which changing management and climate influence the mutualism between a legume such as soybean or alfalfa and its symbiotic rhizobia (Fig. 20). N additions—our initial focus—will interact with other factors including climate variability to determine the adaptive benefit of the mutualism, as measured most readily by plant production and N content. Climate change, as evidenced in rainfall events and warming, and changing



crop management (e.g., cover crops and chemical inputs) affect nodulation, which in turn influences the outcome of the legume-rhizobium mutualism (a latent construct). This construct is comprised of measures of photosynthate supply to the rhizobia, N both in terms of its supply to the plant and plant N content, and plant growth. Free-living soil rhizobia and nodulation are mutually reinforcing variables over time; we include a dashed line to acknowledge this relationship. Changing crop management is predicted to affect the legume-rhizobium interaction by causing evolutionary changes in rhizobium quality (Kiers et al. 2002). This metamodel is a specific application of the more general plant-microorganism metamodel described in Q2.4.

Q2.6. How can improved knowledge of the phenology of predator-prey interactions be used to enhance biological pest suppression in changing agricultural landscapes?

Pest suppression in agriculture must constantly change tactics in response to multiple drivers including climate variability and change, invasive herbivore and weed species, the evolution of pesticide resistance, and new technological options. Invasive insect pests such as the European corn borer (*Ostrinia nubilalis*), the soybean aphid (*Aphis glycines*), and the brown marmorated stink bug (*Halyomorpha halys*) have proven particularly costly (Pimentel et al. 2005) and motivated the introduction of new genetically modified crops (Bt corn) and pesticides (e.g., seeds treated with neonicotinoids). A warming climate allows native and exotic crop pests to extend their ranges (Bebber et al. 2013). Meanwhile, native and invasive predators may respond to the higher abundances of prey, potentially exerting some degree of control. An ecological perspective on biotic interactions involving pests can help us to understand and manage these changing threats, and studying the dynamics of these interactions under changing conditions can inform ecological theory (Tscharntke et al. 2012, Schmitz and Barton 2014) as well as biological management options.

Our work on predator-prey interactions will continue with our longtime focus on ladybeetles (Coccinellidae), important and ubiquitous predators in agricultural systems who prey on numerous species of aphid pests and the eggs and young larvae of other pests. Long-term observations at KBS have documented the spatial and temporal variability of ladybeetle species abundances in both crop and non-crop habitats, and this work has been coupled with shorter-term manipulative studies to determine how species identity, diversity, and seasonal timing affect prey suppression (Section 1.2). The coincident influence of longer-term drivers such as climate change and changes in crop management may additionally—and perhaps substantially—alter predator–prey dynamics and pest suppression in crops.

The ladybeetle guild is sufficiently diverse and dynamic to serve as a model system to examine the controls on and resilience of arthropod predator-prey relationships. The association between arthropod predator diversity and herbivore suppression in landscapes varies (Snyder and Tylianakis 2012). On the one hand, diversity can increase pest suppression because of complementarity between natural enemies or because of facilitation, where the action of one natural enemy increases the success of another (Losey and Denno 1999). Alternatively, increased predator diversity can depress pest suppression via intraguild predation, as when a less effective predator feeds on a more effective predator, decreasing the latter's impact on prey suppression (Rosenheim et al. 1993, Finke and Denno 2004). The relative abundance of different species has also been shown to be important, with more even communities exerting increased pest suppression (Crowder et al. 2010).

Since 1989 we have followed 13 ladybeetle species at weekly intervals over the growing season in all MCSE systems including successional and forest sites. The phenology of some ladybeetle species is predominantly driven by photoperiod, while temperature may be the primary driver in other species. This suggests that climate change could disrupt temporal niche partitioning in ladybeetles, leading to increased competitive interactions between species, and resulting in phenological mismatches between predators and pests. We hypothesize that climate warming will exacerbate the negative impact of *H. axyridis*, the dominant exotic ladybeetle at KBS, on native ladybeetle species by increasing *H. axyridis*' spatiotemporal overlap with species active earlier in the growing season.

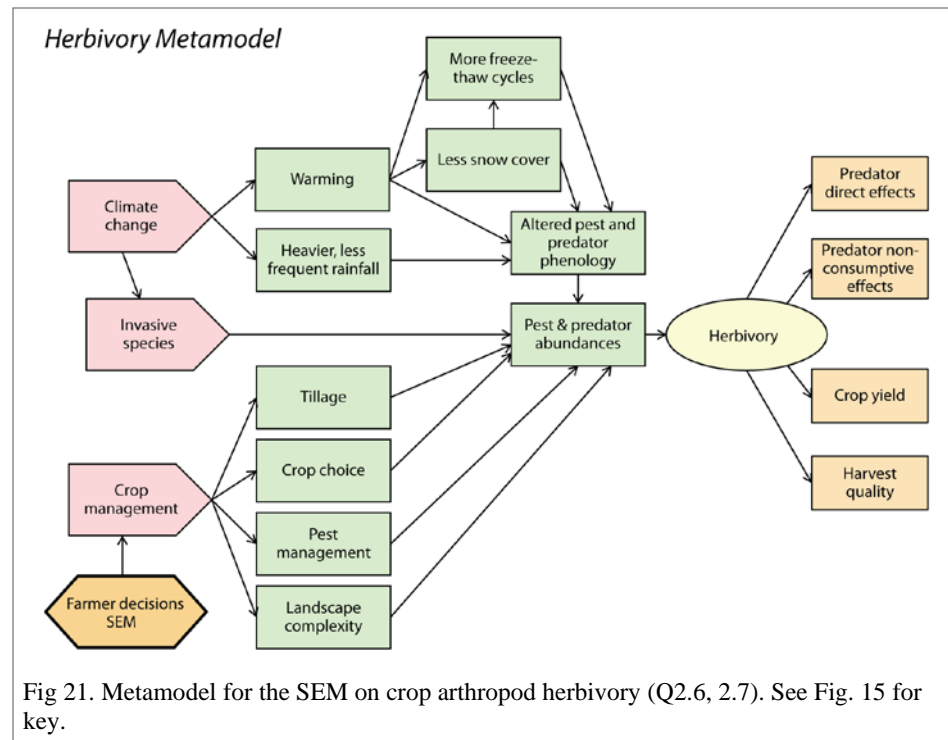
To test these hypotheses, in the next phase we propose to build for the four dominant ladybeetle species at KBS species-specific phenological models that include temperature, day length, and crop type as drivers (Hodgson et al. 2011). The models will allow us to test hypotheses about which species of ladybeetle are likely to co-occur where and under what conditions. We will generate several scenarios based on recent seasonal weather changes (e.g., early onset of warm temperatures in spring; cool/wet vs. hot/dry summers; changing rainfall patterns) and use these scenarios to parameterize the models and generate activity curves for each species, in each crop, under each scenario. Then, within each crop-scenario combination, the overlap in the activity curves of each species pair will be compared to determine how climate changes impact niche overlap. Ladybeetle occurrence data collected in subsequent years will

serve to validate the model predictions.

The hypothesis that climate change will reduce biocontrol efficacy will be tested with a new phenological model for herbivore suppression potential (hereafter HSP) derived from the combined phenological models for each ladybeetle species, weighted by their relative mean abundance and aphid consumption rates (*sensu* Bahlai et al. 2013a, Bahlai et al. 2013b). The HSP model will predict how the coccinellid community suppresses herbivores over the growing season, generating scenarios to show how various climate, agronomic, and ladybeetle community changes affect herbivore suppression. For example, these models will integrate the effects of changing agronomic practices such as the increasing use of neonicotinoid insecticides, which delay the establishment of soybean aphid until later in the growing season. Pest dynamics models will be informed by predictions from the HSP model to determine which conditions are likely to lead to pest population escape and subsequent eruptive dynamics. Finally, we will test the predictions of our HSP/pest models directly at the MCSE using sentinel prey methods under both natural variation in environmental conditions and targeted manipulations such as the Rainfall Manipulation Experiment and warming rings now installed in an ancillary experiment adjacent to the MCSE.

Ultimately our understanding of ladybeetle populations and their predation on aphid pests will be synthesized in an SEM for crop loss to arthropod herbivores. The metamodel in Fig. 21 summarizes the key factors influencing the provision of pest suppression. Herbivory is measured as a latent construct comprised of four indicators—harvest quality, crop yield, direct (consumptive) effects of predators on herbivores, and, as

hypothesized below (Q2.7), nonconsumptive effects of predators on herbivores. Climate change, and specifically changes in seasonal patterns of temperature and precipitation, influences predator phenology and abundance, which in turn affect pest suppression. Shifting crop management practices such as the use of neonicotinoid seed treatments, tillage, and chemical inputs also influence pest and predator abundance and pest suppression. Invasive predators and pests have been and will continue to be important drivers as well.



Q2.7. How and to what degree do the non-consumptive effects of predators on prey (predator avoidance) influence herbivore suppression?

Climate change, invasive species, and shifting crop management practices all impact pest and natural enemy biology. A new frontier in reducing crop losses to herbivory is the potential to manipulate the non-consumptive effects of natural enemies on prey to better enhance pest suppression. Insects can detect visual (Jones and Dornhaus 2011) and chemical (Ninkovic et al. 2013) cues identifying the actual or

potential presence of predators and adjust their behavior in response to these cues, altering patterns of movement (Lee et al. 2011), feeding (Reigada and Godoy 2012), and reproduction (Vonesh and Blaustein 2010). In the presence of predators, herbivores frequently drop from plants (Nelson and Rosenheim 2006), consume less or lower quality food (Schmitz et al. 1997), and have elevated stress responses (Janssens and Stoks 2013) that combine to limit activity and reproduction (McCauley et al. 2011). However, current models of crop herbivore suppression only account for the direct consumptive effects of predators. To expand our understanding of complex predator-prey interactions we will begin new long-term research on the non-consumptive effects of predators on prey using a combination of laboratory, mesocosm and long-term field-based approaches.

We hypothesize that non-consumptive effects on herbivore population suppression can be as important as those of direct predation, contributing to reduced crop damage and increased yield, and as well that herbivores will exhibit more predator-avoidant behaviors to cues from co-evolved predators than they will to new predators. Prior studies have shown that aphids can detect the prior presence of coccinellid predators on a leaf and respond with avoidance behaviors (Ninkovic et al. 2013); however, costs of such avoidance behaviors on aphid fitness are unknown. We will test these hypotheses using both co-evolved and novel associations of coccinellid predators and aphid prey. The seven-spotted ladybeetle (*Coccinella septempunctata*) and bird cherry oat aphid (*Rhopalosiphum padi*) co-evolved in Europe, while multicolored Asian ladybeetle and soybean aphid co-evolved in Asia.

We will conduct lab assays that determine the extent of predator avoidance by these aphids (typically increased movement and dropping) and contrast life history performance (e.g., reproduction, generation time) in the presence of co-evolved and new associations of ladybeetles in a factorial experiment. Both visual and chemical cues will be tested as potential mechanisms of predator detection. Mesocosm experiments will combine multiple predators with different hunting methods (sit and wait, active foliage, and active ground dwelling predators) to examine the effects of predator avoidance under more realistic conditions. Results will inform field experiments to test the likelihood of mobile herbivores' altering oviposition behavior based on their detection of risky habitats. We will place sentinel collard plants (*Brassica oleracea*) in MCSE systems for which we have prior knowledge of predator communities, and use rates of oviposition and larval survival by the cabbage white butterfly (*Pieris rapae*) to test herbivore responses to field-scale cues. The SEM metamodel introduced above (Q2.6) includes non-consumptive effects of predators and will help us determine their relative importance compared to direct consumption of prey.

Human Decision-making (Swinton, Marquart-Pyatt)

Past KBS LTER research (Section 1.2) has estimated economic values of ecosystem services and identified payments that would induce farmers to adopt biologically based practices that enhance ecosystem service delivery (Ma et al. 2012, Palm-Forster 2015). We discovered in particular that the most readily adopted practices are those with low direct costs, low opportunity costs (James et al. 2010, Ma et al. 2012, Kells and Swinton 2014), low participation (transaction) costs (Palm-Forster et al. 2016b), and low risk (Song et al. 2011), all of which can lower necessary offset payments (Ma et al. 2012). We now have a basic understanding of the interacting factors that drive the willingness of farmers to accept ecosystem service payments at farm and landscape scales. This positions us to ask two important long-term questions: 1) how does improved field-scale information, enabled by emerging and developing technologies such as high resolution remote sensing via unmanned aerial vehicles (UAVs), spatially explicit simulation modeling, improved weather forecasting, and big data capabilities, affect farmer willingness and ability to provide ecosystem services; and 2) how might changes in farmer attitudes, resources, and behaviors influence their crop and landscape management decisions. We expect both of these factors to strongly influence farmer decision making, a key driver in all of our ecological SEM models, and thus to strongly influence ecosystem service delivery—which will in turn feed back to affect farmer decisions. We explore these issues with two explicit questions:

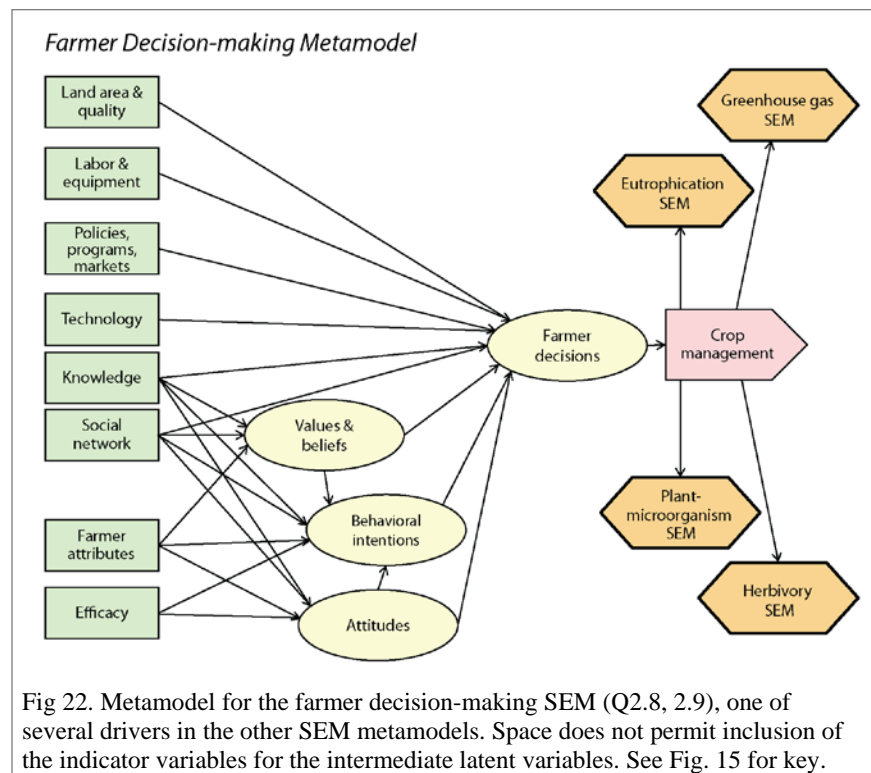
Q2.8. How do farmer traits, farm location, and agricultural management information combine to influence decisions affecting ecosystem services from agriculture?

Research at KBS and elsewhere has shown that farmers are more likely to adopt stewardship practices when they perceive environmental benefits close to home (Ma et al. 2012, Wilson et al. 2014). As technology rapidly develops to deliver tailored, site-specific predictions of ecosystem service outcomes alongside expected crop yield and profitability outcomes (e.g., Lant et al. 2005, Schimmelpfennig and Ebel 2011, Egbendewe-Mondzozo et al. 2015), an important question is whether tailored field-scale ecosystem service information will affect crop management decisions. A related question is whether public disclosure of management practices—made more accessible through mobile device apps that can simulate scenarios for individual fields (e.g., GLWMS 2015)—will affect farmer adoption of conservation practices.

We hypothesize that farmers will opt for ecosystem service-enhancing practices more readily when predictions of ecosystem service benefits are 1) tailored to their farms (rather than offered as general scenarios), 2) targeted to farm fields where ecosystem service-enhancing practices have relatively high impact, and 3) available in a more specific and detailed way. Further, we hypothesize that farmers will be more likely to adopt ecosystem service-enhancing practices if knowledge of ecosystem service outcomes is publicly available. Producing such detailed predictions will require an in-depth ecological understanding of ecosystem services derived from prior and continuing KBS LTER research as well as from the literature, and will as well become more available as technology develops.

Economic field experiments (Harrison and List 2004) continue to grow as an economic research method. We used an experimental auction variant of this method in the current funding cycle to evaluate farmer responses to alternative payment mechanisms for ecosystem services (Palm-Forster et al. 2016a, 2016c). In this next cycle we propose experimental conservation auctions with treatments focused on ecosystem service information, informed by KBS LTER biogeochemical and biodiversity research as well as by other studies and targeted to represent the Eastern Corn Belt. The information will be integrated into model-based simulations of management scenarios that predict crop yields and ecosystem service outcomes at the level of individual fields using field-relevant soil and climate data.

To test the hypothesis that tailored information enhances farmer adoption of ecosystem service-enhancing practices, we will present farmer participants with hypothetical scenarios that vary access to detailed, field-specific simulation results. We will start with experiments based on biogeochemical outcomes, and once suitable simulations can be developed for the landscape complexity configuration, we will explore conditions under which farmers will collaborate to provide pest suppression services across a shared landscape (Stallman 2011, Stallman and James 2015). Model predictions for



each practice will include crop yields (provided in all information treatments) as well as nitrate leaching, P runoff, and GHG emissions as predicted by the Systems Approach to Land Use Sustainability (SALUS) model, which has been validated with KBS LTER findings (Basso and Ritchie 2015). Participating farmers (~20 per auction focus group) will be recruited across landscapes representing relevant gradients: water body vulnerability to excess nutrients for the biogeochemical information experiment, and proportion of natural habitat in farm landscapes for the pest suppression experiment.

A second set of experimental auctions will focus on tailored scenarios for natural pest biocontrol services, varying the spatial management of habitat for natural enemy species, thus interfacing with Q2.6 and 2.7 above. Past research at KBS has established landscape-scale effects on biocontrol (Gardiner et al. 2009, Meehan et al. 2012) and ongoing research is examining finer-scale habitat effects (Woltz et al. 2012). Landscapes could be designed so as to vary the expected abundance of natural enemies, the timing of their arrival in the crop field, and the geographic distance that they can project their biocontrol services.

Answers to these questions will be sought in the context of the farmer decision-making SEM metamodel (Fig. 22), which posits that farmer decisions about what crops to grow and how to grow them arise from farmer attributes (e.g., farmer education), farm resources (e.g., land area and quality, labor and equipment), external incentives (e.g., markets, policies, and programs), and technology. In the experiments these questions address specific farmer attributes: knowledge (about how their own cropping practices will affect ecosystem service outcomes) and social networks (how knowledge by others about the effects of the farmer's cropping practices will influence that farmer's intentions and/or actions).

Q2.9. How do farmers' ecological knowledge, values, and beliefs change over time and affect their willingness to adopt agricultural management practices that provide ecosystem services?

Many Midwest farmers already use one or more biologically based management practice. In past KBS LTER surveys and focus groups, farmer willingness to choose biologically based practices that enhance ecosystem services was greater when they care about environmental stewardship (Ma et al. 2012) or an environmental outcome like renewable energy (Skevas et al. 2014, 2015; Swinton et al. 2016), in agreement with the broader literature on adoption of conservation practices (Prokopy et al. 2008, Reimer and Prokopy 2014). Key to increasing adoption beyond the current group is to understand how and why ecological management choices evolve in a representative sample of farmers engaged in row-crop agriculture. Although long-term information about human choices is available for US consumers in the General Social Survey (NORC 2016) and for selected farming topics in Iowa (Arbuckle and Lasley 2013), in order to link farmer knowledge, values and beliefs to behavior that affects their practices that deliver ecosystem services we need systematic information about changing attitudes and behaviors.

Multiple factors interact to determine farmer decisions, as addressed in our proposed experimental auctions (Q2.8) and illustrated in Fig. 22. People's views and attitudes change with time, however, in ways that are not always predictable from their current behavior. Climate change provides an instructive example of particular importance as its effects may be direct, as a biophysical forcing that manifests itself in changes to landscapes and row crop systems, but could also be indirect, working through the suite of ecosystem services to affect farmer decisions. Temporal variability in how the general public views climate change is well documented (Leiserowitz et al. 2014), though measures of climate extremes on public opinion appear infrequently (Marquart-Pyatt et al. 2014). Farmer survey research reveals more than two-thirds of farmers believe climate change is occurring, yet only a plurality believe human activities contribute to it (Arbuckle et al. 2013, Gramig et al. 2013). An even smaller percentage of farmers perceive climate change as a threat likely to significantly reduce their future yields (Rejesus 2012). Yet as more information becomes available documenting the impacts of current climate changes, such as the occurrence and consequences of extreme weather, the views of farmers are likely to change, making them more likely to adopt practices that confer greater resilience to their cropping systems and mitigate the contribution of agriculture to climate change (Marquart-Pyatt et al. 2014).

We hypothesize that farmers whose perceptions of environmental stewardship are favorable and whose

views about climate change reflect those of the scientific community will be more willing to adopt biologically based stewardship practices that mitigate climate change. We also hypothesize that farmers who have greater familiarity and experience with market-based incentives, policies, and programs will also be more likely to select such practices when they are designed to mitigate or adapt to climate change. Further, we predict that farmers who are presented with information about climate variability and change are more likely to adopt biologically based practices that are shown to make their systems more resilient.

We will test these hypotheses about farmer views on climate change, and environmental stewardship in general, by examining farmers' perceptions and practices at single time points (e.g., for a specific policy or subgroup of farmers) and over time. We will build on experience from past KBS cross-sectional farm surveys (Jolejole 2009, Ma et al. 2012, Swinton et al. 2015b) to design a long-term social survey that will be gathered annually in a representative sample of row-crop producers in the Eastern Corn Belt (Illinois, Indiana, Michigan, and Ohio). Over the proposed funding cycle this will yield a data set at the regional scale that can track, over the long term, evolving farmer perceptions and practices and ecological production conditions. We will use an annual, multi-frame, stratified sampling design. To ensure coverage, we will use both list and area sampling to create our sample of growers in these four states from property records, using a sampling frame of property owners. Data will be collected using a mixed-mode design that includes mail surveys, in-person interviews, and web-based methods to minimize costs and maximize participation. We will administer mail surveys using a modified total design procedure (Dillman et al. 2014), which in our recent experience produced response rates of up to 60%.

In the first wave of data collection, the panel sample will be larger (~4,000) than later to allow for roughly equal sample sizes in wave five after panel attrition. By year six we will have a dataset of about 9,000 observations from a core sample of approximately 1800 farmers stratified across the four states.

Maintaining a panel across the waves of survey data collection allows for examination of factors that lead to changes in farmers' perceptions, resources, and practices in the face of changing contextual or place-based factors. Conducting the survey annually will allow us to encompass events like unusual weather, price fluctuations, and technology and policy introduction that may affect farmers' values, views and/or practices. We cannot quantify these relationships with existing data (e.g., ERS 2016; Arbuckle et al. 2015).

The set of core survey questions will ask growers about their agro-ecological knowledge and values, perceptions, and decisions regarding nutrient management, environmental outlooks, climate change views, production practices, policy views, and biologically based stewardship practices. The survey will also collect standard demographic and socio-economic information about farm households. The survey instrument, to be pre-tested with farmer focus groups, will include rotating modules on biophysical data, ecological data, policy views, program evaluation and participation, and incentives. The survey will enable coupling of ecological information from on-site research at KBS with attitudes and practices by a representative sample of farmers to understand conditions for farmer behavior related to the management of agricultural land, both cross-sectionally and longitudinally. Cumulatively, the full panel of respondents will allow us to examine how annual fluctuations in economic factors like prices and physical conditions like atypical weather might influence adoption of biologically based practices.

2.2 Synthesis

Over the past 25 years KBS LTER researchers have established a firm foundation for documenting long-term changes in agricultural landscapes, both changes linked to row-crop management regimes and changes in unmanaged parts of the landscape, exploring all five core LTER research areas (primary production, population change, movement and transformation of organic and inorganic matter, and disturbance patterns). Research at multiple scales has revealed key drivers and outcomes of biotic, biogeochemical, and socio-ecological processes that interact to provide the multiple ecosystem services provided by agriculture. More than 900 publications, 260 in the current funding cycle, contribute to an unprecedented understanding of the ecology of a representative upper Midwest agricultural landscape. Proposed research builds on this foundation to address the long-term ability of intensive row-crop

agriculture to meet food and fuel needs while minimizing further environmental harm, and to be resilient in the face of changing environmental and social drivers. Ecological knowledge underpinned by theory can provide a sound basis for farm and landscape management decisions that enable long-term solutions.

Our new research framework (Fig. 2) asks how changing drivers (climate, crop management, and invasive species) affect the delivery of critical ecosystem services and their resilience in the face of accelerating biophysical and social change. Five essential services—yield, pest suppression, soil fertility, clean water, and climate stability—benefit farming and society at large. Farmer and landowner decisions, through effects on ecological processes in both managed and unmanaged portions of the landscape, can attenuate or promote the continued delivery of these services, and are influenced by a complex set of interacting factors. A robust understanding of the integrated system sufficient to identify and understand its synergies and tradeoffs will be essential for using this knowledge to design and manage sustainable farmscapes of the future.

New to this funding cycle is our use of a quantitative SEM modeling approach to better integrate the diverse lines of KBS LTER research. In past cycles we have focused efforts on discovering and understanding the ecological pieces and processes that make row-crop systems work, and on identifying the ecosystem services most important and susceptible to change. In this cycle we continue to deepen this understanding, but explicitly consider linkages between ecological pieces and processes (i.e., interactions between different biotic components and between biogeochemical, biotic and social interactions) and initiate a long-term capacity to model the system in order to test our understanding, discover hidden dependencies, and integrate the knowledge necessary to design future sustainable agricultural systems.

We will use SEMs to evaluate relationships among identified factors and in particular to disclose interdependencies, reciprocities, and feedbacks inherent to each part of the system. Our SEM approach draws inspiration from applications in both ecological and social sciences (Grace et al. 2010, 2016; Hoyle 2012), and a similar approach has been applied successfully to transdisciplinary agroecological research projects (e.g., Smith et al. 2014). We acknowledge that the SEM approach may present challenges, as discussed in Section 2.0, but with this tool we anticipate significant scientific advancement.

The specific methodology for our SEM work will reflect current practices in ecology and social science. To evaluate uncertainty we will report a variety of fit statistics and their interpretation along with coefficient estimates

(Paxton et al. 2011). We will use both full and limited information (e.g., maximum likelihood, two stage least-squares) methods of estimation to reveal proposed relations. Each equation in the multiple equation system will be assessed using standard diagnostics (e.g., multicollinearity, heteroscedasticity, and outlier analysis) because the models' overall assessments rely on each individual equation. We will use substantive knowledge to evaluate the coefficient estimates

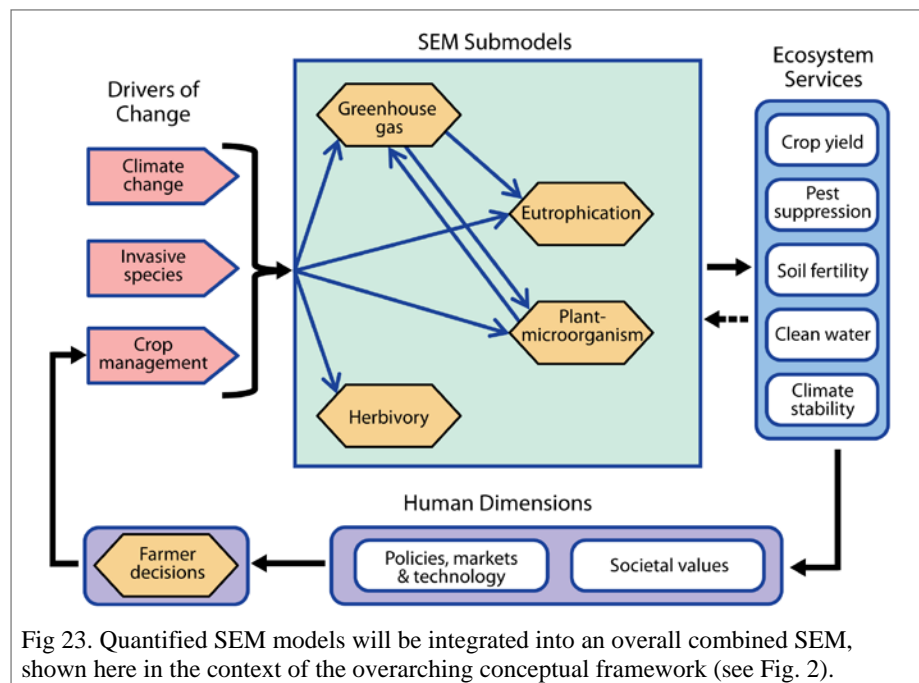


Fig 23. Quantified SEM models will be integrated into an overall combined SEM, shown here in the context of the overarching conceptual framework (see Fig. 2).

regarding appropriate signs, significance, and explained variance. In assessing the models, we will examine the component fit of each individual equation and the overall fit of the system of equations, presenting relevant goodness-of-fit statistics (e.g., Chi-square, CFI, RMSEA, BIC) and model comparisons (West et al. 2012). We will perform analyses of measurement and structural models using MPlus and R (Muthén and Muthén 2012, Grace et al. 2015). Our proposed cross-sectional and longitudinal data for the different submodels allow flexibility. Where we have multiple years of data, we can conduct cross-lagged temporal analyses to specify proposed relations over time and assess the full model, including whether the hypothesized relations are synchronous, reciprocal, and/or cross-lagged. Considering appropriate temporal lags will allow us to assess proposed feedback relationships.

Our SEMs will first be estimated independently for specific areas as depicted in the preliminary metamodels, and eventually each quantified SEM will serve as a submodel to be integrated into an overall combined SEM (Fig. 23) with multiple paths of influence, varied social and ecological gradients, and interrelated processes. Common variables among submodels provide explicit inter-linkages that can be probed to understand their influences on other parts of the system and, ultimately, on the delivery of specific ecosystem services from agricultural landscapes.

2.3 Related Research Projects

Since 2007, with separate funding from DOE's Great Lakes Bioenergy Research Center (GLBRC), we have extended our MCSE approach to a nearby site planted with eight candidate cellulosic biofuel crops. These range from monocultures of switchgrass, *Miscanthus*, and *Populus* spp. to communities comprised of different mixtures of grasses and forbs including restored prairie. In addition, we have larger replicated fields of brome grass (*Bromus inermis*), switchgrass, and restored prairie planted nearby. At both sites continuous corn provides reference. While these experiments are not essential to the success of our proposed research, they will provide valuable complementary information for several of our hypotheses, as they have in the current funding cycle.

2.4 Education and Outreach Activities

We place a high priority on education and outreach and address each by engaging a community of students and stakeholders with our science, including farmers and those who influence farmer decisions, teachers, students, policy makers, and the general public. Key to this approach—and central to our education and outreach framework—is an understanding by all parties of the suite of ecosystem services provided by agriculture and the tradeoffs associated with various management practices. Through dialogue with stakeholders (Fig. 24) we are responsive to emerging opportunities where LTER data can inform solutions to environmental problems and where we can increase awareness of basic ecological science and its broader impacts on environment and society. In turn, this dialogue enables us to assess the success of outreach efforts and to learn about the science needs, questions, and priorities of these groups. An LTER Education and Outreach Coordinator leads and facilitates LTER outreach efforts and works closely with others at the Station who provide outreach, education, and extension programming. Our educators and scientists serve on the LTER Network Education

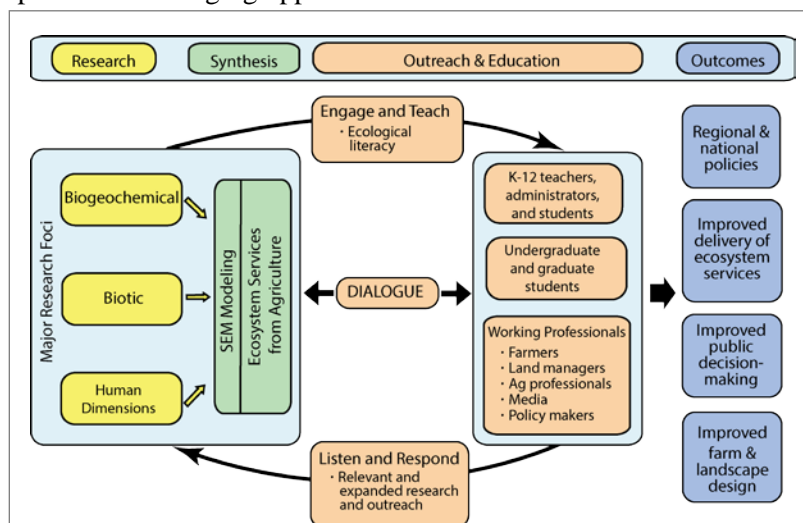


Fig 24. Roadmap describing outreach and education at KBS. Dialogue is central to our overall strategy.

Working Group and participate in NCO activities and initiatives. We detail below proposed activities in specific areas.

K-12 Educators. We will continue our teacher training efforts under the KBS K-12 Partnership for Science Literacy through school year and summer professional development workshops and RET projects, and seek external funding to continue to promote K-12 student learning via teacher-scientist partnerships (see Section 1.4). Participating RETs will create Data Nuggets (Section 1.4) or other curricula that will be archived on the Data Nuggets and K-12 Partnership websites and available to teachers nationwide.

Undergraduate Students. REU evaluations and summaries, including blog posts on our website, illustrate the transformative and educational values of these experiences. KBS-based LTER REUs join a larger cohort of students at the Station supported in part by recent NSF REU site funding. The program includes robust professional development for REUs and mentorship training (including diversity and inclusion training) for graduate students and postdocs. All KBS REUs participate in an end-of-summer research symposium where they present their research to KBS researchers, students, and staff. These REUs—and the many other undergraduate visitors to the site throughout the year—also gain exposure to LTER research via new curricula used in conjunction with the LTER Walking Tour (Section 1.4). We will continue to strengthen existing efforts to link undergraduate education with LTER research and scientists, including class use of the site.

Working Professionals. Continuing education for professional groups including MSU Extension educators, agricultural consultants, NRCS staff, and farmers will continue to be a core focus of our outreach portfolio. Programming will be research-centered on farming for ecosystem services with a particular emphasis on climate change adaptation and mitigation. As such, our education and outreach coordinator will coordinate efforts with PIs and continue collaborations with Extension to train working professionals via workshops and field days, webinars, media pieces, and fact sheets. Our outreach is particularly focused on outreach about farming and climate change, which dovetails with the climate change focus of our farmer decision-making research. We will continue to seek opportunities to engage in dialogue with these groups by hosting discussion events on climate change, reactive nitrogen loss, and other pertinent issues.

Public and Media. Increasingly the public is interested in and concerned about sustainable agriculture. We will continue to disseminate our findings and engage with community members by maintaining our social media presence, blogging on our website, updating our two walking tours, and participating in local science outreach events such as MSU's annual Science Festival. We will reach the public via our established connections with the media, MSU's Knight Center for Environmental Journalism, the NCO, and University Communications offices; we expect to continue to produce 2-3 press releases per year based on forthcoming papers. We will continue to promote opportunities that these organizations provide for science communication training for our graduate students, post-docs, and other scientists.

Policy Makers. We place significant value on efforts to educate and inform national and state decision makers. We will continue to share our news releases and outreach publications with policy makers, including our continuing series on agriculture and climate change, and continue to participate in Congressional and other briefings as opportunities present themselves.

New Activities. New to the coming funding cycle will be efforts to incorporate KBS LTER findings into statewide (and eventually regional) extension programming. Publication of our new site synthesis volume (Hamilton et al. 2015a) has elicited significant interest from extension educators to distill key findings into extension bulletins, web postings, and presentation materials that they can use in their statewide and regional programming, which ranges from workshops to field days to social media, and includes crop advisors and agribusiness concerns as well as farmers. This activity will likely include train-the-trainer workshops, an effective method that we have successfully used to disseminate findings on climate change and agriculture to broader audiences.

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