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The KBS LTER Site: Long-term Ecological Research in Row-crop Agriculture

Project Summary

In 1987 we initiated the KBS Long-term Ecological Research Project in Row-crop Agriculture to examine basic ecological relationships in field-crop ecosystems typical of the US Midwest. Our goal was – and remains – to test the long-term hypothesis that agronomic management based on knowledge of ecological interactions in cropping systems can effectively replace management based on chemical inputs. We established a major field experiment comprising 11 different cropping systems and unmanaged successional communities, corresponding to different levels and types of ecological structure and disturbance and including biologically-based and conventional agricultural management. Within these systems we test hypotheses related to the patterns and processes that underlie ecosystem productivity and environmental performance. Working hypotheses are built around the general topic areas of plant community dynamics, soil microbial populations, insect predator-prey relationships, watershed and field-scale biogeochemistry, human interactions, and regional ecological processes.

Intellectual Merit: With this proposal we build on past work to formulate an integrated model of agricultural landscapes that thoroughly incorporates the interactions between human and natural systems. Our overarching theme for this next research phase is "Farming for ecosystem services in a changing environment," reflecting our desire to understand the full suite of ecosystem services associated with agriculture, including mitigation of undesirable environmental impacts. We propose to focus on responses of the coupled human and natural systems to changing external drivers, including climate change, agricultural intensification (land use alterations), and shifts in global markets.

We use a pulse-press disturbance model to delineate the biophysical interactions in agriculture that produce ecosystem services *vis a vis* human systems. Humans translate perceptions of these services into management decisions and activities, which in turn feed back to affect agricultural production systems and the landscape in which they are embedded, i.e. the biophysical realm. Our research activities are organized into Biogeochemical Dimensions, Biodiversity Dimensions, and Human Dimensions, but are interlinked through biophysical and socioeconomic modeling at multiple scales. We have positioned our research to apply to cellulosic biofuel cropping systems – in addition to food crops – as biofuel crop production is poised to drive a major reorganization of US agriculture to meet future energy needs.

Broader Implications: Our research bears directly on agricultural and environmental management and policies at scales ranging from local (e.g. soil and water conservation) to global (e.g. climate stabilization). Training of graduate students and postdocs will continue to be a major outcome as will providing research experiences for undergraduates. Our work with K12 science teachers continues an established partnership with 11 nearby school districts. Outreach and extension activities reach a diversity of stakeholders through programs designed to meet diverse but targeted needs. Scientific results are not only published in journals but also are frequently communicated directly to lawmakers and management agencies. We anticipate that our research results will be increasingly influential as we enter a new era of carbon markets and escalating interest in mitigating the climate change impacts of agriculture.

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1.0 Results from Prior Support

1.1 Overview

Since 1987 LTER research at KBS has sought to better understand the ecology of intensive row-crop agriculture, with an emphasis on the corn, soybean, and wheat crops that dominate the North Central region of the US (Fig. 1) and have a correspondingly huge impact on human and environmental welfare. Although components of agricultural systems are intensively studied worldwide, much of our understanding comes from highly disciplinary studies conducted in isolation from one another (Robertson and Swinton 2005). Consequently, our understanding of row-crop agriculture and it surroundings *as interdependent ecosystems* is fragmented and incomplete and many of the associated environmental problems remain intransigent (Matson et al. 1997, Tilman et al. 2002, Robertson et al. 2004, Robertson & Vitousek 2009). Climate change and new demands for agriculture to produce both food and fuel (Robertson et al. 2008, Tilman et al. 2009) increase the need for systems-level agricultural research.

At KBS we have built a long-term integrative research program to examine key components of row-crop ecosystems. We do this by integrating results from experimental studies with a multi-decade record of baseline observations in a comparative, landscape-level framework. Our initial focus was on the biophysical underpinnings of ecological processes in row-crop ecosystems. In 1998 we added watershed biogeochemistry (e.g. Hamilton et al. 2001), and in 2004 we added an economic valuation component (Swinton et al. 2007a, b). Since 2004 our work has been guided by a conceptual model (Fig. 2) that integrated our activities around the concept of ecosystem services delivered by agriculture. In the present proposal (see Section 2) we continue and extend our focus on understanding the basic ecology of agricultural ecosystems and landscapes, and we incorporate key research linkages between ecological and social systems in these landscapes. This integration of ecological and social systems is critical to address long-standing environmental and productivity challenges in row crop agriculture.

Our original global hypothesis, still relevant today, is that agronomic management based on ecological knowledge can substitute for management based on chemical subsidies—without sacrificing the high yields that modern agriculture provides for society (Fig. 3). Most of our specific hypotheses have been addressed in the context of the simple experimental design of our Main Cropping System Experiment: replicated systems along a management intensity gradient that includes four annual cropping systems (corn-soybean-wheat rotations ranging from conventional to biologically-based management), two perennial cropping systems (alfalfa and hybrid poplar trees), and a set of early to late-successional unmanaged communities (Figs. 4, 5).

The power of this design lies in the wide range of differently managed, replicated experimental communities where long-term measurements of ecological processes are supplemented by short- and long-term experiments to test mechanistic hypotheses. We also conduct landscape level sampling to address questions related to water quality (Hamilton 2010) and pest suppression services (Landis et al. 2008).

In 2006 we added a major scale-up experiment designed to determine the presence of non-linearities in scaling from 1-ha field plots to commercial-sized farm fields. The scale-up includes all entry points of three main-site management treatments (conventional, low-input, and biologically-based), with all rotation phases every year and each replicated three times (27 fields), and is managed by the KBS Dairy (Fig. 6). Comparisons of agronomic and ecological factors between these fields and our 1-ha experimental plots are used to address questions related to the scaling of ecosystem services delivery, as well as the economic returns from different treatments as viewed from the farmer's perspective (Swinton et al. 2006).

In 2008 we expanded our research with major funding from DOE to include potential biofuel crops. This expansion builds on our longstanding comparisons of annual and perennial cropping systems, and includes experimental cellulosic and grain-based biofuel cropping systems (Fig. 7) designed to examine the delivery of and trade-offs among agronomic, biogeochemical, and biodiversity services.

1.2 Agronomic Services

Agronomic productivity is central to the study of agricultural systems—management options that do not produce sufficient yield are not adopted. Agronomic yields from our conventionally managed rotations have been consistently close to average for non-irrigated row crops in both Kalamazoo County and the 12-state North Central Region as a whole, except during drought years (e.g. 2008; Fig. 8). Significantly, relative yields in our reduced-input and biologically-based treatments (T3 and T4 in Fig. 4) have been close or identical to yields in our conventionally managed treatment for corn and soybean (Fig. 9). In contrast, wheat yields are lower in our reduced-input (10% lower) and biologically-based treatments (40% lower) relative to conventional management (Fig. 9). This may be due to the absence of a preceding N-fixing winter cover crop as fall-planted wheat precludes the potential for an additional over-winter crop that fixes nitrogen. Individual crop yields are reflected in overall treatment results: overall grain yield is highest under no-till management, followed by conventional management, with the reduced input and biologically-based treatments somewhat lower (Figs. 9, 10).

Agronomic yields, however, are not the sole determinant of the value of a row-crop production system. Analysis of the energetic efficiency of alternative cropping systems can be used to determine their overall environmental impact and can inform decisions about the best use of land for agricultural production. Food vs. fuel debates have drawn increasing attention to these issues and our long-term results can be used to compare the energy balance of alternative cropping systems for both food and fuel. Such an analysis (Gelfand et al. 2010; Fig. 10) shows a large range in average annual farming *energy inputs* and *food energy outputs* from various farm management scenarios. While the conventional system had both high energy inputs and food energy outputs, the no-till system out-yielded it using two-thirds of the energy inputs. High tillage intensity accounts for most of the difference. Gelfand et al. (2010) also showed that the *energy efficiency* (energy output: input ratio) was always higher for food production than for liquid fuel production from the same crops, even when crop residues are used for fuel.

We have also examined the climatic controls of corn and soybean yield across the US corn belt (Fig. 11a) as part of our focus on how regional processes and climate change can affect ecosystem services. We compiled crop yield and climate observations for a 30-year period (1971–2001) for the 1053 counties in the North Central Region and used this to develop a simple crop stress index (Gage and Mukerji 1978, Gage 2003). This index is based on climate variables that are readily available – daily maximum and minimum temperatures and precipitation – so this approach has broad potential for evaluating plant stress probability. The stress index predictions for corn yields (Fig. 11b) and soybeans have been integrated into models to project the impacts of climate change on agriculture, and to support development of carbon markets (Grace et al. 2006a and 2006b; Gage and Safir 2010).

1.3 Biogeochemical Services

Greenhouse gas mitigation

Agriculture is responsible for about 8% of total greenhouse gas (GHG) production in the US (EPA 2009), and it has the possibility to mitigate an even higher percentage owing in part to the potential for agricultural soils to sequester carbon (CAST 2004, IPCC 2007). Sequestration must be evaluated in the context of all GHG sources and sinks within managed ecosystems, however, because management practices affect various gases differentially (Robertson 2004). We continue to measure carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) fluxes in all of our cropped and unmanaged systems in order to better understand long-term trends (Robertson et al. 2000, Grandy et al. 2006) in the context of ecosystem development and climate change, as well as soil carbon change in both surface and deep soil on account of management (Grandy & Robertson 2006 & 2007; Loecke & Robertson 2009; Senthilkumar et al. 2009; Syswerda et al. 2010b).

Of greatest significance in this past six year period has been the discovery of a non-linear relationship between N_2O flux and N fertilizer rate. IPCC national greenhouse gas inventories (IPCC 2007) assume a linear relationship based on scores of +/- N fertilizer experiments that show ~1% of added N is later emitted from soil as N_2O. Using a fine-resolution fertilizer gradient we have shown for both corn (McSwiney & Robertson 2005) and wheat (Millar et al. in review) that N_2O fluxes are low at fertilizer-N levels below those at which yields are maximized, and substantially higher at fertilizer-N levels above crop needs (Fig. 12). We have confirmed this relationship for corn grown on-farm at four locations in

Michigan over the 2007 and 2008 field seasons (Hoben 2009; Hoben et al. in review), and have proposed an IPCC Tier 2 N_2O mitigation protocol for fertilized corn in the US Midwest (Millar et al. 2010) that shows a potential for reducing N_2O fluxes from agriculture in the region by >50%. We are presently working with a major offset developer to submit the protocol to the VCS carbon registry, as well as incorporating the data into regional models (Grace et al. 2006a, 2006b) and a web-based GHG calculator for use by farmers, educators, offset developers, and others (McSwiney et al. 2010a).

Water quality

Environments interact at the landscape scale through the surface and subsurface fluxes of water, and provision of high-quality water is an important ecosystem service of agricultural landscapes. The central question of our landscape biogeochemistry component has been "How do current and future land use and landscape patterns affect water quality and quantity?" Since 1999 we have measured hydrochemistry (major solutes and nutrients) at key points along hydrologic flow paths, including infiltrating soil water, ground waters, streams, wetlands, and lakes (Hamilton 2010; Fig. 13).

Understanding how managed and unmanaged soil-vegetation systems affect the quality of water percolating into the unsaturated zone is key to mitigating some of the undesirable effects of agriculture. Kurzman (2006) and Jin et al. (2008a, b) analyzed the evolution of soil water chemistry from precipitation through the root zone. Hamilton et al. (2007) focused on pathways of carbonate mineral dissolution in soils and groundwater systems, specifically examining the GHG contribution of agricultural liming materials, an important part of agriculture's influence on climate. And measured NO_3^- concentrations in soil water beneath the root zone were combined with modeled soil water export to provide estimates of NO_3^- leached from the root zone over 11 years of cropping (Syswerda et al. 2010a). Results (Fig. 14) show significant differences in nitrate export along our management gradient, with highest leaching from the conventionally tilled treatments and vanishingly small rates from our early successional system, with intermediate fluxes elsewhere (Fig. 14). Lower leaching in our annual crops was associated with no-till, cover crops, and biologically-based management; the very low leaching from perennial vegetation suggests that cellulosic biofuel crops may little affect water quality (Robertson et al. 2010a).

Excess NO_3^- leaching to groundwater leads to greater NO_3^- loading of surface waters, but much of this N may eventually be denitrified to N_2O or N_2. The role of streams and wetlands in attenuating N export from agricultural landscapes has been a topic of recent KBS research projects associated with the LTER project. Hamilton was a co-PI of the Lotic Intersite Nitrogen Experiment (LINX), which investigated nitrogen cycling in headwater streams across the US using a coordinated set of whole-stream stable isotope additions (Fig. 15; Peterson et al. 2001; Webster et al. 2003; Mulholland et al. 2008 , 2009; Hall et al. 2009). Streams around KBS represented the upper Midwest US for LINX (Hamilton et al. 2001 & 2004, Raikow et al. 2001, Arango et al. 2008, Beaulieu et al. 2008). Novel N uptake processes were the subject of recent study in KBS wetlands, streams, and lakes (Whitmire & Hamilton 2005), leading to a focused research effort at KBS on the role of sulfur oxidizing bacteria in nitrate uptake (Burgin & Hamilton 2007, 2008, Payne et al. 2009). Whitmire & Hamilton (2008) compared rates of anaerobic metabolism (denitrification, iron reduction, sulfate reduction, and methanogenesis) in hydrologically diverse wetlands.

1.4 Biodiversity Services

Microbial diversity and function

Microbes are key regulators of ecosystem services related to soil fertility, nutrient cycling, and GHG fluxes. New molecular tools provide a rich opportunity to explore how microbial diversity could be managed to enhance ecosystem services, including long-term opportunities for climate stabilization via greenhouse gas (GHG) abatement. The dramatic diversity of microbes in soil (up to 10^6 species g^{-1}; Gans et al. 2005), presents considerable technical and theoretical challenges to understanding their ecosystem functions. Fortunately, however, the recent development of massively parallel pyrosequencing offers an unprecedented opportunity to explore genomic complexity in soil, including novel views of both dominant members and the "rare biosphere" (Sogin et al. 2006). We used this technology to characterize soil microbial communities across our main site treatments and found surprisingly few differences in the bacterial phyla (Fig. 16) or species richness (> 97% identity in 16S rRNA gene sequences; Levine et al., in review). As with other studies of bacterial diversity in soil (Janssen 2006), the phyla Proteobacteria and Acidobacteria were most abundant (~75% of total bacteria). However, there were dramatic and reproducible differences at the species level, especially for Proteobacteria, the most abundant phylum (Fig. 17) and the one that includes the majority of species that catalyze methane (CH_4) consumption and N_2O production.

Detailed molecular surveys of the methane-oxidizing bacteria (methanotrophs) show a remarkable correspondence to rates of methane consumption (Robertson et al. 2000, Suwanwaree & Robertson 2005) along our cropping system gradient: methanotroph diversity is monotonically related to summertime methane oxidation (Fig. 18). Both are lowest in cropped fields and high in late successional forests. The observation that CH_4 consumption and methanotroph diversity increase with successional age of a community suggests that managing lands to conserve or restore methanotroph diversity could help mitigate increasing emissions of this potent greenhouse gas (Levine et al., in review).

We are also using metagenomic tools—large scale sequencing of soil DNA—to assess changes in the genetic composition of entire microbial communities across LTER treatments. An early result of this analysis is the discovery of a previously unknown systematic artifact in metagenomes (Gomez-Alvarez et al. 2009), for which we provide an on-line tool for its removal—a critical step in making quantitative comparisons of metagenomes (http://microbiomes.msu.edu/replicates).

Corrected metagenomic data from the KBS LTER reveal dramatic differences in the abundance and composition of denitrifying bacteria, the microbes that likely are responsible for most production of N_2O at KBS (Ostrom et al. 2010) and elsewhere (Robertson & Groffman 2007). There are differences in the overall abundance of denitrifiers across treatments (higher in row crops), but also in the composition and relative abundance of specific denitrifier species (Huizinga 2006).

Plant community dynamics

Questions about relationships among cropping system diversity, weed communities, and yield led to the establishment in 2000 of the Biodiversity Gradient Experiment (Fig. 19), which allows us to experimentally test for biodiversity effects (Smith et al. 2008, Smith & Gross 2007; Fig. 20). This work has catalyzed integration across the project to explore the relationships among cropping system diversity, plant community composition, and the ecosystem services provided by insect predators (Costamagna et al. 2008) and microbial communities (see above). For example, the higher yields we observe in corn in more diverse cropping systems correlate well with early spring N levels (Fig. 21, Smith et al. 2008).

Unexpectedly, our long-term studies of plant diversity in successional communities are providing fundamental insights that inform the development of new biofuel cropping systems. In particular, our findings elucidate the relationship between plant diversity and aboveground productivity (ANPP) in a variety of US grassland communities (Gross et al. 2000), and the effects of N enrichment on species loss (Gough et al. 2000, Suding et al. 2005, Clark et al. 2007). This cross-site work shows that reductions in plant species diversity following N enrichment are caused by a combination of environmental factors, including the responsiveness of ANPP to fertilization (Fig. 22; Clark et al. 2007), and that aggregate species traits are important predictors of species loss (Suding et al. 2005). This has important implications for the maintenance of biodiversity services in fertilized, mixed-species biofuel systems, as well as for management and restoration of native grasslands in the face of N deposition (Suding et al. 2004, Suding & Gross 2006, Gross & Emery 2007). Importantly, the cross-site Productivity-Diversity-Traits Network (PDTNet) has compiled, synthesized, and published (Cleland et al. 2008) data on responses of over 300 plant taxa to N-fertilization experiments across 10 North American sites (Fig. 23) that can be used for future species- and trait-based analyses of grassland community responses to N deposition.

Insect dynamics

Arthropods provide valuable ecosystem services in agricultural landscapes, including pollination and pest suppression (Isaacs et al. 2009). In prior studies we demonstrated that the invasive soybean aphid (*Aphis glycines* Matsumura)—the most significant threat to soybean production in the US—is regulated by top-down factors across a range of agricultural management intensities (Costamagna & Landis 2006). While a large community of natural enemies preys on these aphids (Kaiser et al. 2007, Pike et al. 2007), two coccinellids in particular—*H. axyridis* and *C. septempunctata*—play key roles both as direct predators of aphids and as intraguild predators on a variety of other predators and parasitoids (Fig. 24; Costamagna et al. 2007 & 2008; Gardiner & Landis 2007). However, because the direct effect of resident predators and parasitoids on aphids is small, intra-guild predation does not cascade down to protect soybean yield. Instead, transient coccinellids who migrate into agricultural fields from the surrounding communities exert strong direct effects on aphids and drive a trophic cascade that leads to increased yield (Costamagna et al. 2008).

We have found that landscape structure significantly affects coccinellid diversity and abundance (Gardiner et al. 2009a) and the potential to provide biocontrol services (Gardiner et al. 2009b). In particular, landscapes with high corn and soybean production have low habitat diversity and significantly reduced biocontrol services (Fig. 25). This analysis allowed us to calculate the value of biodiversity for aphid protection in these landscapes. Natural suppression of aphids was potentially worth ~\$33 ha^{-1} in increased yield and decreased pesticide in 2007 to producers; this summed to >\$239 million y^{-1} for the four Midwestern states studied (Landis et al 2008). And biofuel-driven growth in corn acreage in 2007 resulted in lower landscape diversity, altering the supply of coccinillids to soybean fields and reducing biocontrol services by 24%—costing soybean producers \$58 million y^{-1} (Landis et al. 2008).

1.5 Valuation of Ecosystem Services

Our human dimensions research since 2004 has focused on the economic valuation of ecosystem services—in addition to crop yield—that are associated with row-crop agriculture. We initiated this work with a national workshop at KBS in 2005, and the ensuing special issue of *Ecological Economics* (Swinton et al. 2007a) highlighted how agriculture not only depends upon supporting services (Zhang et al. 2007), but also provides services beyond the basic provision of yield (Swinton et al. 2007b). Apparent from this work is the importance in agricultural systems of valuing the supply side of nonmarketed services; in contrast, most environmental valuation research to date—based largely on services provided in nonagricultural systems—explores consumers' willingness to pay (Wossink & Swinton 2007).

Our research shows that farmers' willingness to adopt practices that generate non-marketed ecosystem services depends on both direct and opportunity costs. Enterprise budgets for our main cropping system experiment show that farmers face trade-offs between reduced profitability and enhanced provision of greenhouse gas mitigation and water quality services from certain low-input systems (Jolejole et al. 2009a). A 2008 contingent valuation survey of 2,000 Michigan corn and soybean farmers found that these profitability tradeoffs mean that most farmers would need payments to adopt low-input cropping systems similar to those at KBS (Jolejole et al. 2009b). The more farmers are asked to change their current systems, the higher the payment they would require to change.

On the demand side, results from a 2009 survey of over 2,400 Michigan households indicate significant public willingness to pay for mitigating lake eutrophication and global warming through payments to land managers for changed practices (Chen et al. in prep). A key challenge for future research will be how to link citizen willingness to pay for individual ecosystem services with farmers' needs to cover additional costs of changed farming practices that produce enhanced ecosystem services.

Economic valuation of natural pest biocontrol services was undertaken using bioeconomic modeling of the invasive soybean aphid pest complex described above (Landis et al. 2008). We demonstrated the value of natural biocontrol via its effect on raising the economic threshold for insecticide application to control damaging aphid infestations (Zhang & Swinton 2009). These benefits suggest potential demand by farmers for setting aside habitat for natural enemies of pests. However, the value of these benefits can be too readily offset by the costs of removing land from production as well as farming around natural habitat, especially when it impedes mechanized equipment (Zhang et al. 2010).

1.6 Publications and Published Datasets

Publications and long-term datasets are listed in Supplemental Tables 1 and 2, respectively.

2.0 Proposed Research

2.1 Conceptual Framework

The long-term core hypothesis of the KBS LTER as originally articulated in 1987 (Fig. 3) can be recast as two overarching questions that describe our proposed future research:

1) How are ecological relationships in row-crop systems and surrounding landscapes altered by changes in the biophysical and socioeconomic environments?

2) In the face of these changes, to what extent can row-crop systems and surrounding landscapes be managed to sustain productivity and the delivery of diverse ecosystem services?

Over the past 22 years of LTER research we have learned much about the organisms and processes responsible for the productivity of our row crops, mostly by field experimentation and comparisons with nearby unmanaged sites in different stages of succession (see Figs. 4, 5 and Section 1 for more on experimental design). We have gained a better understanding of the environmental consequences of different management strategies at scales ranging from small fields to the surrounding landscape to the region. Our results reinforce our understanding that row-crop ecosystems, despite aboveground simplicity, are as ecologically complex as many other ecosystems subject to periodic disturbance. We have also demonstrated ways that biological management can largely replace chemical inputs without penalizing yields, and exposed some of the biogeochemical challenges associated with low-input cropping.

For this next phase of research at KBS we propose to sustain our core, long-term examination of ecological interactions in row-crop agriculture and continue our investigation into how these systems interact with the broader environment, further probing the mechanisms that underlie patterns that have emerged in the project's first 22 years. Additionally, we propose a greater emphasis on ecosystem services as affected by interactions between biophysical and social processes, and a focus on how this integrated human-natural system will respond to changing socioeconomic and biophysical drivers. The theme that embodies our new directions is *Farming for services in a changing environment.*

Our conceptual model underpinning this theme (Fig. 26) is intentionally designed to fit into the strategic research framework of the LTER Decadal Plan (LTER 2007), as articulated in Collins et al. (2007, 2010). Research on agricultural ecology fits naturally into this framework. Our conceptual model highlights the coupling between human (socioeconomic) systems and the cropping systems and landscapes in which they reside, and reflects our desire to balance our attention between both human and natural elements and their interacting linkages.

Ecosystem services link the natural system to human welfare (Fig. 26), and we refer to the altering of agricultural practices to improve the delivery of ecosystem services as "farming for services." Food production is, of course, the primary service provided by agronomic systems to humans, but increasingly society is recognizing the importance of other services such as improved water quality, the protection and enhancement of biodiversity, climate stabilization including carbon sequestration, and social amenities such as verdant landscapes and agrotourism (Robertson and Swinton 2005). In the case of agriculture we may seek practices that mitigate undesirable effects, i.e., "mitigation services" (Swinton et al. 2006 and 2007). An example would be management practices that decrease export of fertilizer nitrogen to the broader environment to reduce nitrogen pollution of ground water and nitrous oxide emission to the atmosphere.

Drivers of change that affect both human and natural systems occur on scales from local to landscape to global, and these comprise the "changing environment" on which we focus our future research. The changing environment is complex and includes alterations in climate, commodity markets, human population and land-use, and social and regulatory environments as well as new developments in agricultural technology such as genetically modified crops. These drivers of change can be broadly classified into either "pulse" or "press" disturbances, depending on whether they occur as discrete events or as gradual changes over a more protracted period, respectively (Collins et al. 2010). They may act alone or synergistically to affect how we farm, where we farm, the profitability and sustainability of farming, and the short- and long-term impacts of agricultural activities on the environment at scales from local to global.

Our research to date has emphasized developing an ecosystem-level understanding of ecological structure (e.g. organisms and their adaptations, population and community assemblages, and habitat structure) and function (e.g. biogeochemical processes, energy capture and flow, and hydrologic dynamics). Linkages between ecological structure and function largely define the mechanisms that support the production of ecosystem services. We have also considered how the ability of row-crop systems to provide these services is affected by factors at scales beyond the field level. Watershed position and landscape complexity can affect many of the linkages between ecological structure and function, and all of these interactions operate in both the biophysical and socioeconomic realms.

Our new conceptual model (Fig. 26) is an expansion of our earlier models that were more focused on ecosystem structure and function (e.g. Fig. 2). Organisms and their interactions as well as ecosystem processes remain important organizational constructs for the project. The main groups of organisms providing biological structure in the row-crop ecosystem include microbes (as they control organic matter and nutrient availability and loss), plants (as they compete for resources and provide habitat and carbon for heterotrophs), insects and pathogens (as they affect plant productivity), and humans (as they intentionally and unintentionally create biophysical and chemical disturbance). Each of these groups has been a focal area of research, and – together with watershed biogeochemistry and regionalization research thrusts that were added in 1998 – they constitute the core research areas of the KBS LTER. In this renewal we focus more effort on interactions and integration among these core areas in order to generate a comprehensive understanding of the drivers and dynamics for the overall coupled human-natural system.

The emergence of a major cellulosic biofuels industry – one of the most important potential changes in US agriculture since 1950 – is expected to occur over the next several decades, and we are positioning our research to inform its development and understand its consequences. Large-scale biofuel crop production will have far-reaching impacts on the structure and functioning of US landscapes, including current agricultural areas and landscapes that are not today under agricultural management (Robertson et al. 2008, Tilman et al. 2009). Whether this industry will be developed with an emphasis on the delivery of diverse ecosystem services or whether it will be simply an extensification of "business as usual" with its attendant environmental liabilities, is very much at play (Howarth et al. 2009). Cropland in the US covers 180 million hectares (ERS 2009); conservative estimates of the land needed to produce the 440×10^6 MT of biomass needed to meet 40-year biofuel projections are ~50 million ha (NRC 2009, Robertson et al. 2010). Even were the 15 million ha of conservation reserve (CRP) land harvested for biomass, the remaining land requirement is substantial, especially in light of the need to increase food production for a burgeoning global population that is ever more affluent.

As noted in Section 1, we have integrated a major new biofuels experiment into our long-term cropping system portfolio, and many of the questions outlined below will utilize the integrated design. The new experiment includes a set of candidate biofuel crops established in a randomized complete block design (Fig. 7). Included are conventional annual row crops (continuous corn and a corn-soybean-canola rotation), as well as cellulosic crops in monocultures (switchgrass, *Miscanthus giganteus*, hybrid poplar trees) and in polycultures (mixed-species native grasses, successional vegetation, and restored native prairie). We are also establishing larger scale-up fields of continuous corn, switchgrass, and restored prairie on both existing cropland and on land that has been in CRP for 20 years. This expansion of LTER at KBS has been underwritten with funding from DOE; once this funding expires (2012 or 2017), long-term maintenance will continue with LTER funds.

2.2 Major Focal Areas

We have organized our LTER research for the coming six years into three focal areas: Biogeochemical Dimensions, Biodiversity Dimensions, and Human Dimensions. Biogeochemistry and biodiversity together form the underlying basis for crop productivity and the delivery of other ecosystem services and for the major environmental consequences of intensive agriculture. Interactions with humans – as recipients of the services provided and as putative managers of many of the pulses and presses that drive the biogeochemical and biodiversity actors – largely determine the quality, magnitude, and rate at which services are delivered. Each of these foci extends from local to landscape or regional scales, and collectively they encompass the major core research areas in our conceptual model (Fig. 26). Integration among these foci and the synthesis of integrated results is a core part of our research design, with modeling to provide an additional extension to the regional context.

Biogeochemical Dimensions

Our research into the biogeochemical dimensions of cropped landscapes is aimed towards understanding the magnitude and quality of services provided by biogeochemical processes and their underlying controls in agronomic systems – including interactions with biodiversity and human management.

Biogeochemical services are among the most notable of those produced by agriculture, and all are sensitive to changes in climate and land use in sometimes complex ways. Adequate provision of nitrogen, phosphorus, and other essential elements to plants is a principal factor underpinning today's high crop yields (Lobell et al. 2009, Vitousek et al. 2009), and keeping these nutrients within the cropping system and out of the larger environment provides an additional service in the form of avoided environmental and human health and welfare costs (Swinton et al. 2007b). Carbon stored in soil provides myriad services ranging from improved water holding capacity to food web support to climate mitigation (CAST 2004). Nitrogen lost to ground and surface waters (particularly as nitrate – NO_3^-) is implicated in the eutrophication of marine coastal zones (Bricker et al. 2007); nitrogen lost to the troposphere traps heat (N_2O) and creates ozone (NO_x), and N_2O that makes it into the stratosphere attacks compounds that protect the earth's surface from biologically harmful UV_b radiation (Robertson & Vitousek 2009, Wuebbles 2009). Phosphorus washed from crop fields causes eutrophication of inland surface waters (Haygarth 1997), and erosion of agricultural soils into streams and rivers remains a major sedimentation issue (Syvitsky et al. 2005).

As described in Section 1, biogeochemistry at KBS has largely focused on soil carbon, nitrogen use efficiency, and greenhouse gas fluxes at the field scale, and on the fluxes of water and nutrients from uplands to lakes, streams, and wetlands at the landscape scale. Work at these two scales began as independent investigations but over time they have increasingly been linked by new work on water fluxes in the unsaturated zone and by advances in groundwater flow modeling, both of which are described later in this section. Another cross-scale linkage is our effort to regionalize our greenhouse gas flux modeling.

Terrestrial biogeochemistry (G.P. Robertson, lead)

We propose to sustain our long-term measurements of important biogeochemical pools and fluxes in our intensive field experiments, and particularly on C and N fluxes, to continue to provide insights that can only be derived from long-term observations of these processes. We now have one of the longest available records of soil carbon change, nitrate loss, and greenhouse gas fluxes under alternative crop management systems, which together have informed discussions of carbon and nitrogen change in response to long-term no-till and organic management (Grandy et al. 2006; Syswerda et al. 2010a, 2010b) and climate change (Senthilkumar et al. 2009).

Importantly, for example, our first decadal sampling of soil carbon pools to 1-m depth showed significant accumulation in some surface horizons but no change in subsurface carbon pools (Syswerda et al. 2010a); our second sampling is due in 2010 and will further help to clarify the current debate about whether no till accumulates carbon or simply redistributes carbon within the profile (Baker et al. 2007, Blanco-Canqui & Lal 2008, Franzluebbers 2009, Kravchenko & Robertson, in review). Likewise, we have found continued, even accelerated loss of soil carbon from the surface horizons of our long-cultivated treatments over the past two decades (Senthilkumar et al. 2009); this finding challenges the long-held assumption that temperate soils cropped for >100 y have necessarily equilibrated with respect to non-erosion carbon change. These changes appear to be associated with slightly higher wintertime temperatures and a presumed greater incidence of the freeze-thaw cycles known to break up soil aggregates, which are a principal mechanism by which carbon is protected from microbial oxidation in KBS soils (Grandy & Robertson 2007) and are also a source of soil microbial diversity (Blackwood et al. 2006, Smucker et al. 2007). We will further pursue this finding in the coming funding cycle, with experiments designed to examine the effects of future cryosphere change (changes in wintertime ice and snow cover) both on soil carbon sequestration as well as on seasonal changes in microbial communities and plant-microbe interactions, as described below (*Biodiversity Dimensions*).

A second long-term finding that has emerged only recently is the importance of long-duration plant cover in cropping systems for providing multiple services including carbon sequestration and nitrogen conservation (Drinkwater & Snapp 2007). So-called perennialization can be achieved by cultivating perennial crops or by using winter cover crops planted to provide green cover from late fall through spring plowing. The cover crop provides additional biomass production that ordinarily does not occur between crop senescence in early fall and the onset of crop growth the following spring, and carbon so captured during this period is returned to the soil as soil organic matter (SOM) when the cover crop is killed. Some portion of the SOM provides carbon to long-term soil carbon pools (Syswerda et al. 2010b), thereby providing a climate stabilization service. Another portion serves to buffer the delivery of nitrogen to the succeeding crop by releasing captured (immobilized) nitrogen at a more measured rate than would be the case were the nitrogen applied as inorganic fertilizer (McSwiney et al. 2010b). And where the cover crop is a nitrogen-fixing legume, the nitrogen captured from the atmosphere can reduce the need to provide fertilizer N – we estimate that cover crops in our reduced input and biologically based treatments provide up to 80 kg N/ha annually, a substantial fraction of the fertilizer-N applied in our conventional management treatment. Cover crops can also solubilize phosphorus for crop use (Gallaher & Snapp, in review).

Perennialization further serves to protect groundwater from excess nitrate leaching. In both our reduced input and biologically-based management treatments, long-term (11 years) nitrate loss beginning 5 years post-establishment was substantially less than loss from our conventionally managed and no-till treatments (Fig. 14) – perhaps mostly due to lower drainage in these systems on account of the additional transpiration by cover crops in the fall and spring, but in part due to capture of residual nitrogen left in the soil from the preceding crop cycle (Syswerda et al. 2010a). We are now also measuring nitrate loss from crops that are intensively instrumented for water flux (see below), and will continue these measurements in the next phase of LTER research in order to better understand the source – and management options – for nitrogen use efficiency in alternative cropping systems. And related to perennialization is the potential for developing perennialized varieties of annual crops (Snapp 2008). Perennial wheat (Glover et al. 2007) is the most promising of these potentials, and we have integrated a perennial wheat treatment into the Living Field Lab Experiment (Section 2.4) to identify the environmental and agronomic potentials of a 3-4 year perennial wheat rotation.

A third area in which our long-term findings have been noteworthy is at the interface of agriculture and climate change. In US row crops, agricultural activities affect climate change primarily through land use conversion and management activities that affect soil carbon storage, nitrous oxide (N_2O) emissions, methane (CH_4) consumption, and other practices that emit or consume greenhouse gases such as agricultural lime application (Hamilton et al. 2007). Agricultural activities are directly responsible for about 8% of US greenhouse gas emissions (EPA 2009), but could mitigate significantly more than this were knowledge and incentives available to do so (CAST 2004).

At KBS we have been at the forefront of efforts to identify potentials for agriculture to contribute meaningfully to climate stabilization (Richter & Mobley 2009), mainly through our efforts to understand soil carbon change (above); nitrous oxide fluxes from both cropped fields (Robertson et al. 2000, Grandy & Robertson 2006, Grandy et al. 2006, Ostrom et al. 2010) and the streams that drain them (Beaulieu et al. 2008, Mulholland et al. 2008); and soil methane consumption (Robertson 2000, Suwanwaree & Robertson 2005, Levine et al., in review). We have also put considerable effort into constructing whole-system greenhouse gas (GHG) balances in order to compare and contrast the magnitude of sinks and sources of GHGs under different management constructs (Robertson et al. 2000, Robertson & Grace 2004, Gelfand et al., in review).

We propose to build on these efforts and in particular to extend our understanding of GHG balances in row crops to include these balances in new biofuel crop production systems. A big unknown is the N_2O response of these new systems. There is the potential for fertilizer-derived N_2O fluxes to obliterate the putative climate benefit of biofuels – whether grain-based (Crutzen et al. 2008) or cellulosic (Melillo et al. 2009). And there are presently no data available from comparative studies documenting the N_2O response to fertilizer in different biofuel crop systems. Theory and long-term evidence from our early successional and hybrid poplar treatments (Robertson et al. 2000, Gelfand et al. 2010) suggest that N_2O fluxes from perennial systems fertilized at N-replacement rates should be very low. Preliminary evidence from our recently-established switchgrass N-gradient experiment suggests that this may not be the case (Fig. 27).

Our terrestrial biogeochemistry goals for the next phase of LTER research at KBS include:

1) Better understanding the consequences of climate change – and in particular of a warmer or more variable wintertime climate – on soil carbon and greenhouse gas dynamics, and the extent to which these changes are associated with changes in soil microbial communities;
2) Refining our understanding of how perennialization (cover crops in annual grain systems and perennial plants in cellulosic biofuel systems) can improve nitrogen use efficiency and organic matter gains;
3) Understanding the functional relationship between N fertilizer application rates and a) crop yield, b) N_2O and other greenhouse gas fluxes, and c) nitrate leaching to groundwater in emerging and candidate cellulosic biofuel crops such as switchgrass, *Miscanthus*, and restored prairie;
4) Using empirical results to better parameterize and validate models of biogeochemical responses to management, and refining web-based tools to estimate the climate forcing of agricultural practices based on LTER results and other studies (e.g. McSwiney et al. 2010a);
5) Refining our ability to conduct full-cost accounting of climate forcing by agricultural activities, with an eye towards building policy tools and methodologies that can be implemented in existing and emerging carbon markets (e.g. Millar et al. 2010);
6) Enhancing our comprehension of ecosystem services linked to biogeochemical processes and how agronomic management can positively affect these services (Swinton et al. 2007);
7) Regionalizing our results by linking predictive models derived from KBS LTER data to spatial data sets and modeling (e.g., Grace et al. 2006a), providing guidance for policy and revealing aggregate benefits at larger scales (Grace et al. 2010).

Ground and surface water biogeochemistry (S.K. Hamilton, lead)

The central questions of our landscape biogeochemistry component have been and will continue to be "In complex agricultural landscapes, 1) how do land use patterns and management practices affect the fluxes of water and nutrients to lakes, streams, and wetlands and 2) how are fluxes altered in transit?" We can now add climate change to the drivers of change that we are considering, particularly through its influence on landscape water balances and surface-water hydrology. Agriculture directly affects water quality and quantity because it is a major contributor of nutrient and sediment loading to surface waters (e.g. Böhlke 2002) and influences landscape water balances (e.g. Hyndman et al. 2007). Ecosystem services provided by agricultural systems include "mitigation services" that reduce the negative impacts of conventional intensive agriculture on water quality and quantity.

We propose to continue our current work on wetlands, streams, and lakes – briefly described in Section 1 – and expand it to investigate how the biogeochemical cycles of C, N, P, Fe and S are coupled in ways that affect nutrient mobility and availability (Burgin et al., in review). Our current work has revealed how coupled nitrogen and sulfur cycling bears on the fate of excess nitrate delivered to surface waters via groundwater discharge (Burgin and Hamilton 2007, 2008), how microbially mediated transformations of iron and sulfur control phosphorus retention and release in aquatic sediments of shallow waters, and the role of fluctuating water levels in mobilizing stored phosphorus pools.

We will also continue to examine how wetlands situated along streams may contribute disproportionately to biogeochemical transformations that affect downstream water quality. While most national and international work– including the multi-site Lotic Intersite Nitrogen Experiment (LINX) study (Mulholland et al. 2008) – has focused on headwater streams, the majority of headwater streams in our region have wetlands and ponds along their flowpaths. We have sampled a number of these "through-flow wetlands" throughout the year and found consistent patterns of N removal (Fig. 28; O'Brien and Hamilton, in prep.). New approaches for whole-ecosystem tracer experiments in these types of water bodies are under development (O'Brien and Hamilton, unpubl. data) in order to resolve N transformations with the same degree of resolution provided for streams by the ground-breaking LINX work.

We are also pursuing strategies to answer a major unsolved question emerging from our LINX studies: What is the long-term fate of N that is assimilated by stream biota? This is important because LINX results indicate that on average only 16% of the total nitrate uptake is directly denitrified (Fig. 15; Mulholland et al. 2008), with the balance incorporated into algal and microbial biomass. Hence we need to know whether assimilated N is merely temporarily detained, to later be released as inorganic N, or if a substantial fraction of it is subject to eventual "indirect denitrification" via coupled remineralization-nitrification-denitrification (Seitzinger et al. 2006, Arango et al. 2008). We have conducted pilot studies to establish methods for in-situ stream isotopic labeling experiments that are designed to test hypotheses about the fate of assimilated N (O'Brien and Hamilton, in prep.). Innovative approaches to investigating the long-term fate of assimilated N were the topic of an LTER ASM workshop led by Hamilton and KBS investigator Jon O'Brien, and we will continue brainstorming on approaches at a follow-up workshop at the joint NABS/ASLO meeting in June 2010. This topic has the potential to become a cross-site study similar to LINX.

Our 2007 site review recommended enhanced linkages between our plot and field-based work and our ground- and surface-water biogeochemistry research. We have made considerable progress towards understanding landscape-level hydrology and biogeochemistry, but some important gaps remain to be filled. Linking terrestrial hydrology with landscape patterns of groundwater flow, and in turn linking groundwater discharge to aquatic ecosystem hydrology and biogeochemistry, requires a multifaceted approach that includes an understanding of:

1) *Terrestrial water balance of various landscape vegetation types:* Since 2008 we have initiated new work on the processes of infiltration and percolation leading to groundwater recharge, based on direct measurements of soil water in the root zone (0-2 m) using continuously monitored time-domain

reflectometry (TDR) profiles (Fig. 29) as well as periodic electrical resistivity imaging (ERT) of soil water over a greater range of depth and area (Fig. 30). This equipment is installed in 10 treatments of the biofuel crop experiment (including both conventional grain crops and cellulosic crops; Fig. 7) as well as in three unmanaged sites – a deciduous forest in early and late successional stages and a fallow field near one of our LTER unmanaged sites. The ERT work is conducted in collaboration with co-I's Remke van Dam and David Hyndman. Modeling the terrestrial water balance is being developed in collaboration with co-I Bruno Basso using his SALUS model, a DSSAT-based model of the soil-plant system that was developed for crops and is being broadened to include diverse plant communities (Fig. 14; Syswerda et al. 2010a, Basso and Ritchie 2010).

2) *Chemical changes as water moves through the unsaturated zone:* Work in the past funding cycle has generated a great deal of information on hydrochemical changes in the root zone (Section 1; Jin et al. 2008a, Hamilton et al. 2007, Hamilton 2010) but the changes that occur in the remainder of the unsaturated zone (below 2 m depth) are not well understood. A dissertation project is currently underway to investigate and model the role of denitrification as water moves through the unsaturated zone.

3) *Landscape patterns and time scales of groundwater flow:* Recent groundwater modeling has generated information on directions, rates, and time scales of groundwater flow in the vicinity of the LTER site (Fig. 31, Bartholic et al. 2007). Hamilton and Landis are working with co-I Shu-Guang Li to apply these models to biogeochemical and ecological research questions, including the role of groundwater discharge in sustaining fen wetlands of particular conservation interest.

4) *Chemical changes as water moves through the groundwater system:* Hydrogeologists typically infer biogeochemical processes in ground waters by measuring hydrochemistry in water samples from wells that intersect ground water at various depths and points along landscape flow paths (Böhlke 2002). There has been some work along these lines in two counties around KBS (Rheaume 1990, Kehew et al. 1996), and we have found interesting patterns in chemical data from wells on KBS property (Hamilton, unpubl. data). Nevertheless, we may need more site-specific information including age-dating of groundwater, which can now be accomplished using CFC gases as tracers (Böhlke 2002, Saad 2008), with measurements offered by service labs (e.g. http://www.rsmas.miami.edu/groups/tritium/order-cfc.html).

5) *Groundwater contributions to surface water bodies:* Our work on the ecohydrology of wetlands, streams and lakes has revealed how major solute tracers such as dissolved magnesium serve as indicators of the relative importance of groundwater contributions to surface waters in this landscape (Hamilton 2010). In addition, results from the terrestrial water balance (#1 above) and landscape groundwater flow modeling (#3 above) will be combined using the *Integrated Landscape Hydrology Model* (ILHM; Hyndman et al. 2007), which draws on hydrologic, geologic, landscape, and remote sensing data in a synergistic manner to assess temporal and spatial changes in hydrologic processes and surface-groundwater interactions.

6) *Biogeochemical and ecological implications of groundwater inputs to surface waters:* Surface waters in the KBS landscape are substantially affected by chemical inputs from ground water (Whitmire and Hamilton 2005, 2008; Hamilton et al. 2007, 2009; Hamilton 2010), and several important questions merit further study. In particular, do we understand the full range of biogeochemical and ecological impacts of increasing N loading via groundwater inputs to wetlands, streams, and lakes? Our ongoing research on coupled elemental cycles addresses one dimension of these impacts, but important knowledge gaps remain, including the effects of high N loading on wetland and aquatic plant communities.

7) *Effects of surface waters (streams, wetlands, lakes) on the biogeochemical signature of through-flowing waters:* The LINX studies and our recent work on wetlands shed light on N transformation and removal, and other work has examined P sources, transformations, and ecological impacts (Reid

and Hamilton 2007, Hamilton et al. 2009, Baas 2009). Hamilton (2010) synthesized existing information on other biogeochemical changes as water moves though the landscape.

Priorities for future LTER-related research include the terrestrial water balance (already underway), hydrologic modeling at multiple scales (beginning now), and linking this hydrologic information with the aquatic biogeochemistry (to follow the hydrologic modeling). Ultimately we seek the capability to apply the hydrologic/biogeochemical models at the landscape scale to generate scenarios of future responses to changing land use, agricultural crops and management practices, and climate change.

Biodiversity Dimensions

Biodiversity provides a range of ecosystem services in agricultural landscapes, some postulated and others known, ranging from pest and disease suppression to nutrient conservation to greenhouse gas abatement and wildlife amenities. Identifying and understanding the importance of biodiversity in most cases requires asking how biodiversity is related to ecosystem function.

Understanding the relationships and unraveling the mechanisms that link biodiversity and ecosystem function has been and remains an important research direction in ecology in general (MacArthur 1955, May 1973, Loreau et al. 2001) and for the KBS LTER specifically. For example, there is strong evidence from grassland experiments that increasing plant diversity improves some ecosystem functions (e.g. Hector et al. 1999; Tilman et al. 2001, 2006), but less is known about the mechanisms that underlie these improvements (e.g, niche complementarity vs. sampling effects). Likewise, there is a paucity of knowledge about how variation in plant diversity affects ecosystem functioning in natural ecosystems (Grace et al 2007; Cardinale et al 2007) or influences other trophic levels (e.g. Scherber et al 2006; Duffy 2002).

Predicted changes in global precipitation and temperature patterns, increased or continuing nitrogen deposition, and land use driven by a wide range of social and economic factors (Fig. 26) are also likely to affect biodiversity and modify the relationships among biodiversity and ecosystem services (Suding et al. 2005, Scherber et al 2006). In the next phase of LTER we propose to continue our measurements of plant, insect, and microbial biodiversity and explore the inter-relationships among these groups and their relationships to ecosystem function. We further propose to begin investigations of how changing drivers – climate and land use in particular – will affect the delivery of biodiversity services from row-crop landscapes.

As described below, climate questions will initially be addressed by examining effects of precipitation variation and warming on annual plant communities and the resultant impacts on other trophic levels and ecosystem processes. Climate driven effects on land use (at landscape scales) will be examined by measuring changes in beneficial and pest insects and their trophic interactions. We will also continue to conduct shorter term, manipulative experiments within the LTER landscape to test specific mechanisms that underlie the relationships between biodiversity and ecosystem services and how this may change in response to changes in external drivers such as climate and land use.

Plant productivity and diversity: Controls and impacts on consumers and decomposers (K. Gross, lead)

Deciphering the controls on net primary production (NPP) is a core research area of LTER and an increasingly important question for understanding ecological processes across biomes because NPP links ecological (population, community and ecosystem) and physical (climate, disturbance) processes. Predicted changes in nutrient inputs (particularly nitrogen deposition), precipitation (amount and temporal distribution), and temperature all will affect NPP (Smith et al 2009, Knapp et al. 2008, Weltzin et al 2003). Our long-term experiments exploring the relationships between biodiversity, productivity, fertilization, disturbance, and succession (Fig. 19-22) provide a unique opportunity to examine both the relationship between diversity and ecosystem function, and how this relationship responds to climatic drivers.

Climate change models predict dramatic alterations in the amount of precipitation and its variability, in particular the frequency and intensity of precipitation events in the Midwestern US (Easterling et al. 2000, Weltzin et al. 2003). At KBS, air temperature and precipitation have both shown increasing trends over the past several decades (Fig. 32), as has the temporal variability of large rain events. Variability in precipitation has been shown to affect species composition and abundance in a wide range of communities, including those that are not strongly water-limited (Buis et al. 2009, Knapp et al. 2002). We are continuing to explore the mechanisms that underlie variation in productivity and its response to fertilization using multivariate analyses that focus on diversity, species traits and climatic drivers as part of the ongoing cross-site collaboration known as PDTNetwork (the Productivity-Diversity-Traits Network). PDTNet involves faculty, postdocs and graduate students involved in long-term studies of the effects of fertilization (particularly N) on grasslands and other herbaceous plant communities. The collaboration involves data and researchers from 9 LTER sites (and several other sites not the LTER Network; Cleland et al. 2008; Suding et al. 2005; Clark et al. 2007; Gough et al., in prep.).

We are also manipulating precipitation in the annual plant community (Robinson & Gross, in prep) and temperature in perennial communities to determine how species-specific responses to these global drivers will influence plant community patterns. Our work on precipitation variation has focused on annual weed species that are common in row-crops and involves both greenhouse and field studies. The field experiments were established in annually-tilled microplots in the T7 early succession treatment (Fig. 4) using rainout shelters (6 mil plastic mounted on wooden frames and metal stakes that extend over the experimental plots) and adding water (precipitation) in controlled amounts at specified times. The first experiment involved manipulations of both precipitation amount and early spring temperatures during plant establishment to simulate larger storms and warmer nighttime temperatures. Early spring temperatures were manipulated using infrared reflective material suspended over the plots in the evening (sunset to sunrise) to passively increase nighttime soil temperature (i.e. Beier et al 2004). Community productivity remained constant but the relative abundance of species changed with increased early season precipitation.

Our other experiment focuses on how plant and soil microbial communities responded to changes in the frequency of precipitation at different levels of total precipitation. While plant communities showed a minimal response to precipitation variability during the growing season, soil CO_2 emissions were significantly affected (Fig. 33), with total seasonal CO_2 flux highest at intermediate levels of variability (imposed rainfall every 10d as opposed to every 4d or 16d; Aanderud et al., in review). Understanding how precipitation delivery and amount interact to affect plant species and communities is important both because these are strong drivers of productivity, and because changes in plant community diversity, composition, and productivity can affect soil microbial dynamics and the processes they mediate, as well as the structure of higher trophic levels – in particular pests and predators in agricultural landscapes (Reynolds et al. 2003 and below).

While global warming has been associated with altered species distributions and has been shown to change the phenology and/or fitness of a few focal species, little work has investigated the consequences of global warming in a community context. In addition to the experiments described above, we are using artificial warming treatments (infrared heaters) to investigate how increased temperatures impact the tri-trophic interaction between soybeans, soybean aphids (a dominant herbivore), and ladybird beetles (aphid predators). This work, led by co-I Jen Lau, has implications for both basic (food web dynamics in a changing environment) and applied (the potential for biocontrol of agricultural pests in future environmental conditions) ecology.

We will also be expanding our research to investigate the relationship between plant and soil microbial communities by focusing on how interactions between plants and soil mutualists vary in response to nutrient additions. Changes in soil N levels have been shown to shift both the legume-*Rhizobium* symbiosis and plant-mycorrhizal associations from mutualism to parasitism (Johnson et al 1997, Karst et al 2008). Similarly, changes in crop rotation and agricultural management can affect "partner availability" (the composition of the *Rhizobium* community) and consequently the stability of a legume-*Rhizobium* mutualism (Kiers et al. 2003). These shifts may be the result of both ecological and evolutionary processes. The N addition treatments in the LTER successional plots (Fig. 34) provide a unique opportunity to investigate how long-term fertilization impacts mutualistic interactions in native and introduced species within both perennial (untilled) and annual-dominated (tilled) communities. A 25-m^2 plot is fertilized annually in the spring with ammonium nitrate (10 g m^{-2}) in each community and species composition and productivity determined from biomass harvests from the central area of the plot in late summer (corresponding to peak biomass). Since 1994, the 1-ha treatment plots in which these experiments are embedded have been burned annually to prevent establishment of woody species. These experiments provide the opportunity to determine if there are differential species responses to this perturbation and the resultant community responses.

Similarly, the different rotations on the Biodiversity Gradient Experiment (Fig. 19) and management treatments of the Living Field Lab (Section 2.4) and main LTER row cropping treatments allow us provide a unique opportunity to examine ecological and evolutionary controls on legume-*Rhizobium* interactions. The research on legume-*Rhizobium* symbiosis and differential effects of warming on plant communities will be led by co-I Jen Lau. Kay Gross will continue to coordinate the work on plant community dynamics, particularly the long-term N-fertilization experiments and the impacts of cropping system diversity on yields and weed communities in the Biodiversity Gradient Experiment; she will also maintain collaborations between KBS and the PDTNetwork.

Linking microbial community structure to function (T. Schmidt, lead)

The metabolic activities of microbes in soil directly bear on a number of ecosystem services including soil fertility and greenhouse gas mitigation. Yet how the composition and dynamics of microbial populations relate to critical ecosystem processes and the response to environmental drivers is not well understood (Zak et al. 2006). A major challenge to unraveling this interaction has been methodological limitations for characterizing soil microbial communities. New technology, however, is providing opportunities for overcoming this barrier. DNA-based surveys now provide a means to characterize the composition of microbial communities and document patterns relating community composition to the biogeochemical processes they catalyze (e.g. Bell et al. 2005; Fig. 18, 35). Linking the structure of microbial communities to the rates and stability of biogeochemical processes and plant community structure will enhance our understanding of and ability to model how biogeochemical cycles will respond to various environmental drivers at local to global scales.

Soils are sometimes viewed as particularly stable environments, and consequently most analyses of microbial communities in soil have been conducted at single sampling times (Youssef and Elshahed 2009). In fact, there have been few systematic efforts to study potential seasonal and interannual variability of soil microbial communities and how dynamics of communities may relate to changes in the biogeochemical processes and plant communities. However, understanding these temporal dynamics is important because interactions between plants and microbial communities and how these feed back to biogeochemical processes are likely to be important drivers of plant community responses to global climate change (Reynolds et al. 2003).

Recent studies at the Niwot Ridge LTER using molecular techniques to characterize changes in soil microbial community structure, coupled with measures of microbial function, have revealed dramatic seasonal changes in the microbial activity and composition of alpine soils (Schmidt et al. 2007). However there are few studies of how microbial communities change in relation to shorter term successional or seasonal dynamics, or how these relate to changes in plant community composition or productivity. We know that plant-microbe associations change over time, but not how this affects plant community composition or biogeochemical processes. For example, in row crops rhizobia are recruited to the rhizosphere of some plants immediately after germination and then as the plants age, the rhizobacterial and bulk soil communities begin to converge in composition, consistent with a decline in the release of root exudates as plants reach the end of their life cycle (Micallef et al. 2009). Changes in the structure and activity of microbial communities that are coordinated with the decomposition of plant material could play an important nutrient synchrony role in cropping systems (Robertson 1997, McSwiney et al. 2010b).

The impact of soil microbes on local and global biogeochemical processes continues to motivate studies of microbial communities across the KBS landscape. While we maintain efforts to cultivate and characterize members of the most abundant bacterial taxa in soil, our focus is shifting towards culture independent, molecular analyses. In this renewal we propose to make the first time-series measurements for a large fraction of the microbial diversity in soils under different agricultural regimes, where we can relate the data to regular measurements of soil properties and key facets of the carbon and nitrogen cycles. Our focus will be on the following questions:

1) What are the patterns of seasonal succession in soil microbial communities across the agricultural and successional landscapes at the KBS LTER, and

2) How do the dynamics in composition of microbial communities in these sites relate to rates and stability of carbon and nitrogen cycling?

We will assess successional dynamics of soil microbial community composition across our 11 crop and unmanaged successional systems (Figs. 4, 5). Samples will be collected monthly from each of the main site treatments and the successional deciduous and coniferous forests. Approximately 440 composite soil samples will be archived per year (11 treatments × 4 plots/treatment × 10 months – samples are not collected when the ground is frozen). A LIMS system now in use will be used to catalog and inventory all samples.

Analyses of rRNA genes have proven particularly informative for estimating microbial phylogeny (Pace 1997) and generating taxonomic inventories of microbial populations (Rappe & Giovannoni 2003). These genes are conserved in all known organisms, and current molecular databases contain more than 500,000 reference rRNA sequences from diverse microbial forms. The major constraint on these studies is the expense of cloning and sequencing individual rRNA encoding genes - the current "gold standard" for studies of microbial diversity. New sequencing technologies offer a means to generate comprehensive profiles of microbial communities, including low abundance taxa, without cloning and at a fraction of the cost of capillary sequencing of individual genes. Massively parallel 454 Life Sciences pyrosequencing applied to variable regions in rRNA genes renders assessments of microbial diversity and richness at a 100 to 1000 times finer scale than analyses of full-length rRNA sequences, providing economical inventories of microbial communities at a fraction of the cost.

We will assess the composition of bacterial communities through pyrosequencing of an amplified portion (V3-V5) of the 16S rRNA encoding gene. We will employ a multiplexing strategy that allows the concurrent collection of ~10,000 tags from each of 40 samples in a single, 4-hour sequencing run. We will perform pyrosequencing using the titanium chemistry from 454 Life Sciences, available at an MSU sequencing facility. We have consistently seen average read lengths of ~380 bases, which will be more than sufficient for the proposed taxonomic assessment.

The 16S gene sequence data will be moved through a pyrosequencing data pipeline that is maintained by the Ribosomal Database Project at MSU (http://pyro.cme.msu.edu). This will produce a database of operational taxonomic units (OTUs: Schloss and Handelsman, 2006) that can be used for calculating a variety of diversity indices (http://viceroy.eeb.uconn.edu/estimates).

Seasonal variation in functional genes will also be explored using the GeoChip in collaboration with investigator J. Zhou. The GeoChip is a hybridization array that detects tens of thousands of functional gene markers, including those involved in carbon and nitrogen cycling (He et al. 2007; Van Nostrand et al. 2009, Wang et al. 2009). Analysis of metagenomes and GeoChip results from T1 and DF have already revealed reproducible differences in the composition and abundance of genes involved in denitrification

(Schmidt and Zhou, in prep), suggesting that both treatment level and successional effects will be discernable through hybridization analysis.

The archived soil and DNA samples represent a valuable resource that will be available for cross-site comparisons of the genetic structure of microbial communities. The samples will be collected and stored in such manner as to permit future studies of gene expression through mRNA analysis.

Based on our analysis of methanotroph diversity (Fig. 18), we will also attempt to increase experimentally methane consumption by manipulating the diversity and abundance of methanotrophs in mcroplots of our cropping system treatments. Methanotrophs cultivated from both sites will be added to soil microcosms, and the magnitude and duration of any enhanced methane consumption will be the metrics used to determine the feasibility of any field-scale manipulations.

Insect diversity and pest suppression (D. Landis, lead)

Understanding the relationship between insect biodiversity and ecosystem functioning in terrestrial ecosystems is a topic of vital importance. The frontier of our understanding about predator-prey biodiversity-ecosystem functioning currently lies in a better understanding of how dispersal of organisms at landscape scales may influence these relationships (Duffy et al. 2007, Bruno and Cardinale 2008).

Insect herbivores and their natural enemies are highly influenced by the structure of agricultural landscapes (Landis 1994, Landis and Marino 1999, Bianchi et al. 2006) with specific habitats acting as metapopulation sources and sinks. Our recent work has focused on using the invasion of the exotic soybean aphid (SBA), *Aphis glycines*, as a model for understanding the interactions of predator communities and herbivores at the plant, field, and landscape levels. SBA is an increasingly important pest of soybeans (Difonzo and Hines 2002) and now occurs in 22 states and three Canadian provinces (Ragsdale et al. 2004). For overwintering it relies on non-crop habitat in the landscape – specifically shrubs in the genus *Rhamnus* (buckthorns).

Unlike other predator-prey systems, the critical feature governing SBA populations appears to be the continual early-season flux of transient predators through soybean fields, principally the adult coccinellid beetles *Coccinella septempunctata* and *Harmonia axyridis* (Costamagna and Landis 2007). Yet we know comparatively little about how these transient predators shape plant-herbivore interactions or how these interactions are modified by plant community diversity at field, landscape and regional levels (Gardiner et al. 2009). The KBS LTER provides a unique system to explore how agricultural management interacts with biodiversity at local and landscape scales to affect an important ecosystem service to agriculture.

We propose investigations in two broad areas: 1) within-field dynamics of predator-prey interactions, and 2) landscape controls on predator-prey interactions and pest suppression.

Our prior work suggests that SBA has both spatial and temporal refuges at the plant and field scale that influence the outcomes of predator-prey interactions. At the field scale, mobile predators (primarily adult coccinellids) encounter and reduce most, but not all local aphid aggregations, creating a shifting mosaic of aphid abundance over time (Fig. 36). Within plants, coccinellid adults preferentially search the upper plant nodes, effectively reducing overall aphid load but again allowing a refuge for aphid persistence on basal nodes (Costamagna and Landis, unpublished data). We hypothesize that these refuges at the plant and within-field scales are critical features regulating soybean aphid persistence and outbreak dynamics. Conversely, the ability of a landscape to supply mobile predators to exploit and in some cases break down these refuges is one of the defining features leading to effective pest suppression.

We will use the Biodiversity Gradient Experiment (Fig. 19) and scale-up fields (Fig. 6) to examine the impacts of predators on SBA at multiple spatial scales. We predict that the rate of transient predator flux though soybean fields is the primary factor determining the level of pest suppression, i.e. fields with high levels of predator flux experience high degrees of aphid suppression while low flux may allow prey outbreaks. However, both field size and the landscape within which soybean fields are embedded can impact predator availability and thus pest suppression. The dependence of the SBA on common buckthorn, *Rhamnus cathartica*, an invasive shrub that is common in forest edge and fencerow habitats (Welsman et al. 2007), is an example of how landscape context will influence the invasion of SBA into soybean fields. Also, the two key SBA predators *H. axyridis* and *C. septempunctata* both emerge from overwintering prior to soybean planting, and thus must initially feed in other habitats. Winter wheat and alfalfa are potentially key agricultural habitats for early-season larval development of these predators because they support spring populations of alternative aphid prey for the coccinellids.

Using a combination of fields from the LTER scale-up experiment, other agricultural fields at KBS, and private farms in the surrounding area, we will explore how the surrounding landscape influences the probability, extent, and timing of SBA infestation in soybean fields that vary in size and landscape position. We will particularly focus on the abundance of buckthorn (overwintering habitat) and the location/distribution of wheat and alfalfa fields (alternative prey for predators). We will collect coccinellids from the soybean fields and use the stable isotopic signature of their elytra (representative of larval food source) to determine from what habitats they have emerged. Isotope signatures of carbon and nitrogen can be used to distinguish initial food sources (e.g. C_4 corn vs. C_3 wheat and legumes vs. non-N fixing plants; Hood-Nowotny and Knols 2007). We will continue our long-term (since 1988) sampling of the coccinellid community in KBS cropping systems and use this dataset to address the hypothesis that *H. axyridis* population dynamics are being driven by SBA (Fig. 37).

Human Dimensions

Although it is humankind's oldest managed ecosystem, agriculture is only now being recognized for its potential to deliver a mixture of ecosystem services in addition to food, fiber, and fuel (Antle et al. 2001, Farber et al. 2006, Swinton et al. 2006). Understanding human motives in managing agroecosystems and encouraging sustainable management calls for exploring human awareness, perceptions, incentives, and constraints with respect to managing these ecosystems for the services they can provide. Research from the latest phase of KBS LTER highlighted the importance and complexity of aggregative effects for multiple ecosystem services across landscapes and over time. Building on past research into economic valuation of individual services, in the next phase of human dimensions research we will expand in three directions: 1) extending the valuation research to multiple services over time, 2) exploring means for farmers to coordinate management across a landscape, and 3) assessing the potential appeal to farmers of management practices emerging from our LTER research.

Economic valuation of multiple ecosystem services over time from one system (S. Swinton, lead)

Twenty years of KBS LTER research have documented that beyond crop yields, row-crop agroecosystems provide a suite of ecosystem services ranging from mitigation of greenhouse gas emissions and nutrient export to pest control by natural enemies (e.g. Figs. 12, 14, 18, 24). Marketed products drive the management of these systems in the commercial world because products are the outputs for which managers get paid. Understanding the value of nonmarket services both to producers and consumers of services is a key step towards designing incentives to induce private managers to provide services that the public desires but for which markets fail. However, estimating the values of these services is complicated by the fact that they are produced as joint products of a given management regime, but consumed separately.

Solving the valuation problem requires either aggregating ecosystem service values by the bundles in which they are produced or else disaggregating production costs to compare cost shares to the benefits of specific services. Conventional research on nonmarket valuation methods (Freeman 2003) offers insights on aggregation over time, but not across ecosystem services. Because ecosystem services are produced in bundles (Wossink & Swinton 2007), the marginal cost of producing a given service may be very small. Indeed, such complementarities as well as supplementarity and substitutability in input use contribute to the nonlinearity of the aggregate unit marginal costs of ecosystem service provision (Hoehn 1991, Barreiro-Hurlé and Gómez-Limón 2008). Other contributors include the opportunity cost of income foregone by not using more profitable practices and the heterogeneity of land quality.

Nonlinearities of aggregation exist too on the ecosystem service consumption side, because services are consumed by people at such different scales (e.g. local well water to global climate), by people at highly skewed income and wealth levels, and by people with very diverse preferences. Yet if agroecosystems are to be managed more sustainably, ways are needed to define the combinations of land and management systems where ecosystem services can be provided at lowest cost (including instances where costs are lowered by coordinated behavior across different managers).

We will test methods for aggregating ecosystem service values using both time series and cross-sectional data. Time series observations from our main cropping system experiment (Fig. 4; 1993-present) and our scale-up fields (Fig. 6; 2006-present) will be the basis for dynamic enterprise budgets that can capture the changing crop net returns (a proxy for opportunity cost). Ecosystem service data over time (especially greenhouse gas fluxes and nutrient export to ground water and surface waters) will be linked to values using benefit transfer methods, preferably benefit functions (Wilson and Hoehn 2006). The availability of multi-year, multi-site data will also permit estimation of variances for these bundled ecosystem service production values, facilitating estimation of their temporal and spatial stability.

More promising yet is the opportunity to utilize a unique set of survey data on Michigan crop producers' willingness-to-accept (WTA) payments to provide increased ecosystem services along with consumers' willingness-to-pay (WTP) to receive increased ecosystem services from land management practices. Using this 2008-09 data set gathered with co-I Frank Lupi (Section 1.5), we will test econometric hypotheses regarding additivity, complementarity and substitution of WTA and WTP values. We will also use these data sets to determine the conditions under which producer and consumer values for ecosystem services coincide.

Coordination of landscape-level ecosystem services across farms and communities (S. Swinton, lead)

Certain important ecosystem services that are only partially present at a site emerge at the scale of a landscape. Prominent examples include biodiversity-mediated services that require landscape-level habitat configurations (Gardiner et al. 2009) and recreational/aesthetic services that emerge from a landscape of varied vegetation and topography (Bolund & Hunhammar 1999).

When land parcels are managed by many individuals, coordinated behavior may be needed in order to attain the scale and landscape configurations that would foster desired ecosystem services from these parcels. Such landscape-level services as natural pest biocontrol pose classic economic common pool resource problems when habitat set-aside imposes costs (Zhang et al. 2010), but nonparticipants cannot be excluded from enjoying the benefits. The nature of the ecosystem service management coordination problem will vary with the characteristics of the agricultural system, the managers, and the policy setting. Hence, key research questions are

1) What agroecosystem management practices offer landscape-level ecosystem services? Of special interests are two types:
    a. habitat set-aside for biodiversity-mediated services (e.g. natural pest control, pollination, birds & mammals), and
    b. landscape level agronomic-driven services (e.g. reduced erosion, floods, drought, improved water quality, soil fertility, greenhouse gas mitigation).
2) How does land quality interact with management practices to affect the provision of landscape-level ecosystem services; and

3) How and under what conditions can people be persuaded to cooperate on land management, and how do information, attitudes and incentives affect willingness to participate?

Research into the relationship between landscape-level management practices and ecosystem service outcomes (#1 above) will take advantage of the varied landscape surroundings of our 27 scale-up fields in place since 2006 (Fig. 6). Expanding on the methods of Gardiner et al. (2009), we will associate surrounding land cover with site observations for a range of ecosystem services, including soybean aphid and corn rootworm pest regulation, water quality regulation, soil carbon and nitrogen stocks, and marketable crop yield (including both grain and biomass residue). Multivariate analyses will be applied to identify links between land quality, management practices, land cover and associated services (#2 above). In order to understand conditions for coordinated landscape management, we will convene focus groups in various communities to explore land manager attitudes and the effects of changed information. Using experimental economic methods, information and incentive treatments will be tested in repeated games to see their effects on the willingness of participants to coordinate behavior (Parkhurst and Shogren 2003). Our past experience with experimental auctions in focus group settings has highlighted differences in bidding behavior between farm and non-farm populations (Lupi et al. 2009). Focus group feedback has also proven indispensable in informing the design of questionnaires that subsequently achieved very high response rates in surveys of farmers (Jolejole 2009) and households (Chen et al., in prep).

Socioeconomic evaluation of new cropping practices (S. Swinton and S. Snapp lead)

All ecosystems are dynamic, and managed ecosystems on working lands are especially so due to the activity of markets and the evolution of technology and policy. After over 20 years of study of seven management treatments, scientific knowledge from our main cropping system experiment is contributing to the development of new sustainable cropping practices that merit evaluation prior to wider diffusion. These new practices are largely designed to enhance the provision of nonmarketed ecosystem services that are of potential interest to farmers who care about the environment and/or who anticipate being paid for certain services such as mitigation of greenhouse gas emissions.

Among the emerging research questions about ecosystem services associated with potential new practices are these, each of which has been discussed in earlier sections:

1) How effective is land inoculation with methanotrophic bacteria? How do greenhouse gas fluxes compare with similar treatments lacking land inoculation?
2) What specific management practices in non-crop areas enhance habitat resources for crop pest predators or pollinators? What is the magnitude and quality of these habitat effects on resulting arthropod-mediated services?
3) What are the ecosystem service levels and tradeoffs associated with intensifying the presence of living plants within conventional row crop production (e.g., winter cover cropping, rotation with perennial crops, double cropping with new shorter duration varieties)?
4) How are these ecosystem service levels and tradeoffs affected by residue removal (e.g., for biofuel use)?

Upon established evidence of ecosystem service benefits, each of these areas deserves a phased *ex ante* assessment of potential appeal to farmers. Steps in the evaluation begin with simple expected profitability measures: a) enterprise budgets to assess costs and returns via marketed provisioning services and b) budget-based estimation of incentives required to make adoption attractive (where added private costs exceed added private benefits). Where potentially attractive scenarios can be developed, community-based assessment may be undertaken, including c) convening farmer focus groups to discuss potentially promising practices and their ecosystem service consequences, and d) conducting economic experiments with farmer focus groups to test adoption of new cropping practices under different scenarios of ecosystem service tradeoffs and incentives.

Although introducing farmer-driven innovation into our cropping systems is outside the scope of this proposal, we intend to seek outside resources to survey farmers in regard to innovative practices and associated ecosystem services. By associating these practices with LTER results, it may be possible both to quantify potential benefits from farmer practices and to identify potentially promising long-term research avenues for future investigation.

Conceptual Integration and Synthesis

In our LTER research to date, we have addressed most of the major ecological factors that underpin the productivity and affect the environmental performance of intensively managed, high-productivity row-crop ecosystems typical of the upper Midwest. We have also evaluated alternative agricultural practices that might have less environmental impact, and we have compared these intensively managed systems to unmanaged communities at different stages of ecological succession. Our intent is to build a holistic view of row crops as *ecosystems* sufficient to permit a reasonable understanding of how they function and how their management can be improved to make them sustainable in the long term, including considerations of both profitability and environmental integrity. We must continue to integrate and synthesize our results to translate this complex and multifaceted body of research into theoretical advances for the field of ecology and, equally important, to provide practical advice for practitioners and policymakers. Our KBS LTER site volume for the Oxford series is currently in prep and we will post chapters as they become available on our web site this Spring.

Our conceptual model depicts the ways in which the human and natural systems are coupled and hence represent a dynamic system responding to changing drivers in complex ways (Fig. 26). The model also indicates the kinds of information we will need to integrate and synthesize and where we need to work harder to fill in gaps. Modeling with multiple approaches and at multiple scales will be necessary to synthesize the various components of this research program, and ultimately we seek to build the capacity to generate scenarios of alternative futures based on this modeling. Examples of data integration, synthesis, and modeling efforts that are already underway, as explained throughout the above text, and will be further pursued include:

1) Determination of net climate forcing (global warming potential) of alternative agronomic management regimes, incorporating greenhouse gas emissions, soil C sequestration, fossil fuel use, and other greenhouse gas sources and sinks (Robertson and Grace 2004);
2) Spatially explicit models that regionalize our results to understand implications for climate forcing (Grace et al. 2006a);
3) Full-cost economic and energy accounting of alternative agronomic management regimes (Robertson et al. 2000, Gelfand et al. in review);
4) Spatial habitat models to simulate relationships between habitat for natural enemies of agricultural pests, the efficacy of predation in controlling pest damage, and consequences for crop yields and income (Zhang et al. 2010); and
5) Spatially explicit biophysical, biodiversity, and socioeconomic models of alternative landscapes under scenarios of widespread conversion of existing agricultural or marginal fallow lands to biofuel cropping systems, currently conducted as part of our GLBRC research but informed by – and generating models and results pertinent to – our LTER treatments.

2.3 Long-term Experiments, Sampling Protocols, and Monitoring

The field research we propose will be performed largely in the context of our existing experimental design. Sampling protocols and schedules are already in place for these experiments and will be maintained with little change to keep continuity (protocols are found on our web site). Our main long-term experiments, each of which will be maintained into the future, are:

1) **The Main Cropping System Experiment** (Figs. 4, 5) has been in place for >20 years and provides the context for most core research on site. The 60-ha Main Experiment site has been subdivided into seven different 1-ha cropping systems (Fig. 4), each replicated in one of six blocks in a randomized complete block design, with an eighth never-tilled system nearby. Four of these eight systems are annual crop rotations, two are perennial, and two are successional systems in native vegetation.

The annual crops are corn-soybean-wheat rotations. Treatments 1 and 2 receive standard levels of chemical inputs, based on regional best management practices (BMP) and MSU Extension recommendations. Treatment 1 is chisel plowed (mold-board plowed until 1996) and Treatment 2 is under permanent no-till management. Treatments 3 and 4 are biologically-based systems with a winter leguminous cover crop. Treatment 3 receives 1/3 of the chemical inputs added to Treatment 1: herbicide at normal concentrations but applied (banded) only over the plant rows, and nitrogen fertilizer at starter rates only at planting (for corn, ~30 kg N ha^{-1}). Treatment 4 (certified organic) receives no chemical inputs at any time. Both T3 and T4 receive additional post-planting cultivation and T4 is rotary-hoed to control weeds. No treatements receive compost or manure.

The perennial systems include continuous alfalfa (Treatment 6) and hybrid poplar trees (Treatment 5), the latter on a 10-year rotation cycle. Treatment 7 is a native successional treatment, abandoned after spring plowing in 1989, and since 1996 burned annually to prevent tree establishment; many areas of southwest Michigan were burned annually from ca. 700 AD to maintain open oak savannah. Treatment 8 is a never plowed site, 200 m south of the others, that serves as an historical control for soil organic matter studies.

The Main Cropping System Experiment also includes three additional unmanaged treatments, each replicated three times in the larger KBS landscape (Fig. 5). These include a set of three 60-70 year-old mid-successional communities (SF; abandoned from agriculture in the 1950s), a set of three small 50-60 year-old conifer plantations (CF), and a set of three late-successional forests (DF), two of which have never been cut. All of these sites are within 3 km of the main experimental site on the same soil series. Within each of these sites is a 1 ha sampling area laid out in a manner similar to plots of the main experimental site.

A full Main Cropping System Experiment sampling thus includes 55 treatment plots: 7 main site treatments (Treatments 1-7) arranged in 6 replicate blocks; Treatment 8 with 4 replicate plots; and SF, CF, and DF each at three replicate locations (42 + 4 + 9).

In each treatment plot is a permanent set of 5 sampling stations at which most within-plot sampling is performed. Additionally, treatment plots typically host microplot experiments that focus on testing specific mechanistic hypotheses, such as N-addition plots to test the relationship between nutrient availability and plant diversity and predator-exclusion plots to examine the role of predators for controlling invasive insects. Some microplot experiments are permanent (such as annually tilled microplots in Treatment 7 (early succession) plots; many are shorter-term.

Regular measurements on the Main Cropping System Experiment are detailed in Supplementary Table S2 and include for all treatments 1) soil moisture, pH, bulk density, inorganic N, and N mineralization; 2) microbial biomass and abundance; 3) plant species composition, above ground net primary productivity (ANPP) including trees where present, litterfall, and crop yield; 4) N and other soluble ion concentrations in low-tension lysimeters installed at 1.2 m depth (Bt2/C horizon) in all treatment plots; 5) predaceous insects, in particular coccinellids; and 6) a number of weather variables. Precipitation chemistry is monitored at a replicate weather station 2 km distant (to avoid contamination by agricultural activities on site), with samples sent to the NADP/NTN central laboratory for analysis. Soil carbon is measured to 1-m depth at decadal intervals in all treatment plots. The soil seed bank is sampled on a 6-year cycle.

2) **The Biodiversity Gradient Experiment** (Fig. 19) was established in 2000 to provide a range of communities that differ only in plant diversity and timing of tillage: 22 replicated treatments range from continuous monocultures of corn, soybeans, and wheat to highly diverse cropping systems of three crop rotations with two different cover crops, and allow us to test the direct effects of crop diversity on community and ecosystem processes. Also included are two annually-tilled successional treatments, one tilled in fall and the other in spring, and a no-plant (bare soil) treatment. Plant species richness thus varies from 0 to >15 in any given 3-year rotation cycle. Treatment plots are 10 × 20 m replicated in each of 4 randomized blocks. Yield is the main response variable that we measure but the experiment has been popular for spinoff studies.

3) **The Nitrogen Fertility Gradient Experiment** (Fig. 8), established in 1999, allows us to test annually for N and water resource limitations in our main cropping system experiement, and to exampine how incremental increases in N availability (9 levels of fertilizer N from 0–294 kg N ha^{-1} for corn) affect ecosystem processes. The irrigated block was added in 2003, at which time we also syncrhonized crops with the main site experiment; fertilizer is not added in soybean years. Plots are 5 × 30 m arranged in a partially randomized complete block design: 2 irrigation treatments × 9 fertilizer levels × 4 replicate blocks. We sample yield as our main response variable but the experiment is used for short-term greenhouse gas and other studies, and presently hosts an automated trace gas flux system for year-round measurements of N_2O, CO_2, and CH_4 fluxes (4 times per day in one of the nonirrigated blocks).

4) **The LTER Scale-up Experiment** (Fig. 6) has three of our main site treatments installed on 27 fields managed commercially by the KBS dairy to allow us to test the scalability of research results from our 1-ha Main Cropping System Experiment plots. In Fall 2006 we assigned fields managed by the dairy to one of three annual crop treatments (Conventional-T1, Reduced-input-T3, or Biologically-based-T4 treatments) and to one of three rotation entry points (corn, soybean, or wheat). This provides three replicate fields for each treatment by entry point combination (3 treatments × 3 entry points × replicates). Fields range in size from 1 to 7.5 ha, adjoin a variety of different habitat types, and have a variety of perimeter complexities. Agronomic inputs and yields are closely monitored in these fields, which are available to investigators for additional whole-field measurements. To date the fields have been used for economic analysis (enterprise budgets) and insect sampling.

5) **The Living Field Lab (LFL)** was established in 1993 by former LTER co-PI Richard Harwood to investigate the benefits of leguminous cover crops composted dairy manure in two integrated systems compared to a conventional and an organic agricultural system. The term "integrated" in this case refers to targeted, banded application of herbicide, reduced tillage, and stringent accounting of N inputs using the pre-side-dress nitrate test (PSNT) or N analysis of composted dairy manure. During the past 14 years, a crop rotation of corn-corn-soybean-wheat was compared to continuous corn where every entry point of the rotation was present each year. A number of soil and crop variables were measured at the LFL from 1993-2003 (Table S2); since 2006 the LFL has been managed by co-PI Snapp, who has initiated new studies including a perennial wheat project.

6) **The Great Lakes Bioenergy Research Center (GLBRC)** experimental plots (Fig. 7) were established in 2008 to provide a context for comparing the productivity and environmental performance of alternative biofuel cropping systems and for asking fundamental questions about the ecological functioning of these novel managed ecosystems. Eight different cropping systems have been established in a randomized complete block design that includes, in order of increasing plant diversity, continuous corn, a corn-soybean-canola rotation, switchgrass, *Miscanthus giganteus*, hybrid poplar, mixed-species native grasses, successional vegetation, and restored prairie. Regular measurements at the GLBRC plots are similar to those made at our main cropping

system experiment, but also include TDR soil water profiles, electrical resistivity imaging of soil water, and automated chamber measurements of greenhouse gas exchanges. The site was established with DOE funding which also underwrites most of the intensive sampling. At the end of DOE funding (5-10 y) the site will remain part of the LTER project. We also are establishing larger scale-up fields of continuous corn, switchgrass, and restored prairie on both existing cropland and on land that has been in CRP for 20 years at sites 10 km distant. These GLBRC scale-up fields have eddy covariance flux towers to measure carbon dioxide exchange at the whole-ecosystem scale, and are also sampled for yield and a variety of soil biogeochemical and insect diversity attributes.

2.4 Short-term Experiments, Empirical Studies, and Modeling

Many of the results described in Section 1 represent short-term experiments and empirical studies, including cross-site studies funded by additional grants such as the Lotic Intersite Nitrogen Experiment (LINX). Many other projects funded on other awards use the LTER site and data, as evidenced by the publication lists (see Table S1). Graduate student research, a key part of our overall research portfolio that is funded to a significant extent by LTER, tends also to be short-term research and is almost always experimental in approach, often involving spinoffs or side studies as well as the use of data from the core experiments. Finally, biofuel sustainability research funded by the DOE Great Lakes Bioenergy Research Center (GLBRC) functions as a short-term, large-scale augmentation of LTER research, even though it may last for 5-10 years.

Several lines of modeling are conducted in connection with the research we have detailed above, including these that will remain active areas of LTER research:

1) Our development of the MASIF (Modeling Applications System Integrative Framework) modeling framework (see Section 1.7) is important to our efforts to scale local LTER knowledge to regional levels, and thus important to our aim of helping to effectively forecast ecological change and its consequences across the 12-state North Central Region. MASIF provides a framework in which geospatial databases for climate, soils, and land use within the region are made available to process-based models that then produce spatially-explicit output for analysis and visualization. We have to date used MASIF to characterize drought severity patterns in the region since 1972 (Gage 2003) and MASIF/SOCRATES (Grace and Ladd 1995) to predict changes in regional soil carbon (Grace et al. 2006a and 2006b) and nitrous oxide emission (Grace et al., in review) as a consequence of changing climate and agronomic practices.

2) We are building hydrological models at scales from the soil-plant system to the landscape, using data from both the LTER and GLBRC projects. The landscape hydrology models were described above (see *Ground and surface water biogeochemistry*). Field-scale modeling of the soil-plant system is being developed using both the EPIC and SALUS/DSSAT crop models, in collaboration with César Izzauralde (GLBRC) and Bruno Basso (LTER co-I), respectively.

3) Finally, we will continue to utilize LTER data to develop and inform models of insect response to shifting agricultural landscapes (Landis et al. 2008). We will integrate predator, pollinator, and economic response models to explore the impact of cellulosic biofuel crop additions into the landscape (co-PI's Landis and Swinton, co-I Isaacs, and GLBRC collaborators César Izzuralde and Claudio Gratton). In collaboration with LTER co-I Mary Gardiner, we are also developing ecological niche models of common buckthorn occurrence in the landscape to investigate the impact of buckthorn suppression programs on soybean aphids and coccinellids.

2.5 Regionalization, Cross-site, and Network Activities

Regionalization has been a core area of KBS LTER research led by former coPI Stuart Gage, who has retired now and will not continue as a PI; his work is summarized in Section 1. Future efforts towards regionalization include the modeling described above, designed to cover multiple spatial scales. As noted earlier, we consider our primary region to include the USDA 12-state North Central region (Fig. 1).

We have been very active in cross-site activities and will continue to make these activities a high priority. We had a strong presence at the 2009 All Scientists Meeting (35 KBS participants) and led several ASM workshops and will be hosting two post-ASM working groups, one led by a KBS postdoc and another by a KBS graduate student. Lead PI Robertson chairs the LTER Science Council (2007-2011) and thus has had an active role in designing and promoting network science initiatives. In the coming years we envision continued or new involvement in the following cross-site and network activities:

1) *PDTNet.* KBS has been an active, charter player in PDTNet, a consortium of PIs, postdocs and former graduate students from 10 LTER sites plus Jasper Ridge in California. Co-PI Gross led KBS involvement.
2) *ClimDB, HydroDB, and EcoTrends.* KBS is a standing contributor to network-level databases, including Ecotrends (www.ecotrends.info), which includes KBS data for weather, lake ice cover, plant and insect abundance, and primary production.
3) *Social Science Committee.* Co-PI Swinton has been actively involved in the LTER network of social scientists. Following the 2006 LTER All Scientists Meeting, he organized a workshop on ecosystem services from working lands with social and biological scientists from KNZ, SGS, JRN, HFR, and KBS. He also collaborated in the national webcast course developed by LTER network social scientists in 2008 from CWT/University of Georgia.
4) *LINX & STREON*. Co-PI Hamilton has been involved in several cross-site aquatic ecosystem research initiatives, and has been a PI for the Lotic Intersite Nitrogen Experiment (LINX), which remains active although is not presently funded. Hamilton also was also an initial proponent of the Stream Ecological Observatory Network (STREON), now a part of NEON. NEON has since determined that KBS does not qualify as a STREON/NEON site and is too distant from the core site in the Upper Peninsula to serve as a satellite site.
5) *Network Synthesis Projects*. We expect to participate in the emergent cross-site initiatives for Future Scenarios, Inland Climate Change, and Disappearing Cryosphere, all of which mesh well with our new conceptual orientation (Fig. 26). KBS investigators have participated in several planning workshops.
6) *Other Networks*. We have plans to become involved in the National Phenology Network (www.usanpn.org) as a part of KBS outreach activities, and we are pursuing funding for joining the Global Lake Ecological Observatory Network (GLEON; www.gleon.org). The lake observatory would be established on Gull Lake, with hydrological links to our cropped landscape, and led by co-I's Jay Lennon and Elena Litchman as well as Hamilton.

The KBS LTER also has several active linkages with international LTER projects. We have had several exchange visits with the Chinese as well as the Taiwanese Ecological Research Networks (CERN and TERN, respectively), including visits to KBS in 2009 by representatives from both groups and collaborative work with CERN by co-I Sasha Kravchenko. Co-PI Hamilton has worked with Brazilian researchers including hosting two exchange visits of graduate students from their LTER group working on the Pantanal wetland, and collaborations have produced several co-authored publications (Girard et al. 2010, Oliveira et al. 2010a and 2010b). Co-PI Swinton and German LTSER researcher Cornelia Ohl just completed a book chapter on integration of socioeconomic dynamics into long-term ecological research, building on U.S. and European experiences (Ohl & Swinton 2010). Presently we are participating in organizing a workshop for ILTER Agricultural Sites together with French LTER organizers. We expect these relationships to continue.

2.6 Figures

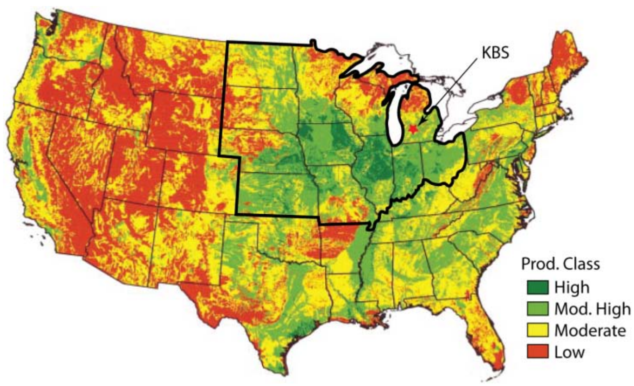


Fig. 1. Location of KBS in relation to agricultural productivity. The North Central Region is the USDA's nomenclature for the area that includes the US corn belt, and which we have identified as the region best represented by the KBS LTER site. Annual precipitation at KBS averages 890 mm with about half falling as snow; mean annual temperature is 9.7 °C. Base map from Nizeyimana et al. (2001).

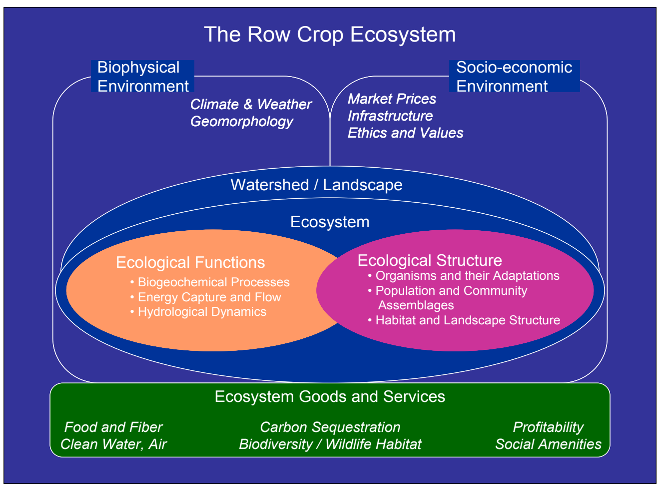


Fig. 2. The KBS LTER conceptual model formulated in 2004. Our revised conceptual model is presented later (Fig. 26)

Global Hypothesis
That agronomic management based on ecological concepts can effectively substitute for reliance on chemical subsidies in production-level row-crop ecosystems.

Corollary 1
By manipulating interactions among organisms, we can design agricultural systems to minimize external inputs and losses and optimize economic yield.

Corollary 2
Nutrient subsidies can be minimized primarily by manipulating plant-microbe interactions; herbicide subsidies by manipulating crop-weed-consumer interactions; and pesticide subsidies by manipulating plant-insect-pathogen interactions.

Corollary 3
Effective manipulation will require a solid, basic understanding of the underlying mechanisms that regulate organisms' interactions under both natural conditons and intensive management.

Fig. 3. The KBS LTER global hypothesis formulated in 1987 for our field-scale research. For 2010 corollaries have been expanded to include interactions and human dynamics depicted in our revised conceptual model (Fig. 26).

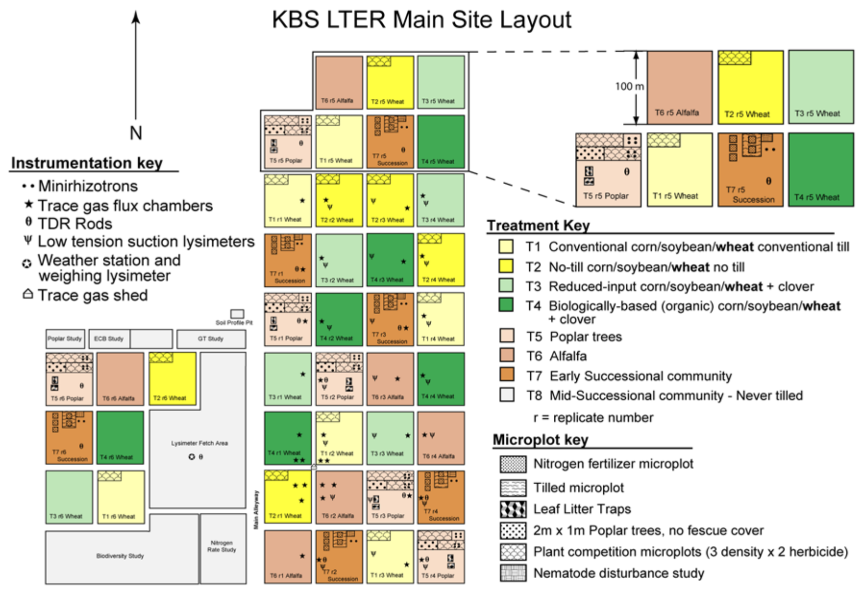


Fig. 4. Experimental layout of the Main Cropping System Experiment at the KBS LTER site. Block 5 (of 6 total blocks) is expanded at upper right to show plot details. In addition to the eight treatments shown here are 1-ha plots in unmanaged vegetation (Fig. 5): three older successional fields (40 - 60 years since abandonment), three conifer plantations (40 – 70 years since establishment), and three late successional deciduous forest stands, for a total of 11 types of replicated communities on the same soil.

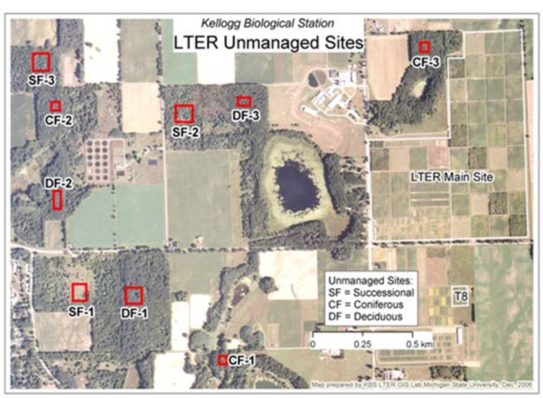


Fig. 5. Aerial photograph showing the main LTER site (upper right portion of photo; see Fig. 4) and (red rectangles) the mid-successional communities and forest stands. SF = mid successional fields/forests abandoned from cropland ca. 1950, CF = conifer-dominated forest stands, and DF = deciduous forest sites.

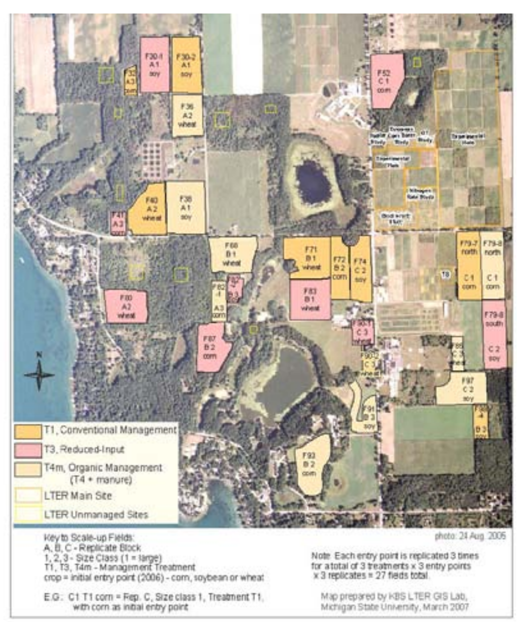
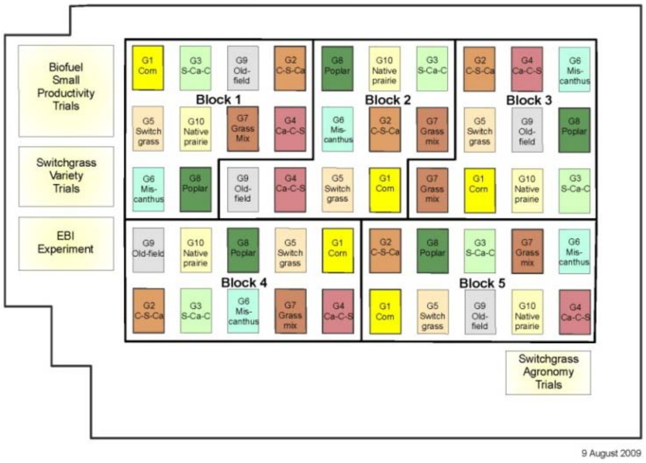


Fig. 6. LTER scale-up fields (n=27) established in 2006 to test questions about the scalability of results from our 1-ha main site plots.



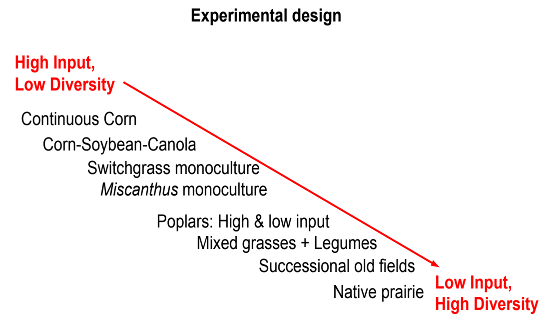


Fig. 7. Left: Biofuel cropping system experiment added in 2008. Eight systems ranging from monocultures to highly diverse (above) are installed in a randomized complete block design (n=5 blocks) with 30×40m plots.

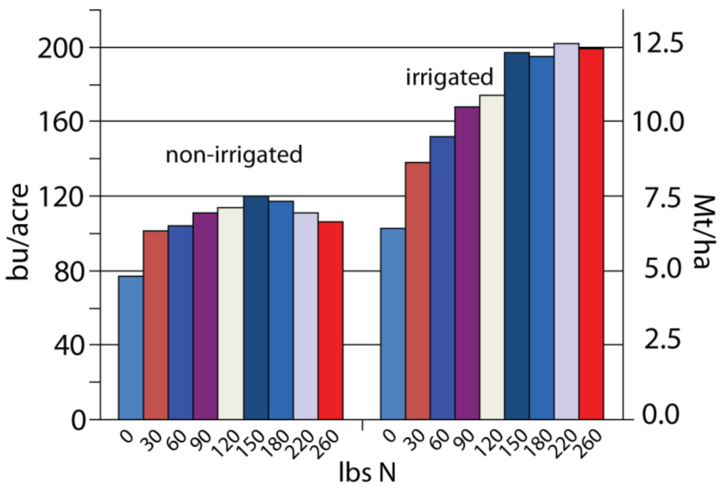


Fig. 8. 2008 corn yields in our Nitrogen Fertility Gradient Experiment, in which main-site crops are N fertilized at different rates (0-292 kg N/ha or 0-260 lb N/acre) and either irrigated or not irrigated. Results from this randomized complete block experiment (n=4 blocks) inform constraints on primary productivity for a given crop year – in this case for the local drought year 2008. National average corn yields for 2008 were 9.7 MT/ha (155 bushels/acre).

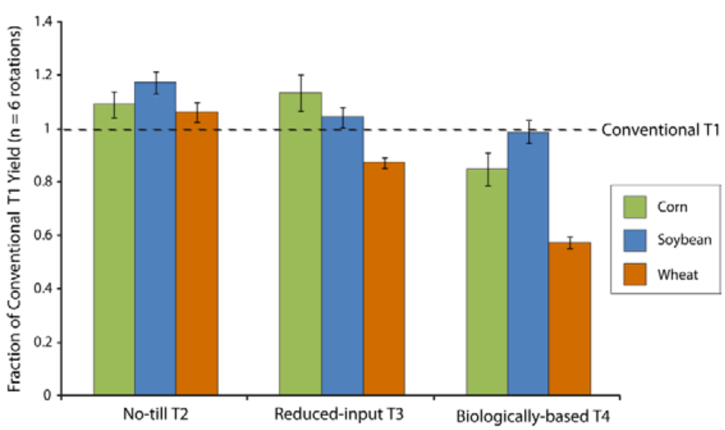


Fig. 9. Relative yields from our Main Cropping System Experiment in No-till (T2), Reduced-input (T3), and Biologically-based (T4) cropping systems compared to yields in the Conventional management (T1) treatment (dashed line). Vertical lines within bars represent standard error (n=6 replicate blocks); each bar represents relative yield for the crop specified over six 3-year rotations (18 year total period).

Management System	Crop Yield (Mg ha^{-1} y^{-1})			Crop Rotation Energy Balance (GJ ha^{-1} y^{-1})		
	Corn	Wheat	Soybean	Farming Energy Inputs	Food Energy Output	Net Energy Gain
Conventional	5.90	3.54	2.33	7.1	72.7	***65.6***
No-Tillage	6.25	3.74	2.65	4.9	78.5	***73.6***
Reduced Input	5.23	3.09	2.57	5.2	66.9	***61.7***
Biological	4.08	2.05	2.48	4.8	53.1	***48.3***
Alfalfa	6.85			5.5	26.1	***20.6***

Fig. 10. Crop yields and energy balance for the LTER grain and alfalfa treatments over 18 years (1989-2007; Gelfand et al. 2010).

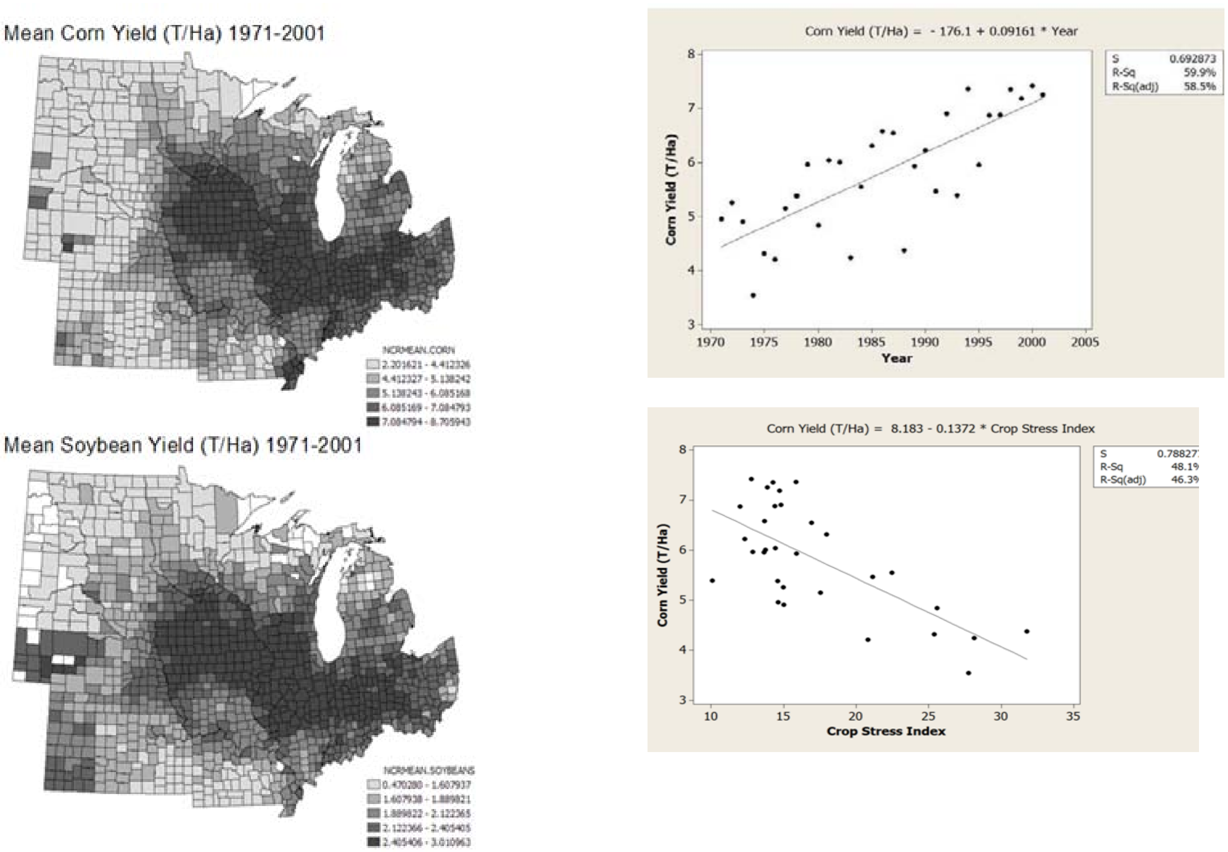


Fig. 11. A (left): Corn (upper left) and soybean (lower left) yields by county across the Midwest US. B (right): Increasing corn yields over time (upper right) and the relationship between corn yield and the Crop Stress index (lower right). From Gage and Safir (2010).

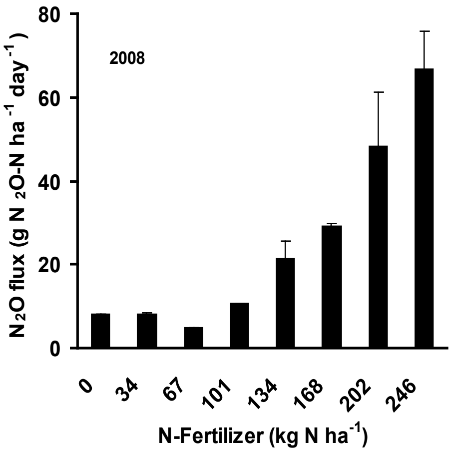


Fig. 12. N_2O emission response along the Nitrogen Fertility Gradient Experiment (see Fig. 8 legend) for the 2008 corn crop Millar et al., in prep). Maximum yields were achieved at ~120 kg N/ha (Fig. 8).

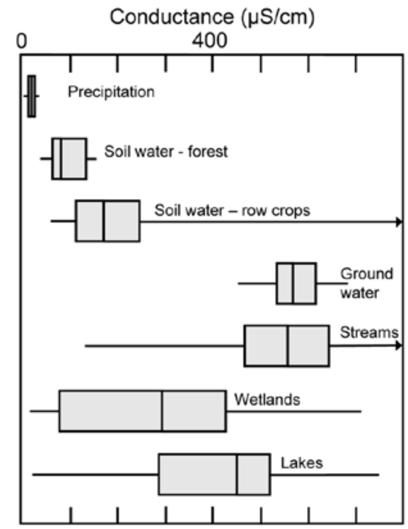


Fig. 13. Specific conductance in diverse waters at KBS site, representing hundreds of samples collected between 1996-2008 (Hamilton 2010). Soil water is collected from low-tension suction samplers at 1.2m depth.

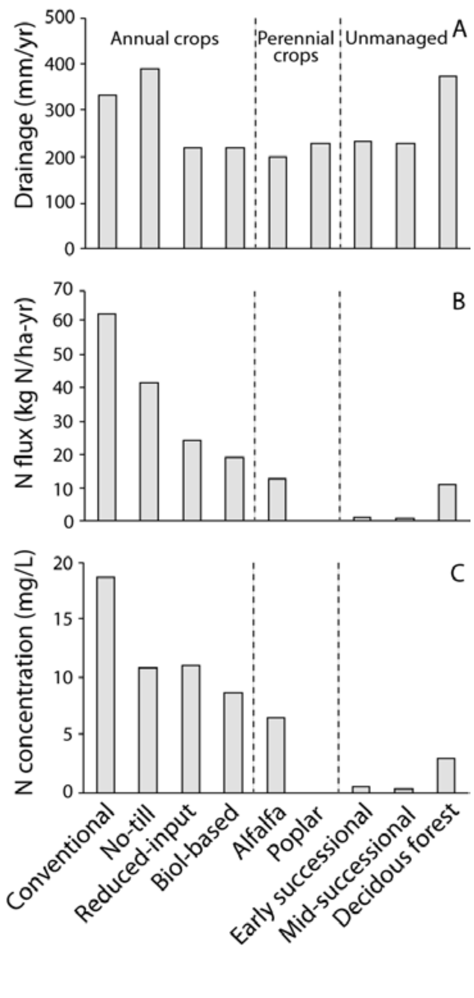


Fig. 14. Nitrate (NO_3^-) leaching losses from the LTER treatments (Syswerda et al. 2010a). Modeled water drainage (A) was combined with NO_3^- concentrations measured at 1.2 m depth during periods of drainage to estimate mean annual NO_3^--N fluxes (B) over an 11-year period (1995-2006). Volume-weighted mean NO_3^--N concentrations in drainage water (C) were calculated from the flux and drainage data. For the 4 annual cropping system treatments, the 11-year period spanned 3.5 full corn-soybean-wheat rotations. Error bars for (B) and (C) (not shown in this figure) are <10% of mean values.

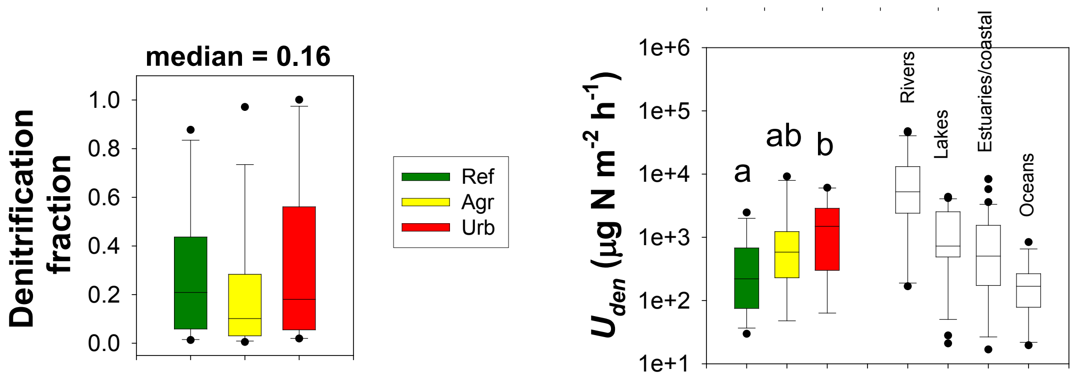


Fig. 15. Stream denitrification results from the Lotic Intersite Nitrogen Experiment (Mulholland et al. 2008). Streams were classified as reference, agricultural, or urban land use. Nine of the 72 experiments were performed around KBS; all were performed in 2003-2006. Figures show the fraction of total NO_3^- uptake ascribed to immediate denitrification (left) and rates of NO_3^- uptake for immediate denitrification compared with other aquatic ecosystems (right).

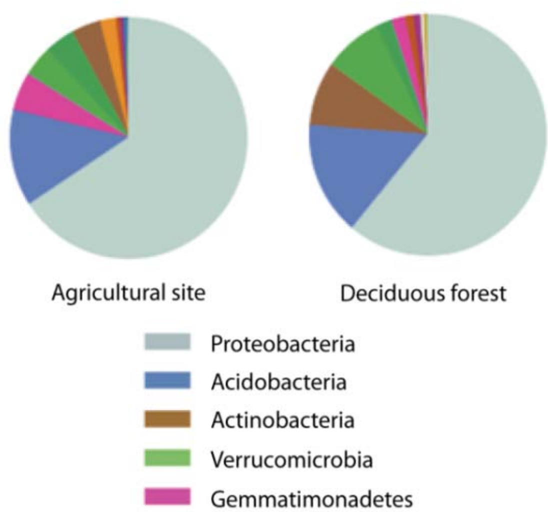


Fig. 16. Phylum level composition of KBS LTER bacterial communities based on ca. 100,000 sequences per site.

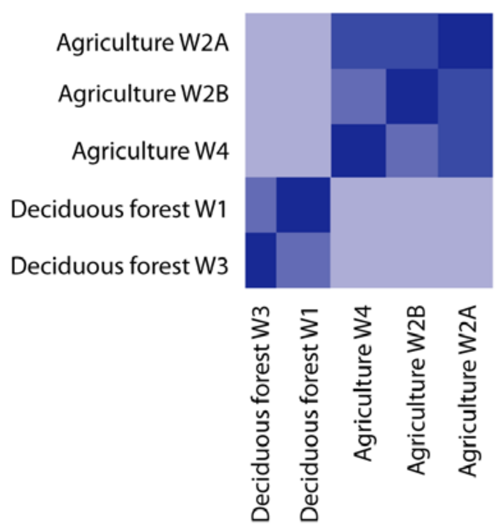


Fig. 17. Species level similarity of KBS LTER bacterial communities based on comparison of 16S rRNA gene sequences. Increased color intensity denotes increased similarity.

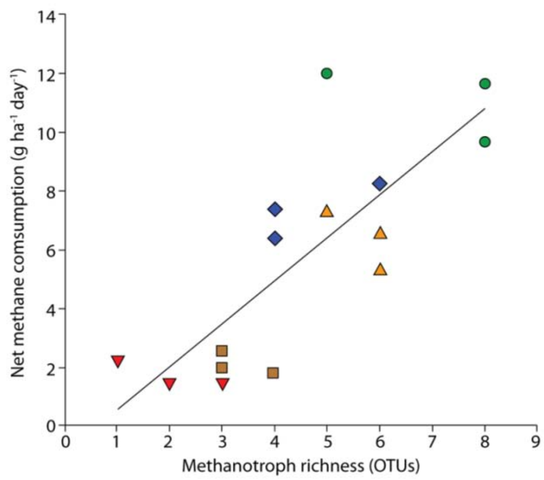


Fig. 18. Correlation between methanotroph diversity and methane consumption (June-August) across landscapes at the KBS LTER. A simple linear regression is presented (r^2 =0.62, p <0.001) with operational taxonomic units (OTUs) defined as peaks in the tRFLP analysis that have been identified as *pmoA* genes. Symbols are as follows: Agricultural management of historically tilled land (Ag; ▼), early successional fields abandoned from agriculture in 1989 (ES; ■), mid-successional fields on either historically tilled (SF; ▲) or never tilled soil (MG; ◆), or a late successional deciduous forest (DF; ●). From Levine et al., in review.

Diversity Level	(Trt)	Total Species	Species/ year
A	(B1-2)	10	5-7
B	(B3-5)	5	1-3
C	(B6-8)	4	1-2
D	(B9-11)	3	1
E	(B12-14)	2	1
F	(B15-17)	2	2
G	(B18-20)	1	1
H	(B21)	0	0

Fig. 19 (left). Layout of the Biodiversity Gradient experiment (1 of 4 randomized complete blocks) on the KBS LTER main site. Each plot is 9 x 30 m. Diversity level refers to the number of species in a rotation (total species), which can be 1-3 years in length.

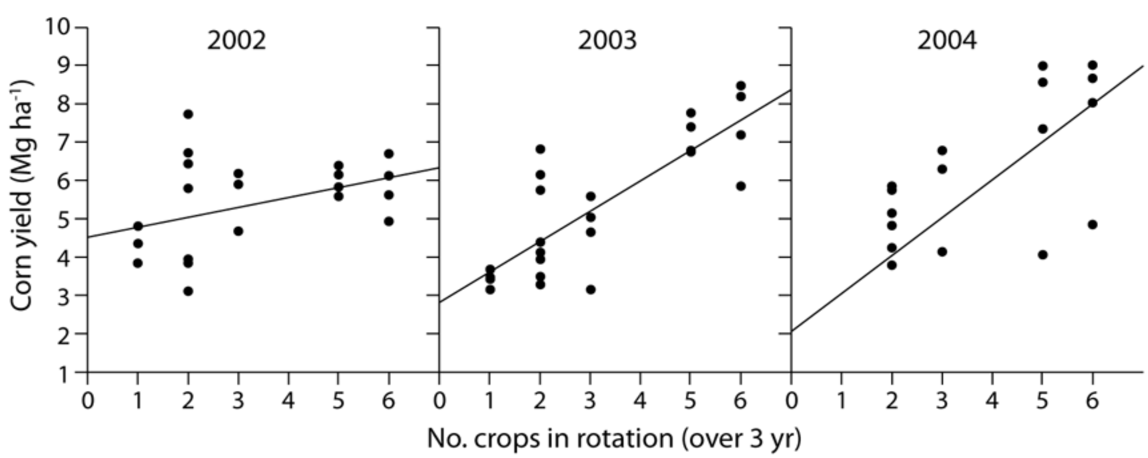


Fig. 20. Regression between corn yield and crop diversity (number of crops over a 3-year rotation) in the Biodiversity Gradient experimental plots across years (see table in Fig. 19). From Smith et al. (2008).

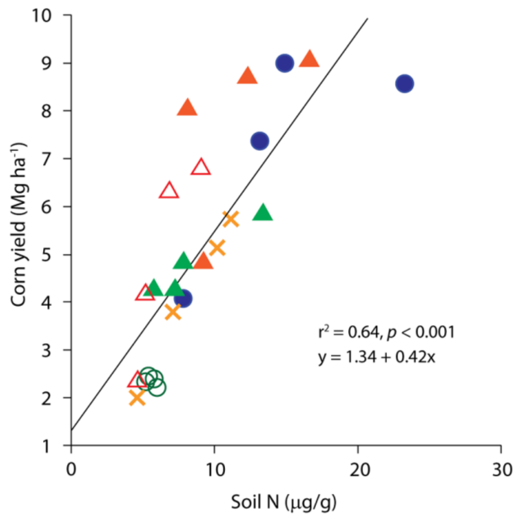


Fig. 21. Relationship between corn grain yields and early season (June) inorganic soil nitrogen during 2004 in the Biodiversity Gradient experimental plots. Symbols indicate different diversity treatments as in Fig. 19: 1(O), 2 (X), 3(▲), 4(∆), 5(▲), and 6 (●). From Smith et al. (2008).

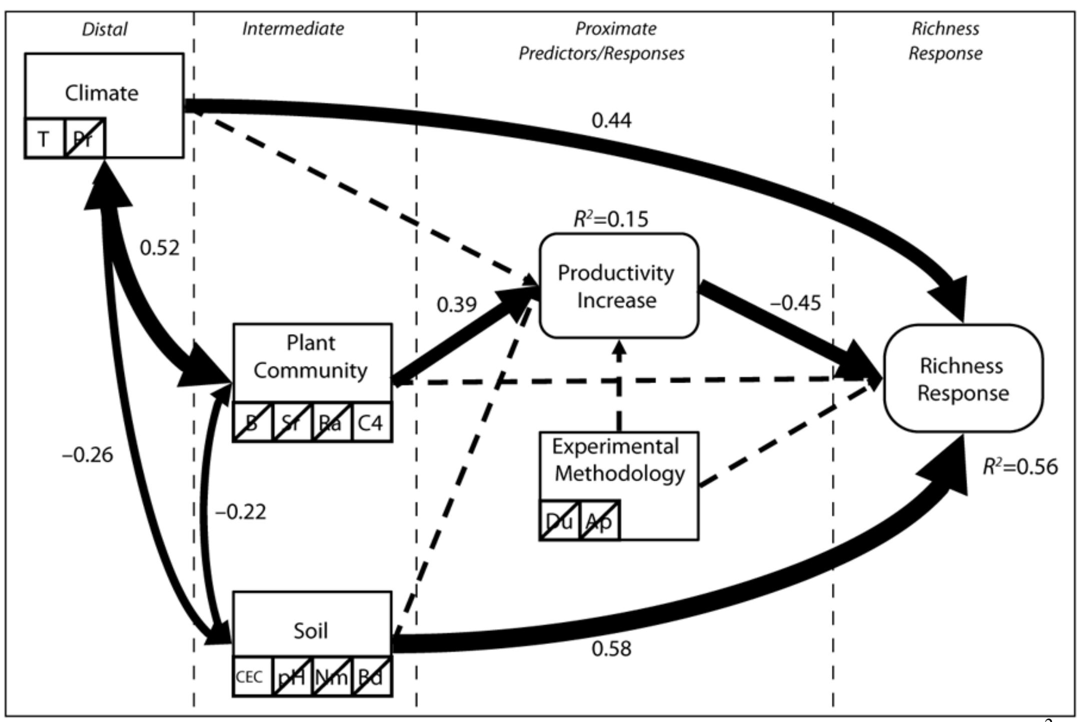


Fig. 22. Structural equation modeling to predict the species richness response to N fertilization (X^2 = 2.838, P = 0.416) based on the PDTnet data synthesis. Partial regression coefficients are given for unidirectional arrows and correlations for bidirectional arrows. Arrow sizes approximate relationship strengths (non-significant pathways are dashed). Predictors are T, temperature; Pr, precipitation; B, standing biomass; Sr, species richness; Ra, proportion of rare species ; FG, relative abundance of different functional groups; CEC, soil cation exchange capacity; pH; Nm, net N mineralization over the growing season; Bd, bulk density; Du, duration of study; Ap, fertilizer application rate). Predictors not included in the final model are crossed out. From Clark et al. (2007).

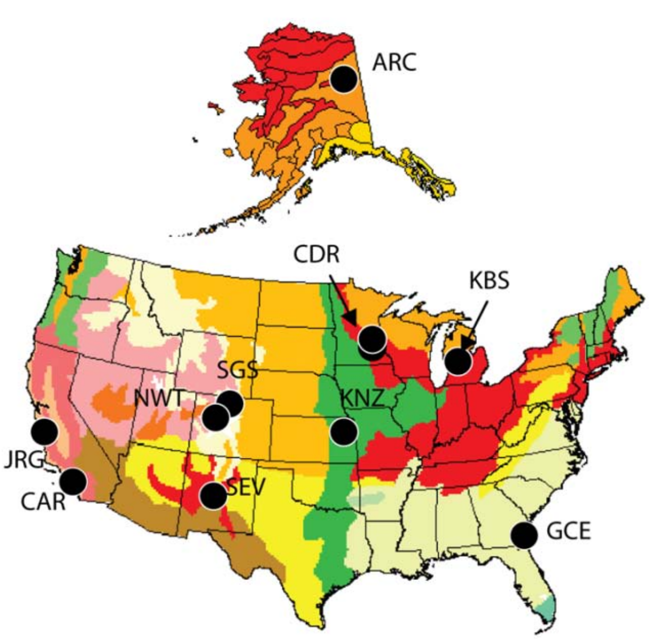


Fig. 23. Location of the 10 sites included in the PDTNetwork analysis of nitrogen enrichment experiments (Cleland et al. 2008). Map delineations are Holdridge life zones. Sites include: ARC (Toolik Lake, AK, arctic tundra); CDR (Cedar Creek Natural History Area, MN, abandoned agricultural fields and native savannah) JRG (Jasper Ridge Biological Preserve, CA, annual grassland); KBS; KNZ (Konza Prairie, KS, tallgrass prairie); NWT (Niwot Ridge, CO, alpine tundra), SEV (Sevilleta National Wildlife Refuge, NM, arid scrub-grassland); SGS (Central Plains Experimental Range, CO, shortgrass steppe); GCE (Georgia Coastal Ecosystems, Sapelo Island, GA, coastal salt marsh) and CAR (Carpenteria, CA, coastal salt marsh).

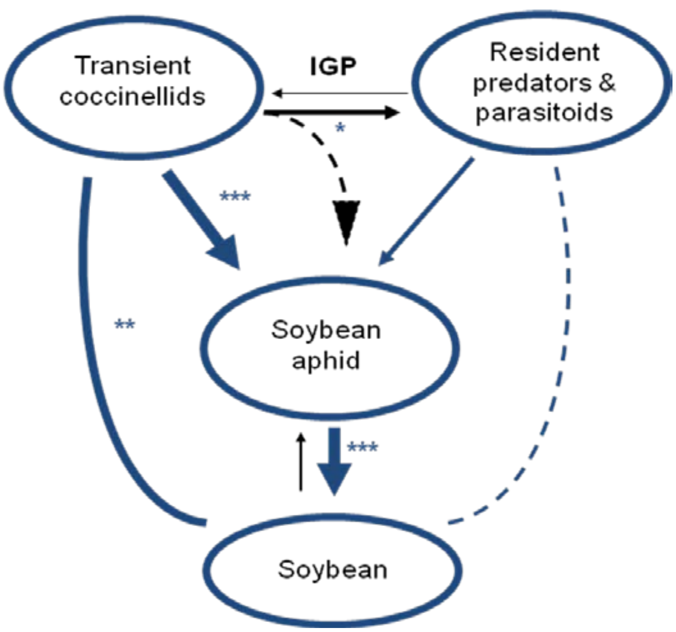


Fig. 24. Summary of tri-trophic level interactions in the soybean aphid system. Thickness and direction of lines indicate the magnitude and direction of negative impacts. Dotted lines represent potential interactions that have not been shown to occur and asterisks represent increasing levels of statistical significance P=0.05-0.001. Data from Costamagna & Landis (2006), Costamagna *et al.* (2007), Gardiner & Landis (2007), Costamagna *et al.* (2007), Costamagna & Landis. (2007), Costamagna *et al.* (2008).

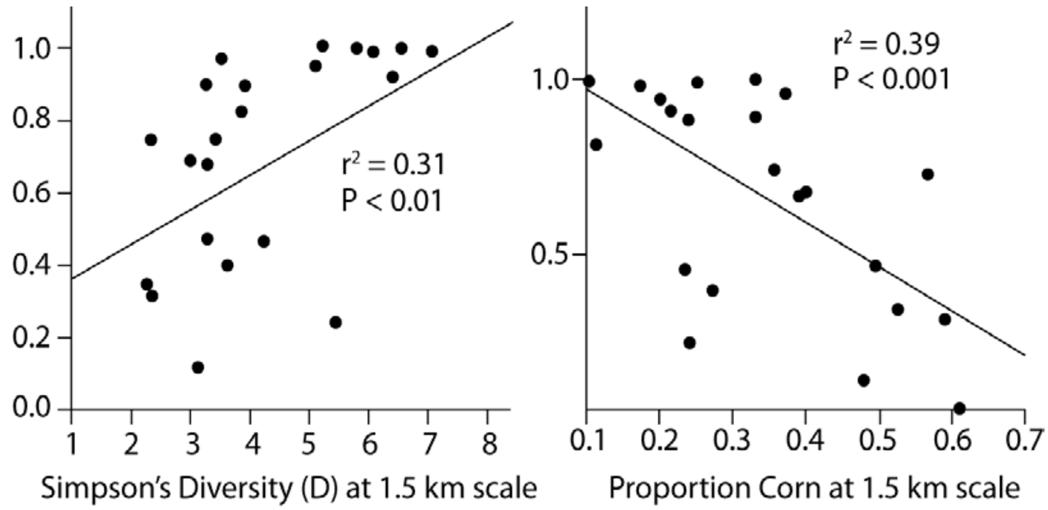


Fig. 25. Relationship of biocontrol service index (BSI) and landscape diversity (left) and BSI versus proportion corn (right) at the 1.5 km scale surrounding the focal soybean field (Gardiner et al. 2009).

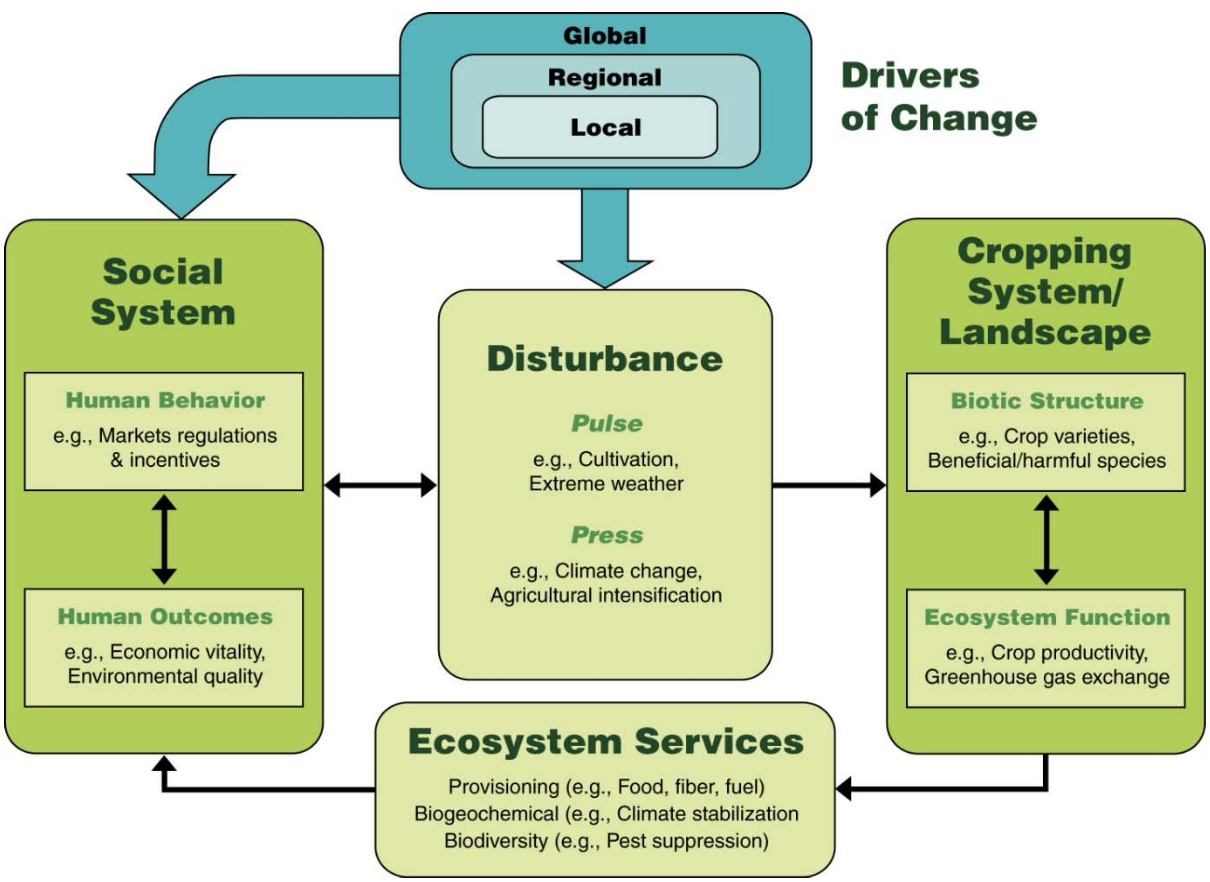


Fig. 26. Conceptual model for the forthcoming phase of the KBS LTER program.

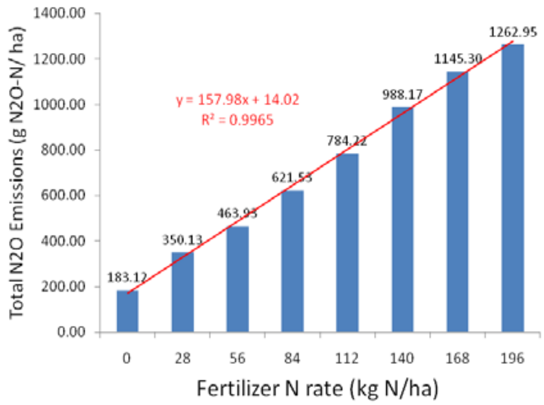


Figure 27. N_2O emission response to N additions in establishment-year switchgrass fertilized at 8 different N rates from 0 to 196 kg N/ha. Each bar represents the average total seasonal flux from 4 replicate plots, each sampled on 19 dates over the period 16 June to 18 September 2009 (fertilized 17 June). From Ruan et al. unpublished.

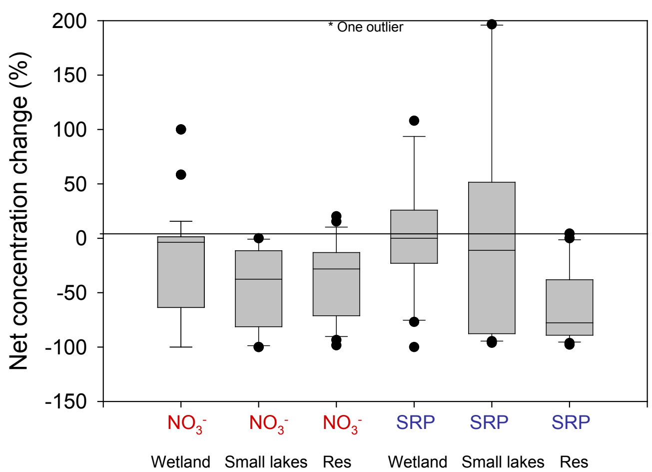


Fig. 28. Net change in concentration of nitrate (NO_3^-) and soluble reactive P (SRP) in through-flow wetlands, small lakes, and reservoirs (18 sites sampled throughout the year: O'Brien and Hamilton, in prep.). Substantial reductions in concentrations were predicted by hydrologic load, a metric that accounts for residence time and depth of the water body.

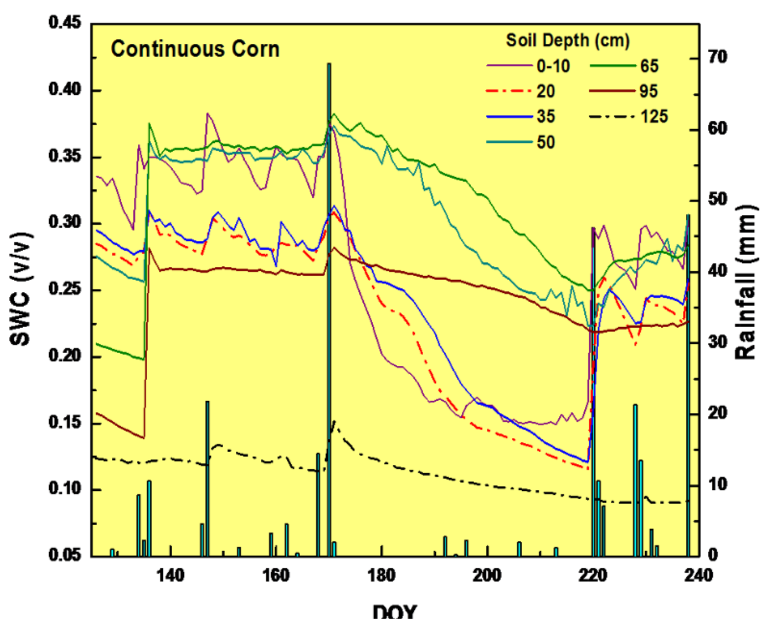


Fig. 29. Volumetric soil water content (SWC) measured by time domain reflectrometry (TDR) probes at the continuous corn treatment of the biofuel crop experiment over the 2009 growing season. Similar data are being collected for a diversity of vegetation cover types including mixed-species grasslands and forest as well as row crops.

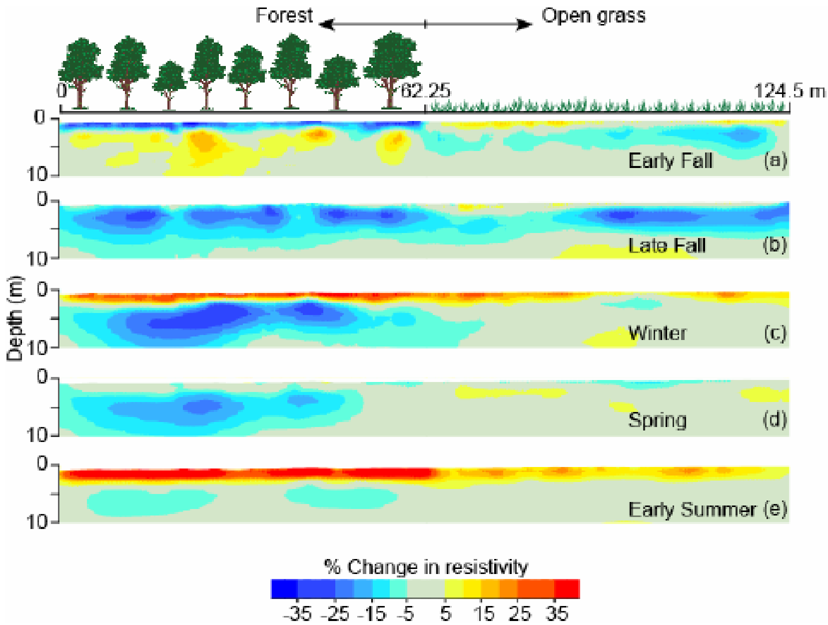


Fig. 30. Electrical resistivity images of soil water at a forest-to-field transect near the MSU campus (from Jayawickreme et al. 2008). An increase in resistivity indicates drying, while a decrease indicates wetting. Similar data are now being collected for a diversity of vegetation cover types including mixed-species grasslands and forest as well as row crops at KBS.

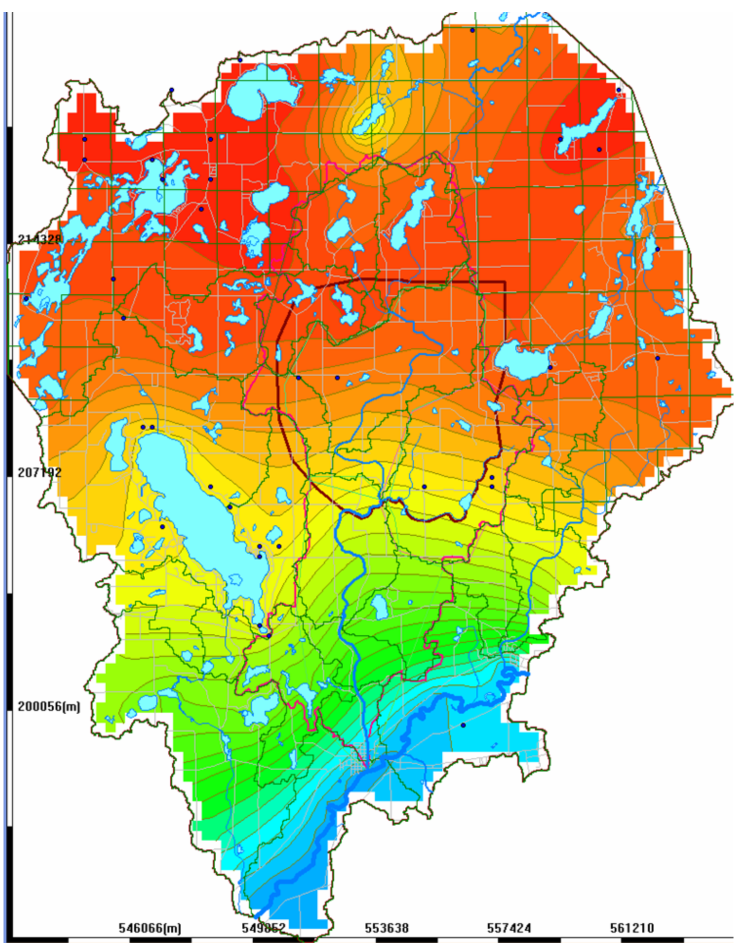


Fig. 31. Groundwater elevation in the vicinity of the KBS LTER, derived from modeling based on well records of static water levels and particle-size composition in the upper (unconfined) aquifers of glacial deposits (Bartholic et al. 2007). Gull Lake is the water body in the southwest quadrant. The Kalamazoo River appears at the bottom of the figure, flowing from northeast to southwest.

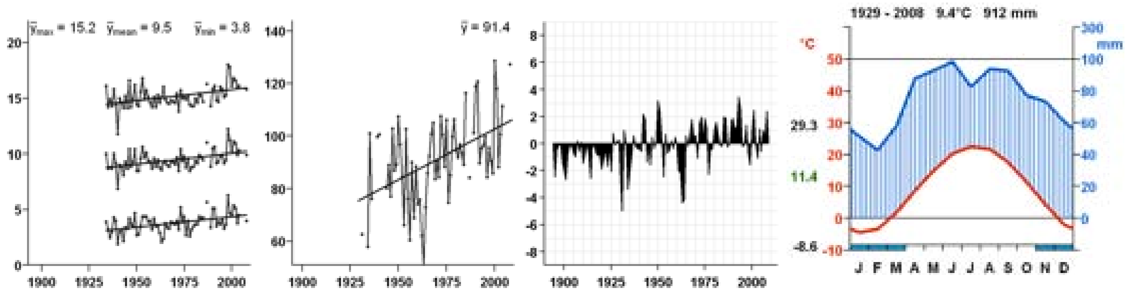


Fig. 32. Long term (1929-2008) trends for temperature and precipitation at KBS. From left to right: a) mean annual maximum temperatures (upper line), minimum (bottom), and mean (middle) in °C; b) total annual precipitation (cm); c) annual Palmer Drought Severity Index (PDSI), and d) monthly average precipitation and mean temperature in a Walter-Lieth diagram. Negative PDSI indicates water deficit conditions for the region. Graphs from Peters et al. (2010); www.ecotrends.info.

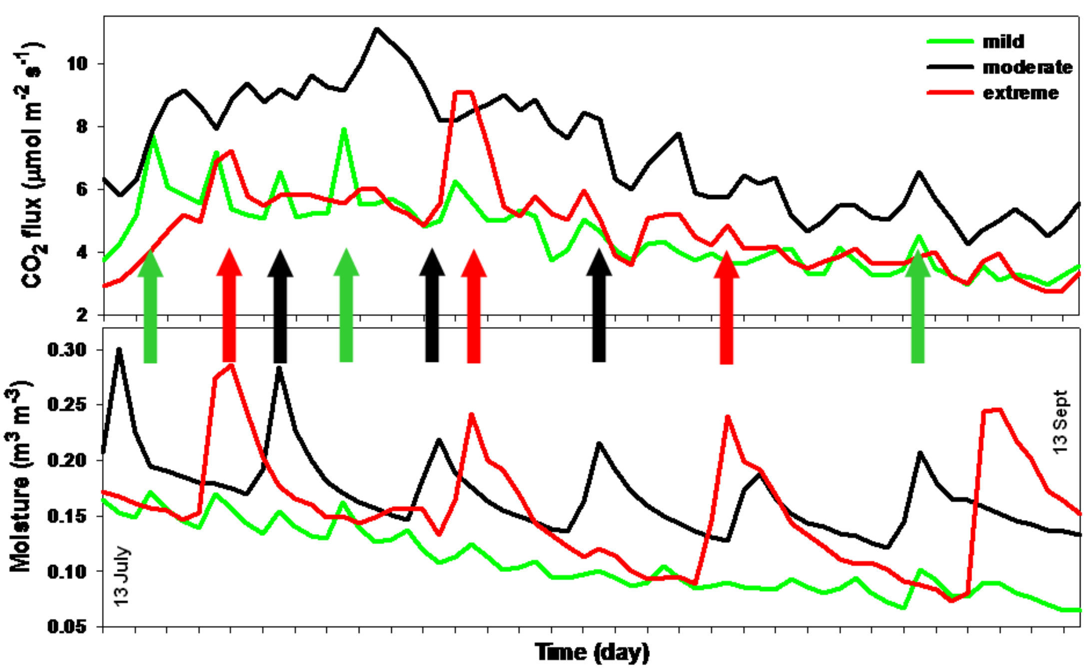


Fig. 33. Effects of precipitation manipulations on soil CO_2 flux (top) and moisture from 13 July to 13 September in the annually tilled microplot of our T7 Successional Field treatment. Precipitation manipulations varied only in the timing of rainfall events – the same total amount of water was delivered to each treatment over the experimental period (May-September): Mild= every 4 days; Moderate= every 10 days; Extreme = every 16 days. CO_2 and soil moisture measured continuously for 80 days with *in situ* real time infrared sensors (Aanderud et al. in review).

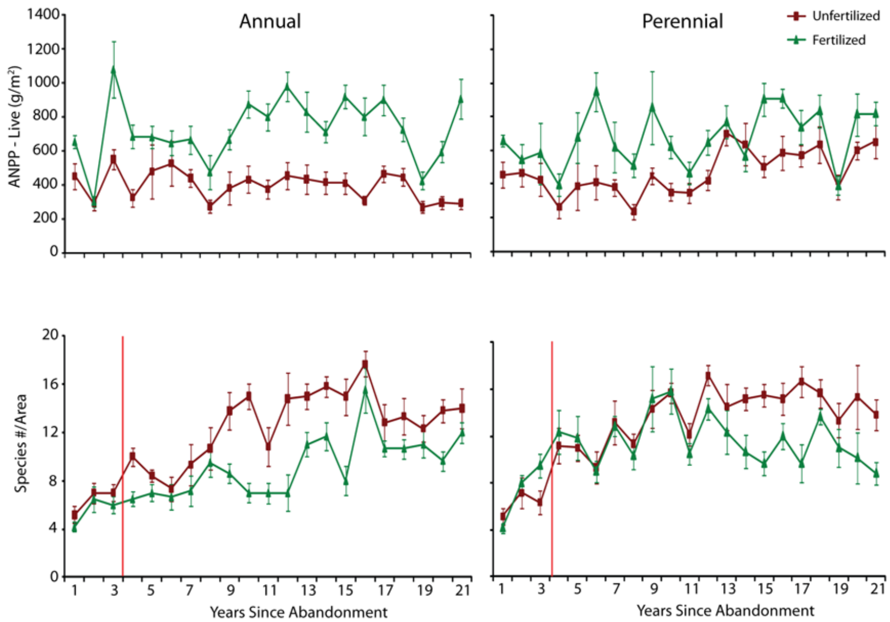


Fig. 34. Annual estimates of above-ground productivity (top) and species richness (bottom) in annual (left) and perennial (right) plant communities in fertilized and control experimental treatments in the successional treatments on the KBS LTER. Species richness is determined from biomass harvests and reported as species per m^2 for years 4-20; species/0.20 m^2 in years 1-2 and species/0.30 m^2 in year 3. Plots were abandoned from agriculture in 1989 (year 1).

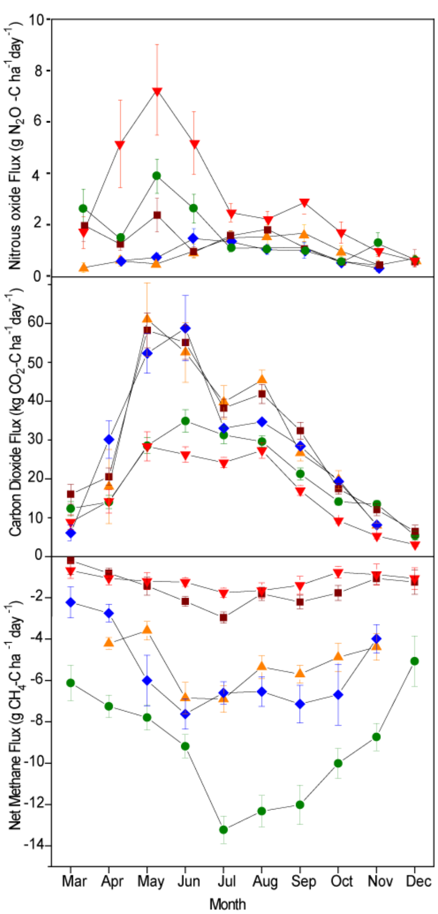


Fig. 35. Average monthly rates of nitrous oxide production (top), CO_2 production, and methane consumption (bottom) by soils at the KBS LTER. Symbols indicate agricultural management: historically tilled land (T1; ▼), early successional fields abandoned from agriculture in 1989 (T7; ■), mid-successional fields on either historically tilled (SF; ▲) or never tilled soil (T8; ◆), and late successional deciduous forest (DF; ●). From Levine et al., in review.

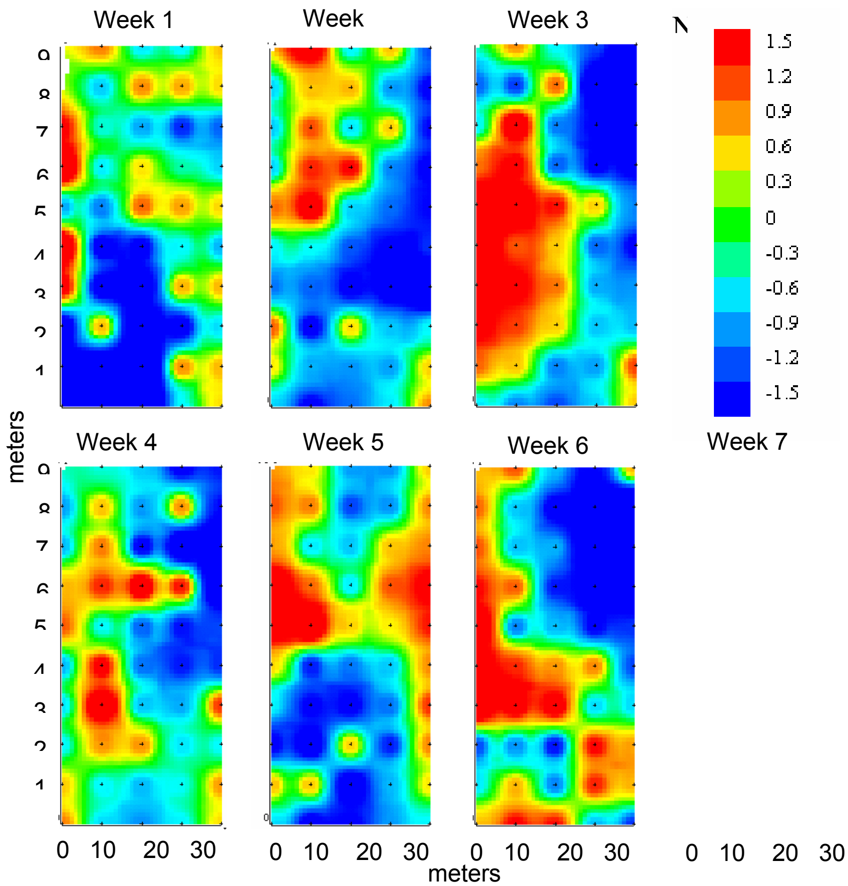


Fig. 36. Spatial distribution of soybean aphid populations over seven consecutive weeks in a Michigan soybean field in 2003. Cluster analysis values ≥1.5 (in red) indicate aphid aggregations, values ≤ -1.5 (in blue) indicate gaps in aphid distribution. Dots represent the sampling coordinates (n = 49 per date). Note the shifting patterns of aphid aggregation driven by transient predators coupled with persistent refuges at the plant scale.

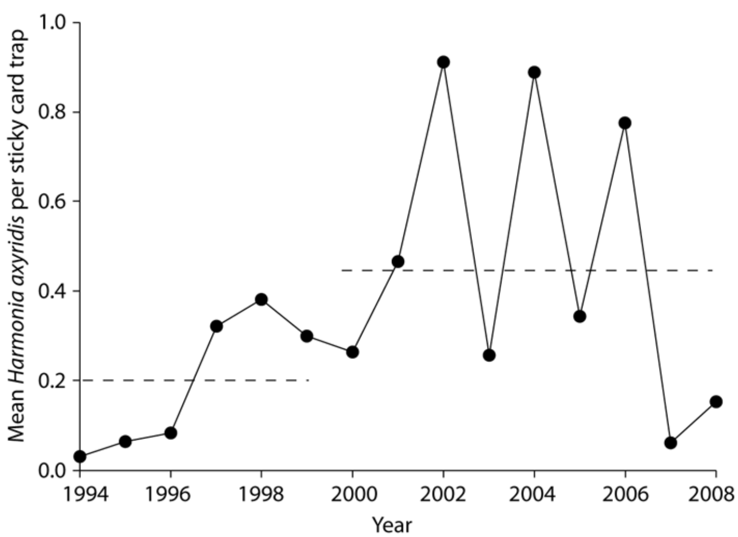


Fig. 37. Mean number of *Harmonia axyridis* captured on yellow sticky card traps placed in multiple crop and non-crop habitats at KBS, 1994 to 2008. Dotted lines show the mean numbers of *H. axyridis* from 1994-1999 (before soybean aphid arrival) and from 2000-2008 (after arrival). Note the response of *H. axyridis* following years of local soybean aphid outbreaks (2001, 2003, 2005).

3.0 Project Management

Overall Leadership. The KBS LTER Project is led by an Executive Committee (EC) chaired by lead PI Phil Robertson. Also serving on the Executive Committee are project co-PIs Kay Gross, Steve Hamilton, Doug Landis, Tom Schmidt, Sieg Snapp, and Scott Swinton, as well as our Education and Outreach Coordinator Julie Doll and our to-be-named Research Coordinator (see below). The EC meets bimonthly or more often as needed. Members of this committee have specific responsibilities:

Robertson as lead PI and chair of the EC provides overall project leadership; he is the principal project contact for NSF, the LTER Network, and the University, and has overall responsibility for senior project staff.

Each co-PI actively participates in all decisions regarding project coordination, management, and scientific direction; supports site promotion including hosting visitors, providing presentations, and promoting the use of the site by students and colleagues; leads efforts to secure outside funding for workgroup research; participates in Network-level activities; and prepares or coordinates workgroup data for incorporation into the site database. Additionally, each co-PI leads specific research areas:

- Agronomic Dynamics (Snapp)
- Plant Dynamics (Gross)
- Microbial Dynamics (Schmidt)
- Insect Dynamics (Landis)
- Human Dynamics (Swinton)
- Watershed (Hamilton) and Field-scale (Robertson) Biogeochemistry

Project Coordinators. Two academic specialists provide high-level project support and coordination. These are new positions, created with university support in 2009, intended to address leadership transition issues identified in our 2007 site review. A follow-on internal review in 2008 identified alternatives for addressing these issues, among them the creation of positions to provide administrative support and leadership in the areas of outreach and overall research coordination. These positions, coupled with the creation of oversight committees, have allowed Robertson to continue as lead-PI. Both are academic specialist (non-tenured faculty) positions funded with a university cost-share contribution (see Section 7).

One position is a ***research coordinator position***, expected to be filled in spring 2010. Responsibilities of this position include promoting research potentials to prospective investigators, including students; coordinating KBS participation in network partnerships and responses to network initiatives; organizing all-scientist meetings; helping to organize responses to emerging research opportunities; preparing reports to agency and other partners; coordinating annual reviews of project and information management activities; and acting as first point of contact for prospective investigators.

The ***outreach/education position*** is held by Julie Doll, who is responsible for the development and delivery of educational and outreach programs and materials. This includes workshops for stakeholders, including agribusiness professionals, farmers, extension educators, staff of state and federal regulatory agencies and NGOs, and other publics as described in Section 5. Doll works closely with other faculty and staff involved in education/outreach at KBS, particularly MSU Extension personnel. She is also responsible for coordinating programs for graduate students and undergraduate interns working on site, and works closely with the KBS GK-12 and Math and Science Partnership coordinators (Section 5).

Committees. Three project-wide committees currently advise the Executive Committee in specific areas. Members of the ***Research Advisory Committee***, co-chaired by Hamilton and Swinton, include both KBS co-Investigators and researchers not otherwise associated with LTER, and provide advice on research direction and new initiatives. This committee, first formed in 2008, meets twice per year. The ***Education and Outreach Committee***, co-chaired by Gross and Schmidt, is charged to provide advice on K-20 and public outreach efforts, and also meets twice per year. C.W. (Andy) Anderson, our network educational representative, also helps to lead this committee. A third, ***Agroecology Committee***, is co-chaired by Snapp and Landis and provides agronomic advice, including specific management recommendations for our main cropping system experiment. Included on this committee, which meets twice per year, are farmers, county extension educators, and university field crop specialists. A new ***Information Management Committee*** will be formed in 2010 to provide advice to the EC and Information Manager on data recruitment issues as described in Section 4.

Technical Staff. Core project staff include a Project Manager (Stacey VanderWulp) responsible for most core sampling activities including analyses, and who reports to Robertson. VanderWulp supervises the laboratory staff that includes a research technician (Cathy McMinn) and 2-3 seasonal employees. Our full-time Information Manager (Sven Bohm) also reports to Robertson and is responsible for data management. A second database programming position is being added in 2010 (see Sections 4 and 7.4).

Co-investigators. Co-investigators (Section 8) are organized into the six research topic areas noted in Section 2 and above. The purpose of the topic groups is to stimulate discussion of research results and plans among members of the groups to better identify emerging topics and trends that bear further investigation. A number of the projects underway on site with non-LTER funding emerged from these types of discussions. Topic groups meet irregularly at the discretion of the topic group leader, but at least annually at our all-scientist retreat. This is usually an overnight meeting at KBS that involves research presentations, posters, and discussion groups. Our 2009 meeting (http://lter.kbs.msu.edu/meetings/16) had 88 participants.

Site Promotion. We promote use of the site by actively encouraging colleagues and students to consider research at KBS, and through our web site (http://lter.kbs.msu.edu/) at which we post site description and access information. During the period 2004–2009 we hosted 79 non-LTER funded research projects on site, ranging from $5k doctoral dissertation improvement awards to several >$1M/y collaborations. Nineteen of these projects are led by non-MSU researchers. Funding agencies include USDA (NRI/AFRI, Sustainable Agriculture, NCR Regional Projects, and Special Grants programs), NSF (Ecology, Ecosystems, DDIG, RTG, EHR, ICEB, Biocomplexity programs), DOE (Global Change), Canada's NSERC/CRSNG, the Michigan Agricultural Experiment Station, and private foundations such as the A.W. Mellon Foundation and the Electric Power Research Institute. In 2008 the Univ. of Wisconsin and MSU formed the DOE Great Lakes Bioenergy Research Center (GLBRC); the sustainability portion of the Center (~$4M/y) is based at KBS with field sites at KBS and Arlington, WI (see Section 2).

Site Access. As do other LTER sites, we maintain the KBS site as a national research facility available to all scientists with a legitimate research interest. Access to the site is limited in order to protect the integrity of existing experiments, but we welcome additional experiments and sampling activities that 1) are relevant to overall project goals of understanding ecological interactions in row-crop ecosystems, 2) are best answered in a stable long-term experimental setting such as that provided by the LTER site, and 3) meet the project's data-access criteria. We require of researchers working on site or with samples from the site written assurance that they will follow procedures expected of all researchers on site (explained at http://lter.kbs.msu.edu/about/site_access/about.php). We require of all researchers submission of a formal site use request form (via a form at the url above) that is reviewed and approved by the PI and EC.

Leadership Change. Since the beginning of the last renewal period we have had a normal level of senior and co-investigator turnover. Long-time co-PI Stuart Gage retired in 2008 and with this proposal rotates out of the co-PI group. In 2005 the university created a senior faculty position in soil and cropping systems ecology to fill the absence created by Dick Harwood's earlier retirement, and Snapp was recruited to that position and is now a co-PI. Robertson, Gross, Hamilton, Landis, Schmidt, and Swinton continue as co-PIs from as early as 1988. Three additional faculty positions with LTER associations have been created at MSU since 2004, partly in response to NSF reviews, and will add considerable strength to the project. Stuart Grandy was hired into a soil biology position created after Eldor Paul's retirement, and two Sociology positions were created in 2009 to strengthen our ability to address socioecological questions: Diana Stuart will join MSU in 2010, and an Assoc. Professor now being searched will also be associated with the project. These four additions to the MSU faculty since 2004 are an additional signal of MSU commitment to project success (see also Section 7.4 University Cost-sharing). We are hopeful that Gage's large-scale modeling / regionalization expertise will be likewise replaced in the coming years.

4.0 - Information Management

Philosophy and Goals

Our priority for data management is to curate and distribute accurate research data from the site in a consistent, timely, and accessible manner. We serve information to local, Network, and community-based users, and strive to do so in a way that facilitates interdisciplinary research. Our primary goals are 1) to ensure the long-term integrity of KBS databases, 2) to allow data to be retrieved easily, 3) to facilitate the inclusion of data collected by site investigators, and 4) to provide metadata sufficient to allow appropriate analyses and interpretation by future investigators.

Information Management System (IMS) Design and Implementation

Scope. Data collected as part of KBS research activities are managed locally on PostgreSQL and PostGIS open-source, object-relational, scalable database systems that run in a Linux environment on our database servers. The servers are mirrored on campus, 60 miles distant, via a Gigabit fiber connection to the National LambdaRail. A local telecom company provides a 10Mb/s backup link (Table 4.1).

All data and metadata are made available online as specified and prioritized in the Data Access Policy for the LTER Network. Our policy (http://lter.kbs.msu.edu/data/terms_of_use.php) relies on ethical behavior in terms of the use of the data by others, and stresses that investigators who have collected the data have primary rights to publication; beyond this we put no restriction on use of data by others and we do not track data access. Core data are available to researchers as soon as they are uploaded and quality checked.

No data are stored off-line, and our publications database (http://lter.kbs.msu.edu/publications) serves publications by year, author, experiment, and treatment. We also include research protocols, including step-by-step instructions for field and lab personnel, in our publicly accessible database.

Various GIS files, imagery and thematic maps are accessible via our Maps and Imagery web section. LIDAR elevation surveys and ground-based GPS elevation surveys are presently managed with PostGIS, an extension of PostgreSQL for spatial data. This year we will move all core GIS files into PostGIS, which will facilitate access of these files from our website. Aerial photos taken annually are made available from our website as KML files for viewing in Google Earth or as .jpg files. All airphoto missions and metadata are detailed on the web; photos (many orthorectified) are available at full resolution by request. Software in use includes ArcGIS as well as image analysis software (ERDAS and Definiens). GIS-grade GPS is used to track sampling locations.

We also maintain a catalog of archived samples—primarily stored soil and plant material dating from project inception in 1988 (Table S2). Physical samples are stored in two purpose-designed archive rooms in a new LTER field lab built in 2008. In one room ground plant samples are stored in metal cabinets and microbial samples in -80^{o} freezers; another room houses ~2000 ground soil samples in boxed mason jars. The building has automated backup power and archive rooms are fire-protected by a CO_2-based system.

Since 2001 we have collected real-time sensor data from our weather station, and more recently from our CO_2 towers, TDR installations, and continuous trace gas monitoring systems. Datalogger data are collected via our network of RF401 radios, while data from the flux towers and trace gas monitoring are collected via 802.11b wireless links. Data are retrieved with the Campbell Loggernet software, or via polling from a local message server. Custom scripts check for invalid entries and upload the data directly to the database. If the polling is interrupted for more than one day, an instant message is sent to the information manager.

Design

The KBS IMS conforms to current best practices with respect to data and metadata encoding, backup and media migration, system administration, security, scalability, and query capability. It is designed as a series of loosely coupled RESTful web applications with a central Postgres database acting as the integration point. By adopting a RESTful application design, caching and scaling technology developed for the web can be used to scale the system outward in response to higher loads. By keeping the system modular, upgrades in one part of the system do not affect the availability and functioning of other parts. It allows us to test new functionality in a separate application and later extract the functionality if it is used in multiple contexts. We are striving to push data upload and QA/QC capabilities out to the users and minimize the involvement of the IM staff, this allows us to maintain more data without larger IM staffing. Development of the QA/QC applications and the main metadata application are done in a behavior driven development style which provides us with a testing framework that allows changes to be made while ensuring that the system remains stable and functional.

We store all non-spatial (and some spatial) data in the core database. HTML, EML, and comma delimited representations of the data/metadata are generated on the fly from the database; this ensures consistency among the different representations. Storing data in a central database makes it possible to query the data efficiently and quickly. Keeping the logic of the IMS system in the middleware allows us to remain database agnostic and will simplify future technology transitions. In addition we use open data formats as much as possible to ensure the long term accessibility of the data.

System administration. Routine server and data maintenance and monitoring are automated whenever possible. Where QA/QC apps are not used, custom scripts are used to transfer and upload data and the scripts are archived alongside the voucher data to provide documentation of the procedures used. Users are managed through an NT Domain style system, but we plan to move that responsibility to the Station's IT team as they make the transition to MS Active Directory.

Security. All access to the database through the website is routed through prepared statements to prevent SQL injection attacks. The database ports are firewalled to prevent access except from specific IP addresses or through the KBS VPN system, with all communication with the database SSL encrypted. User access to the machines hosting the database is restricted. The user account for the web app has only read access to the data layers, but has read/write access to the metadata. QA/QC apps have read/write access to their data only. Postgres has functionality to ensure database integrity and access controls.

Full weekly backups are supplemented with daily incremental backups, with encrypted copies made both to tape at KBS and to disk space at the Network Office in Albuquerque. Tapes are moved to other buildings on the KBS campus. An annual snapshot of the database and voucher data is copied to optical write-once media stored in the IM office. Daily backups are kept for 3 months, weekly backups are kept for 6 months, and one weekly backup per month is kept for 24 months.

To date, we have not had need to store sensitive data such as the location of endangered species or personal information, but have the capacity to do so, either by using security features available in PostgreSQL or by implementing appropriate controls in the middleware.

Web page. Our data catalog web page (http://lter.kbs.msu.edu/datasets) conforms to the 2008 Guidelines for LTER Web Site Design and Content. This includes presentation of the LTER Network identity; links to other sites via siteDB; a hierarchical navigation system that includes a whole-site (including database) search capability; and other compliant content: 1) identification of signature data sets at the top of our catalog page; 2) a database search capability by core area, owner, and keyword; 3) links to the network MetaCat system and to network-wide databases such as ClimDB and EcoTrends; 4) Links from our home page to our data catalog; to contact information; to a searchable personnel directory; to our searchable site bibliography; to research highlights ("vignettes"); to summaries of our research foci, goals, and each of our long-term experiments; to our education and outreach activities; to our data access policy; and to our site access policy and request forms; 5) information for visiting researchers is provided via a link on the Station's web site (www.kbs.msu.edu), as is a calendar of events and a jobs and internships listing; and 6) documentation of IMS architecture, procedures, and protocols.

Staff. Data management is supervised by a full-time professional Data Manager (Sven Bohm) who coordinates the data-related activities of Project Manager (PM) Stacey VanderWulp (responsible for

QA/QC, synthesis, and summary of most core datasets, protocols, and metadata updates), Suzanne Sippel (responsible since 2003 for GIS, remote sensing, and other spatial datasets), and Barbara Fox (responsible for managing the KBS LTER web site). This model has been in place since 1997 and has worked well. We are currently in the process of hiring a database programmer to work under Bohm's direction (see Section 7.4); this will provide additional time for recruiting student-derived datasets to the catalog.

Review. Our IMS is reviewed for content and presentation, and sections revised as required when needs are identified by our information manager, staff, or researchers. Our main data catalog page was completely overhauled in 2009, for example, in response to the need to make the site network-compliant and more user-friendly, and our spatial data (aerial photos, GIS layers, maps) were reorganized several years ago in response to researcher requests. Our mid-term site review in 2007 noted that we "have developed an excellent information management (IM) program over time" but also identified areas for improvement:

- *Graduate student training and the incorporation of grad student datasets into our IM framework.* We encourage graduate students and others working on site to archive their data in our data catalog (and in fact make it a check-off requirement for site access) but have not to date had the resources to actively encourage or enforce compliance. A standard data submission protocol was implemented in 2007 (http://lter.kbs.msu.edu/about/site_access/data_submission.php) and has made submissions easier, but what is most needed is an individual to bird-dog investigators. The planned addition of IM staff will help, and we will additionally implement a project tracking function.
- *An IM committee to advise the PI and IM on data recruitment issues.* We have not to date formed a permanent IM committee, but in light of growing needs and additional resources, will do so in 2010. An initial charge to the committee will be to develop recommendations for graduate student IM orientation and for effective ways to encourage non-core data submission.
- *The IM should stay in regular contact with other members of the LTER IM network and participate in Network activities.* Bohm fully participates in Network IM activities; see below.
- *Links to LTER network databases be included on the KBS website, and to network collaborations.* This is now a Network compliance issue and to the best of our knowledge we are fully compliant.

Integration with site science. We make available to all investigators, including graduate students, advice on integrating project science into the KBS IMS, and have attempted to clarify and streamline the IMS data and metadata submission process.

Policies. Our data release, access, and use policies comply with LTER Network policies as noted earlier, and are clearly stated on our web page, as are suggested acknowledgements for publications.

Metadata. Metadata are EML 2.0-compliant at level 5 for all datasets. We will be upgrading to the new EML version 2.1 soon. Metadata are stored in the relational database alongside the data. Computable metadata attributes are queried from the data to be sure metadata do not become outdated.

Data. Data generated by the core laboratory are screened initially by PM VanderWulp, who reviews data with the appropriate co-PI and then transfers the data to IM Bohm. Individual investigators are responsible for QA/QC of their own data, though a secondary review by the PM or IM has at times caught early errors. The IM then works with the lab that generated the data to ensure that the metadata standards are met prior to organizing and posting the data on-line. As resources allow, the information manager periodically reviews/validates key datasets.

Contributions to LTER Network and community activities. IM Bohm attends all LTER Information Manager meetings and is currently a member of the IM Executive committee. He participated in the 2009 projectDB workshop and has been active in the Controlled Vocabulary group. KBS will host the 2010 annual IM meeting. We consistently contribute data to the Network databases ClimDB and HydroDB and have contributed 55 datasets to EcoTrends (excluding the 359 economic datasets from non-KBS sources).

Table 4.1. Key features of the KBS Information Management System.

Feature	Details
Local Area Network	Supported by MSU (Station-based) IT staff; Windows domain supporting a mix of Windows, Linux, and Mac workstations and servers; Gigabit connections between buildings and routers, mix of Gigabit and 100Mb/s service to the desktop; fiber optic connections installed in 2009 to LTER field lab and main research site, wireless connections to other sites.
WAN Connection	Gigabit fiber connection to the LambdaRail, backup by 10Mb/s link to TDS.
Web Server	Apache web server running on a pair of virtual machines to provide automatic failover and load sharing (Ubuntu Linux).
Database Software	Postgresql 8.4 and Postgis on Dell Poweredge and IBM xSeries servers , hosted on Ubuntu Linux. Hot spare on campus linked by WAN connection above.
File Server	Windows 2000 on IBM xSeries server; 1Tb RAID 5 + 1 SCSI disk array.
Data Retrieval	Download of datasets through the website. Direct read-only access to the database as requested.
Data Storage	RAID 5 + 1 hot spare on all servers, hot spare database server on campus. Current storage available ~ 7 Tb, storage array allows relatively inexpensive expansion to 17 Tb.
Backup	Daily incremental backups and weekly full backups of servers, with co-PIes to tape at KBS and to disk space hosted by the Network Office in Albuquerque. Tapes are moved to other buildings on the KBS campus. Annual snapshot of the database and voucher data co-PIed to optical write once media, stored in IM office. Daily backups are kept for 3 months, a weekly backup is kept for 6 month, a monthly backup is kept for 24 months. Automated reports of backup failures are sent to the IM and MSU IT staff.
Wireless	Wireless 802.11b cloud at the LTER site and building managed through MSU Wireless services; point to point 802.11b on site for instrumentation. Campbell RF401 network for lower throughput sensor connections.
Monitoring	Reciprocal service monitoring deamon software watches servers, databases, websites, and data loggers for failure every 5 minutes, with instant message notification to the IM (http://mon.wiki.kernel.org/index.php/Main_Page).
Video conferencing	Polycom station available in KBS library; a conference room is now being renovated into a Polycom teleconference facility ($200k).
GIS	ArcGIS, ERDAS, Definiens, PostGIS, Geoserver, Trimble GIS-grade GPS recievers

5.0 Outreach

We place a high value on outreach activities locally and nationally and actively seek opportunities to educate the public, policy makers, students, teachers, and agronomic and natural resource professionals about the ecology of row-crop landscapes and the importance of taking a systems approach to their understanding. In 2009, with University support, we recruited LTER Education and Outreach Coordinator Julie Doll to lead and facilitate LTER outreach efforts. We detail below activities in specific areas.

5.1 Educational Activities

K-12 Educators. The KBS-K12 Partnership for Science Literacy (www.kbs.msu.edu/education/k-12-partnership), supported since 1996 with sLTER funds, continues to provide ~80 science teachers from 14 districts around KBS in-depth exposure to ecological science topics based on LTER core areas. The Partnership supports four 1-day school-year workshops for teachers plus a week-long summer science institute. We have leveraged sLTER resources with an EHR Teacher Retention and Renewal award (2000–2005), an NSF Targeted Math and Science Partnership grant with three other LTER sites (2008–2013), and two GK-12 awards (2005–2008 and 2009–2014) that have supported graduate fellows' working directly with teachers in their classrooms. Eight GK-12 fellows per year are based at KBS.

University Students. A number of educational programs affiliated with KBS, MSU, and nearby colleges and universities continue to use the LTER site for formal teaching activities, including classes from MSU (both KBS and campus-based courses) and the University of Michigan. We have also supported REU and other undergraduate interns to work on site to gain hands-on research experience with support from NSF, DOE, and other sources; this includes 35 students since 2004, including many in underrepresented groups. Graduate students are actively encouraged to participate in all aspects of LTER research and outreach activities, including All Scientist Meetings. Since 2004, 42 students have received their degrees working on site (see Section S1 Publications) and currently 26 LTER students are pursuing dissertation research. We have also contributed LTER data to the Ecological Society's *Teaching Issues and Experiments in Ecology* series on climate change and agriculture (Wilke and Kunkle 2009).

Working Professionals. The KBS LTER site has been used extensively for continuing education for professional groups including county Extension educators, agricultural consultants, NRCS staff, and farmers. Since 1995 we have annually hosted part of an international Agricultural Ecology course sponsored by various international development agencies such as USAID, USDA-FAS, the CGIAR system, and the World Bank; an International Biofuels course started in 2009. Recent educational programs included field days (summer 2007 and fall 2008) that attracted hundreds of regional farmers and Extension educators; two training workshops for national conservation staff and Extension professionals (summer 2008); soil quality and cover crop workshops (winter and summer 2009); and a workshop on sustainable food and fuel systems (summer 2009) for over 50 Extension educators from 7 states.

Public. We have expanded our efforts to reach citizens by sponsoring educational booths at local and state venues – e.g., county fairs and expos – where LTER staff and scientists share our research with a wide variety of audiences and ages. In 2009 we contributed a Greenhouse Gas Calculator to the Smithsonian's Dig it! soil exhibit; this professionally-animated interactive activity puts students in the role of a farmer, deciding what crops to grow and what farming practices to use to balance high yield with lower greenhouse gas emissions. Over 2,000,000 visitors have seen the exhibit since its opening in July 2008; the calculator is also on-line (http://forces.si.edu/soils/index.html) with K-12 curriculum materials under development. In addition, we are in the process of making LTER research results more accessible to the public via research highlights on the KBS web page (www.kbs.msu.edu/research/lter), and we are developing a walking tour of our main site with assistance from an undergraduate education intern.

Policy Makers and Media. We place significant value on efforts to educate and inform national and state decision makers. In 2005 PI Phil Robertson participated in a congressional briefing on broader impacts of LTER research, sponsored by AIBS; in 2007 co-PI Kay Gross participated in a congressional briefing on ecosystem services from agriculture co-sponsored by the Ecological (ESA) and Agronomy (ASA) Societies; in 2008 Robertson and co-PI Doug Landis participated in briefings on the sustainability of cellulosic biofuels, sponsored by ESA; and in 2009 co-PI Sieg Snapp participated in an international briefing on the ecological management of nitrogen sponsored by NSF. In 2006 co-PI Swinton and co-I Frank Lupi organized a AAAS symposium on ecosystem services in agriculture that attracted national media attention, and in 2008 Swinton and Gross participated in a national web seminar on ecosytem services in agriculture sponsored by ESA and the Council on Food, Agricultural and Resource Economics. In 2009 we also participated in a climate change and agriculture briefing to the Michigan state legislature, co-organized by Doll, which was followed by a field tour for legislative staff, and a follow-on request to host a field visit for all members of the Michigan House Agriculture Committee this spring. Other state and federal legislative staffers have visited KBS on an ad hoc basis. Also at the national level, we have co-authored 3 recent Policy Forum pieces in *Science* (Robertson et al. 2008, Vitousek et al. 2009, and Searchinger et al. 2009), and the policy value of KBS LTER results were specifically highlighted in a fourth *Science* article this past fall (Richter & Mobley 2009). The 2007 ESA Policy Whitepaper on Biofuels Sustainability was led by Robertson, and an ESA *Issues in Ecology* piece on biogeochemical effects of biofuel crops is in press, co-authored by co-PI Hamilton and Robertson.

5.2 Future Plans

As demonstrated in Figure 5-1 (below), through dialogue with stakeholders we will be responsive to emerging opportunities where LTER data can inform solutions to environmental problems and we can increase awareness of basic ecological science and its broader impacts on environment and society. In turn, this dialogue will enable researchers to benefit from the local knowledge of citizens and learn about the science needs, questions, and priorities of these groups. K-12 programming will continue to be an important component of what we do. With C.W. (Andy) Anderson's leadership, KBS is partnering with SGS, BES, and SBC in a recently funded NSF Targeted Math and Science Partnership (MSP) award ($12.5M/5y), designed to enhance environmental science literacy by developing learning progressions for key science concepts of biodiversity, carbon, and water. Through this and the new GK-12 award—both conducted under the umbrella of the KBS-K12 Partnership for Science Literacy—we will continue our efforts to promote student learning in science and math via teacher-scientist partnerships and professional development activities for teachers. For undergraduates we anticipate expanded research experiences as the REU program at KBS grows, and we expect to continue to strengthen and expand existing efforts to link undergraduate programming at MSU's main campus with LTER research and scientists.

We also expect to expand other outreach activities in a more targeted way now that we have a full-time education and outreach coordinator. In particular, we plan to more proactively engage farmers and other agricultural professionals, NGOs, community organizations, elected officials, and interested public in discussions about the development of sustainable agricultural landscapes. Programming will be research-centered on *Farming for Services in a Changing Environment* (Fig. 26 of Section 2), with a particular emphasis on climate change mitigation through agricultural practices. As such, we will continue collaborations with MSU Extension to train Extension educators, farmers, and policy makers via training workshops and field days, media pieces, and fact sheets. In addition, through dialogue with stakeholder groups and working with LTER co-PIs, Doll will translate core messages from the KBS LTER synthesis book into media for various audiences. We will continue to strengthen information dissemination via:

- K-12 curriculum and assessment materials, developed by GK12 and MSP fellows and teachers as part of our learning progressions research, including schoolyard biofuel plots in our 11 partner districts;
- Fact sheets, media pieces, brochures, and walking-tour displays;
- Programs, including outreach events, field days, workshops, and training programs;
- Internet access, for which we will expand our newly created LTER outreach pages and respond to stakeholder needs for additional modes to access information, e.g., social media outlets.
- Global outreach in agroecology through international agricultural development networks.

In sum, we have a vibrant outreach and education portfolio that we seek to maintain and strengthen.

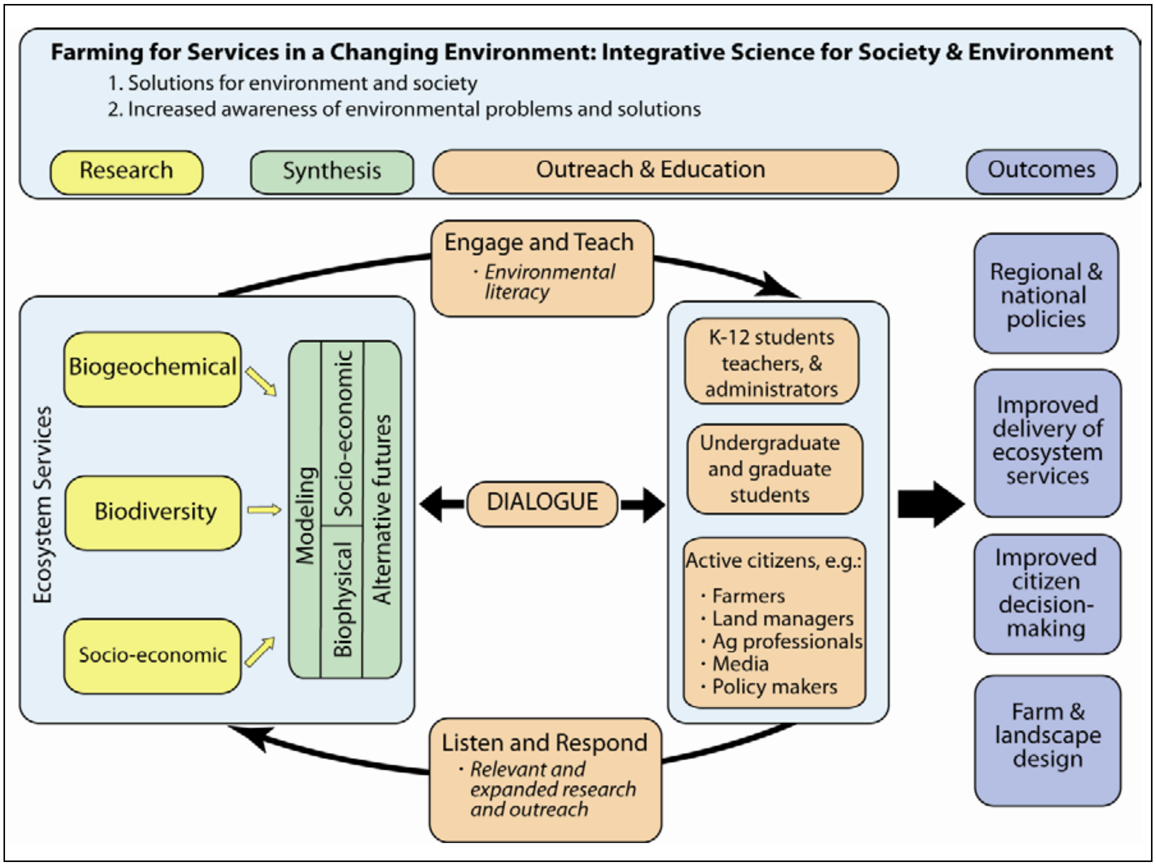


Figure 5-1. How outreach and education fit into the KBS research roadmap. Our aim is to provide our primary audiences—K-12 educators, university students, and citizens including farmers, agricultural professionals, NGOs, policy makers, media mavens, and others who influence public and private decisions—with the knowledge and information they need to make decisions informed by science and to be literate about ecological science and its broader impacts. Through dialogue, we will engage and teach audiences while recognizing the views and needs of the interested parties. In turn, this dialogue will enable researchers to benefit from the local knowledge of citizens and learn the science needs, questions, and priorities of these groups. The information flow is two-way, ensuring relevance for research on agroecosystems, and cogeneration of knowledge.

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8.0 Biographies

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Supplementary Material

Table S1. Publications from LTER research since the prior renewal in 2004. Categories include journal articles (169), books (3), book chapters (35), theses and dissertations (43), and several miscellaneous publications. Not listed are several hundred meeting abstracts.

Journal Articles

Ambus, P., and G. P. Robertson. 2006. The effect of increased N deposition on nitrous oxide, methane, and carbon dioxide fluxes from unmanaged forest and grassland communities in Michigan. *Biogeochemistry* 79: 315-337.

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Supplemental Table S2. Data sets available from the KBS web site (***http://lter.kbs.msu.edu***). There are 62 datasets total, 51 datasets with data tables, and 176 data tables. In 2009 we averaged about 450 non-staff accesses to datatables per month; about half of our visitors were internal to MSU (48%).

For visitors to the KBS web site, about 60% are returning visitors and 40% first-time visitors. Most visitors came from the US (88%) followed by Canada (2%) and India, UK, Taiwan, and Australia all at about 1%. We get about 39% of our visits from search engine results and 23% from referring sites. On average, visitors appear to spen about 5 minutes on the site.

Data sets available from the KBS web site:

LTER weather station (5863 daily records, 97,000 hourly records, 416,000 5-minute records)
- Absolute/Relative humidity (since 1992)
- Air Pressure (since 1992)
- Temperature/Precipitation, (since 1988)
- Solar Radiation/PAR (since 1992)
- Wind speed and direction (since 1992)
- Soil temperature and moisture (1992-1993 and since 1997).

KBS National Weather Service Station (>22,000 daily records):
- Daily Maximum/Minimum Air Temperatures/Precip (since 1980).
- Monthly Maximum/Minimum AirTemperatures/Precip (since 1980).
- Daily Maximum/Minimum Air Temperatures/Precip/Snow (since 1948).
- Monthly Maximum/Minimum Air Temperatures/Precip/Snowfall (since 1948).

National Atmospheric Deposition Program/National Trends Network (NADP/NTN)
>9600 + records since 1979; via link to KBS at http://nadp.nrel.colostate.edu/NADP)
- Weekly, Monthly, and Annual Precipitation Chemistry
- Ion Concentrations (mg/L)
- Annual and Seasonal Total Deposition for N, S (kg/ha)

Kalamazoo Hospital National Weather Service Station (36,493 daily records)
- Daily Maximum/Minimum Air Temperatures/Precip/Snow (1887-1987).
- Monthly Maximum/Minimum Air Temperatures/Precip/Snowfall (1887-1987)

Spatial Variability (initial site survey)
- Soil Physical Properties (65 files)
- Soil Chemical Properties (58 files)
- Soil Biological Properties
  - Microbial Populations and Processes (89 files)
  - Nematode Trophic Groups (44 files)
- Plant Biomass and CN Content (24 files)

Main Experiment
- Microbial Biomass C/N 860 records (1989-1996)
- Microbial Number and Volume 436 records (1990-1996)
- Trace Gas fluxes >9197 records (since 1991)
- Soil Moisture >11,446 records (since 1989)
- Agronomic Yields >564 records (since 1989)
- Stand counts >24 records (2003)
- Soil Inorganic N >10,634 records (since 1989)

Soil N mineralization >2,264 records (since 1989)
Soil C/N >1,200 records (since 1989
Soil bulk density 334 records (1995,1996)
Soil pH >5,439 records (since 1989)
Soil water chemistry (Ca, Mg, K, Na, N, S, P, pH) >1,194 records (from 1999)

Plant C/N >1,976 records (since 1989)
Deep core soil survey >2,293 records (1989, 2001)
Seedbank >8,197 records (1990, 2002)
Spatially Explicit Yield (yield monitor) >41,7381 records (since 1996)
Modeled soil water (SALUS) >15,706 records (1989-1998)
Earthworm survey 60 records (1994)

Photo Archives
Herbarium Image Archive 348 records
Herbarium Specimen Database 7082 records (1947-2002)
Insect photo archive 505 records

ANPP
Crops Biomass 5,249 records (since 1990)
Non-crop species and biomass 34,161 records (since 1990)
Cover crop biomass 547 records (since 1990)
Litter fall mass 5,535 records (since 1991)
Poplar diameters 2,304 records (since 1990-1998)
Poplar harvest 12 records (1998)
Coppice stems 494 records (since 1999)
Poplar branches 40 records (1999)
Tree diameters 11,283 records (since 1998)

Species Lists (Biodiversity)
Amphibians 17 records
Birds 149 records
Bryophytes 12 records
Fish 94 records
Fungi 17 records
Insects 45 records
Mammals 33 records
Protozoa 8 records
Reptiles 14 records

Insect Trapping Survey
Species, Number 399,889 records (since 1989)

Biodiversity experiment
Soil Moisture 80 records (2001)
Agronomic Yields 264 records (since 2000)

ECB study (Bt Corn)
Agronomic Yields 36 records (since 2001)

Country State + Regional Yields 2,380 records (since 1970)

Living Field Laboratory
- Soil classification 120 records (1922,1992)
- Soil texture 380 records (1992,1993)
- Agronomic Yield 1,400 records (1993-2002)
- Carbon mineralization 2,660 records (1999-2001)
- Nitrogen mineralization 3,640 records (1997-2001)
- Plant C/N 2,100 records (1993-2002)
- Soil nitrate 12,600 records (1993-2001)
- Leachate volume and nitrate 3,640 records (1993-2003)
- Soil water chemistry (NO3, NH4, P, K) 228 records (1993-2003)
- Soil nutrients pH, P, K, Ca, Mg 856 records (1992-2002)

Aphid Collection Tower
- Number and Species of Aphids captured (23,200 records) (since 2002)

Human population 141 records (1990-2009)

KBS Lidar Elevation 15,811,000 records
GPS elevation 11,292 records
Veris carbon estimates 5,866 records

Methane consumption as influenced by nitrogen fertilization and tillage
- CH_4, CO_2, N_2O 949 records (2002)

Nitrogen Rate Manipulation in Row Crop Agriculture
- Yield 575 records (2000-2008)
- N_2O fluxes 726 records (2001-2003)

Plant community and ecosystem responses to long-term fertilization 5,777 records (1989-2007)

University of Toledo's mobile CO_2 flux tower 318,831,000 records (2007-2008)

Stream water chemistry
- Ca, Mg, K, Na, N, S, P, pH, O_2, discharge 65 records (1999-2009)

Supplemental Section S3 – Postdoctoral Mentoring Plan.

Each of our PIs has had, or currently has, a postdoctoral researcher in their lab, and each may co-sponsor a postdoc for the proposed research. We propose to share past and present approaches to mentoring, and to work together to develop new initiatives. The integrative nature of our proposed research and the diversity of expertise among the PIs will provide fertile ground for postdoctoral mentoring. We propose a range of activities, including group programs that will involve each of the participating labs and individualized programs that involve one-on-one mentoring between the faculty mentor and the postdoctoral researcher.

Group program – Seminar on Academic Success. Recognizing that new PhDs now face a bewildering variety of career opportunities in challenging economic times, we want to introduce our postdoctoral researchers to the perspectives of science professionals from a variety of disciplines. To this end, we will require each of our postdocs to participate in seminars on academic success offered through MSU at KBS. The activity is organized by postdoctoral researchers who develop the topics and seek scientists from academic and other institutions to lead weekly sessions. KBS is now installing a state-of-the-art teleconferencing facility that will be identical to one in the Plant and Soil Science Building on campus and that together will allow participation by individuals at both locations. The list of topics for the spring 2010 offering includes *career options in academia, balancing career and family, maximizing productivity and recognition, publishing, finding and landing grants, landing an academic job, ethics and responsible conduct in science, and academic networking and politics.* Several LTER PIs are weekly leaders in the series.

Individualized programs. We will require our postdoctoral researchers to develop an *Individual Development Plan* (IDP; http://opa.faseb.org/pdf/idp.pdf), as developed by the Science Policy Committee of the Federation of American Societies for Experimental Biology. This mentoring tool improves communication by clarifying responsibilities of the postdoctoral fellows and their mentors. Postdoctoral obligations include self-assessment, and development and implementation of an IDP. Obligations of mentors include identifying/discussing career opportunities, providing feedback on the IDP, and establishing regular reviews of progress.

Institutional support. The Center for Academic Future Faculty Excellence (CAFFE) is a recently-funded NSF initiative at MSU that provides support and professional advice for early-career faculty, postdoctoral researchers, and graduate students (http://grad.msu.edu/caffe/). CAFFE suggests that postdoctoral mentors assess the level of skill and knowledge in teaching, negotiating, collaboration, and time management skills, then sets development priorities taking into consideration the disciplinary area and the career path chosen by the postdoctoral researcher. KBS is an institutional partner in CAFFE, and we will ensure that our postdocs and mentors are aware of CAFFE resources and support.