193247145

COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

PROGRAM ANNOUNCEMENT/SOLICITATION NO./CLOSING DATE/if not in response to a program announcement/solicitation enter NSF 04-2

NSF 04-2

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DEB - ECOLOGICAL BIOLOGY CLUSTER

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NSF PROPOSAL NUMBER

0423627

DATE RECEIVED	NUMBER OF COPIES	DIVISION ASSIGNED	FUND CODE	DUNS# (Data Universal Numbering System)	FILE LOCATION

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386005984

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TITLE OF PROPOSED PROJECT **The KBS LTER Project: Long-Term Ecological Research in Row-Crop Agriculture**

REQUESTED AMOUNT
$ **4,920,000**

PROPOSED DURATION (1-60 MONTHS)
72 months

REQUESTED STARTING DATE
12/01/04

SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE

CHECK APPROPRIATE BOX(ES) IF THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW
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☐ HISTORIC PLACES (GPG II.C.2.j)
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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 U.S. 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. To test this hypothesis we established a series of sites comprising 11 different cropping systems and successional communities, corresponding to different levels and types of ecological disturbance. Within these systems we test hypotheses related to the patterns and processes that underlie ecosystem productivity and nutrient retention. Working hypotheses are built around the general topic areas of plant community dynamics, soil microbial populations, the dynamics of insect consumers, watershed and field-scale biogeochemistry, human interactions, and regional processes.

Over the past funding period we have made substantial progress towards addressing many of the initial hypotheses set out some 15 years ago. During this period we have developed successful biologically-based cropping systems, successfully tracked both changes in the various taxons that appear to be important to row crop functioning as well as changes in important ecosystem-level attributes, and addressed and identified a number of new questions related to understanding the key relationships in these systems.

With this proposal we present a substantially revised conceptual model that organizes our ecological understanding of these systems into components focused on ecological structure (which includes organisms and their adaptations, population and community assemblages, and habitat structure) vis a vis ecological functions (which include biogeochemical processes, energy capture and flow, and hydrologic dynamics). Linkages between these components largely define the mechanisms that underlie the production of ecosystem goods and services: those products that provide the economic and social rationale for farming. For the renewal period we propose new research in existing areas of project strength and propose to add to our portfolio research on the valuation of the ecosystem services provided by these important systems.

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1.0 Results from Prior Support

1.1 Overview

The KBS LTER site was initiated in 1987 to provide a context for examining the ecological basis for commercial row-crop agriculture. This type of agriculture - mainly corn, soybean, and wheat production - dominates what is arguably the most productive portion of the North American landscape and has a correspondingly huge impact on human and environmental welfare. Agricultural systems are also among the most intensively studied systems worldwide, yet most of what is known about these systems still stems from narrowly-defined, highly disciplinary studies of specific properties and processes conducted in isolation of one another. Consequently, our ecological understanding of row crop systems *as ecosystems* is fragmented and incomplete and many environmental problems associated with agricultural production remain intransigent (Robertson et al. 2004). Our aim as a site has been to help remedy this situation by building a program of long-term integrative research on row-crop ecosystems. Our research strategy targets the examination of key components of these ecosystems, conducted in a comparative, landscape-level framework that integrates results from experimental studies at different scales with a multi-decade record of baseline data.

KBS is located in the northeast portion of the U.S. corn belt (Fig. 1) and our study area includes a replicated series of annual row crops, perennial forage crops, and unmanaged successional and older growth communities used for ecological and historical comparisons. Since 1987 we have been conducting experiments designed to address interactions among four processes central to the row-crop ecosystem: 1) nutrient availability, 2) herbivory and disease, 3) plant competition, and 4) crop productivity. In 1998 we added watershed scale biogeochemistry to our focus, and additionally initiated efforts to extend investigations to a regional level and to explore ways to incorporate relevant social science questions into our research. We are now well-positioned to significantly further our understanding of the ecological regulation of crop productivity and the environmental impact of row crops within the larger landscape, guided by a new conceptual model that better articulates interrelationships among these components.

Our original global hypothesis, still relevant today, is that in modern high-yielding crops agronomic management based on ecological knowledge can effectively substitute for reliance on chemical subsidies. We continue to make substantive headway towards addressing both this hypothesis and its corollaries (Fig. 2), though we remain far from a comprehensive understanding of most of the underlying mechanisms that allow for substitution.

Most of our hypotheses have been addressed in the context of a simple experimental design: replicated systems along a management intensity gradient that ranges from intensively managed annual crops to unmanaged successional communities. The design includes 11 systems: 4 corn-soybean-wheat rotations under conventional, no-till, low-input, or organic management; 2 perennial crops, one herbaceous (alfalfa) and one woody (poplar trees); 1 set of early successional communities abandoned from cropland in 1988 and burned annually since 1996; 2 sets of mid-successional communities, one 40 – 60 y post-plowing and the other 50 y post-clearing (never plowed); and 2 types of forests, one dominated by planted conifers and the other a native old-growth deciduous community (Figs. 3 and 4). The power of this design lies in its provision of a wide range of replicated communities (n = 3-6) with the same pedogenic history that differ in key ecological characteristics (e.g. plant species diversity, productivity, litter quality, microclimate). This allows us to test specific hypotheses from which we can better infer mechanisms operating in row-crop ecosystems — mechanisms that can then be tested with specific manipulative experiments. We take baseline measurements from all 11 of our ecosystem types, but not all ecosystems are used to test every hypothesis. Additionally, we also sample sites in the landscape to address questions related to movement and watershed dynamics (Fig. 5).

1.2 Net Primary Productivity

Net primary productivity (NPP) is central to the study of agricultural systems — without sufficient yield the enterprise becomes marginalized and the ecosystem converts, most often to either unmanaged succession or a built environment. Agronomic yields at KBS have been consistently close to average yields for non-irrigated row crops in both Kalamazoo County and in the 12-state North Central Region as a whole, except for drought years (2 of the past 6 years). Significantly, yields in our low-chemical-input and zero-chemical-input treatments (T3 and T4 in Fig. 3) have been close to or identical to yields in our normal chemical input treatments (T1 and T2). Over the past 3 rotation cycles wheat in our low-input T3 treatment has been about 15% lower than wheat in T1, and in our zero-input T4 treatment wheat and corn have been respectively 50% and 75% of T1 yields (Fig. 6). During non-drought years, total ANPP of corn is ca. 15 MT ha^{-1} y^{-1} in our conventionally managed systems. This contrasts with <5 MT ha^{-1} y^{-1} in the successional fields and ca. 10 MT ha^{-1} y^{-1} in our forested sites.

1.3 Plant Community Dynamics

The major focus of our plant community dynamics work has been to examine the causes and consequences of biological diversity in row-crop agriculture. With the increasing emphasis on developing agricultural systems with lower chemical inputs, there is a growing awareness of how the associated communities (weeds, insects, and microbial) respond to changes in agricultural management and the consequences this has for both crop production and nutrient cycling. We have approached this by focusing efforts in three main areas: (1) comparing the diversity, production, and species composition of the weed communities that emerge in the different row-crop systems (T1-T4) on the main experimental sites; (2) comparing the diversity and composition of the emergent weed community to the soil seed bank; and (3) determining if the observed differences in weed communities affect crop production. Additionally we have continued observations on the long-term effects of disturbance and fertilization on the composition and successional trajectories of our experimental old-fields. These successional treatments provide us with an opportunity to test hypotheses about community assembly and responses to perturbation (e.g. Huberty et al. 1998) and afford increasing opportunities for cross-site collaboration, synthesis, and integration with other grassland LTER sites (e.g. Gross et al. 2000, Gough et al. 2000).

Our work on weed community responses to differences in cropping systems and management has shown that lower input systems have more abundant and diverse weed communities whose composition is more predictable over time (Menalled et al. 2001). The introduction of a winter annual (wheat) into the rotation can substantially affect weed community composition (Smith and Gross, in prep.), and these differences in weed production and diversity can affect yield in some crops (wheat), but not others (soybean; Gross & Smith 2003). Our results also indicate that a high biomass, high diversity weed community can have the same effect on crop yields as a low biomass, low diversity community, suggesting that compensation and competitive interactions among the weed species may reduce their effect on crop yields (Fig. 7). This is a particularly exciting finding that we plan to explore in more detail in the renewal, particularly because weed diversity influences the diversity, abundance, and effectiveness of beneficial insects in row-crops. Additionally, our long-term studies of successional dynamics and responses to fertilization in old-fields have resulted in increasing opportunities for synthetic analysis of the relationship between productivity and diversity across LTER sites.

1.4 Insect Consumers

The application of ecological principles in the design and implementation of farming practices is a central tenet of ecologically-based management in agriculture. The use of cover crops, crop rotation, and crop residues to enhance biological diversity and maintain nutrient cycling mechanisms are important steps toward this goal. Another important strategy is predator conservation, a fundamental component of ecologically-based pest management. Most of our recent insect work has concentrated on attaining a better understanding of the role of landscape complexity on the population dynamics of beneficial insects, those that prey on economically important crop pests. We use the Coccinellidae (lady bird beetle) complex to address these questions.

Over the past 6 years we have continued to measure insect abundance at three spatial scales (individual plant, field or plot, and landscape) and three temporal scales (daily, seasonal, and two or more years). These measurements have allowed us to document the importance of edge habitats and landscape position for over-wintering predators, the response of predators to vegetation type, the rate of response of predators to prey populations under different disturbance scenarios, the invasion of a new lady beetle (*Harmonia axyridis*) and prey (the aphid *Aphis glycines*) and their effects on existing beetle populations, the importance of specific non-target plants (e.g. dandelions) in some lady beetles' life cycles, and factors other than crop and management for causing predator population fluxes (Colunga-Garcia et al. 1997, 1998; McKeown 2003)

Whole-community analysis reveals that the two dominant exotics *Coccinella septempunctata* and *Harmonia axyridis* are likely able to coexist due to a temporal separation between their adult phases. *C. septempunctata* is most active during the mid-growing season while *H. axyridis* is most active later (Fig. 8). However, this pattern became less clear in 2000 and 2001 as *H. axyridis* began to dominate most of the landscape. *H. axyridis*, *C. septempunctata*, *Coleomegilla maculata*, and *Cycloneda munda* exhibited varying mechanisms of niche separation in our mixed environment of corn, soybean, and edges with natural vegetation. *C. maculata* uses corn as a primary habitat. *C. munda* thrives at the edges of row crops, venturing into them only when food is abundant. *H. axyridis* is found in all habitats but increases in abundance late in the growing season. *C. septempunctata* prevails early in the growing season, showing a marked preference for soybean. We have also documented a 5-year population cycle for *C. septempuntata*, the dominant coccinellid in 1989. We cannot yet explain the cycle, which may alternatively influence or reflect the temporal diversity and abundance of other species in the complex (Fig. 9).

1.5 Microbial Community Dynamics

One of the principle microbial hypotheses tested in the past research period is that "soil microbial diversity is driven by heterogeneous distribution of resources and habitats in soil." A suite of physiological and molecular approaches was used to test this hypothesis and to further examine the ecological significance of microbial diversity in soil.

Studies on the spatial heterogeneity of microbial biomass indicated that over 50% of the variance could be explained at scales less than 18 cm: a scale represented by the rhizosphere and heterogeneity of available substrates. Both phospholipid fatty acid and Biolog assays suggest that plant species composition impacts the activity and functional diversity within soil microbial communities (Broughton and Gross 2000). Furthermore, characterization of extracted DNA revealed that the highest diversity of microbes is associated with the light fraction of soil, which is composed of rapidly cycling carbon including freshly deposited plant residues (Blackwood et al. 2003). One factor controlling community structure at this spatial schedule is the differential capacity of microbes to respond to newly available substrates. The ecological strategies of evolutionarily diverse bacteria was correlated with the number of rRNA operons per bacterial genome: bacteria possessing multiple copies exhibited increased competitive fitness when nutrient availability fluctuated, while those possessing few copies appeared more efficient at growth under constant, low-nutrient conditions (Klappenbach et al. 2000).

While it is generally accepted that microbial communities in soil are critical to the health and productivity of the biosphere, these communities remain largely unexplored. Surveys of microbial diversity using molecular methods reveal extensive diversity, including the presence of several phyla of bacteria for which there are few cultivars (Buckley and Schmidt 2002; Fig. 10). We refined approaches for microbial cultivation and isolated representatives of two prominent but poorly understood bacterial phyla, Acidobacteria and Verrucomicrobia (Fig. 11). The metabolic potential and ecological significance of these isolates are now being studied.

The diversity and ecological role of microbes in the nitrogen cycle was studied both by characterization of pure cultures of denitrifiers (Cavigelli and Robertson 2000, 2001) and community analysis of genes involved in that pathway (Bruns et al. 1998; Stres et al. 2004). These studies suggest that denitrification is the major process responsible for increased production of nitrous oxide in agricultural fields. Culture-independent methods were also used to assess the impact of historical land use on microbial community structure. Based on the abundance of seven common bacterial groups in soil, it is evident that treatments sharing a history of cultivation have the most similar microbial communities and that the effects from cultivation are evident for at least a decade post-abandonment (Buckley and Schmidt, 2001, 2003).

1.6 Biogeochemical Fluxes

Environments interact at the landscape scale through the surface and subsurface fluxes of water. Groundwater discharge in this glacial landscape supports numerous lakes, wetlands, and streams. The central question of our landscape biogeochemistry component is "How do current and future land use and landscape patterns affect the fluxes of water and nutrients to lakes, streams and wetlands, and how are fluxes altered in transit?" We have since Spring 1999 measured hydrochemistry (major solutes and nutrients) at key points along hydrologic flow paths, beginning with precipitation and including infiltrating soil water, ground waters, springs, streams, wetlands, and lakes. Sampling emphasizes surface waters and soil water infiltrating from the rooting zone of various LTER treatments. Precipitation chemistry is monitored at KBS by the NADP/NTN program. In addition, associated studies of wetland and stream hydrology and biogeochemistry have been conducted with separate funding (e.g., Webster et al. 2004, Hamilton et al. 2001, Peterson et al. 2001, Whitmire and Hamilton, in review).

The diverse hydrochemistry of surface and groundwaters in the vicinity of the LTER site is demonstrated by specific conductance (a measurement of the total ion content) for various water bodies (Fig. 12). Groundwaters pumped from wells or collected from groundwater-fed springs tend to be rich in Ca^{2+}, Mg^{2+}, and HCO_3^-, indicating strong influence of dolomite mineral dissolution. Sediment porewaters from shallow water bodies are also rich in ions. Streams show a hydrochemical signature resembling that of local groundwater. Lakes and wetlands are more variable, reflecting the variable contribution of groundwater discharge and direct precipitation or overland flow to their water budgets. Samples from suction lysimeters beneath LTER treatments approximate the composition of water leaving from the root zone; these waters often have not yet attained the hydrochemical signature of the deeper groundwater, indicating that much additional dissolution of dolomite occurs deeper in the glacial drift. This evolution of hydrochemical signatures across landscape flow paths provides information on key biogeochemical processes and is a topic of continuing study, as discussed later in this proposal.

At the field scale our biogeochemical work has focused on soil carbon, nitrogen use efficiency, and greenhouse gas fluxes. Results from our carbon work continue to inform our understanding of the mechanisms that control the acquisition of C and its turnover through various soil pools (e.g. Paul et al. 2003, Willson et al. 2001). Our concurrent investigations of CO_2, nitrous oxide (N_2O), and methane (CH_4) have allowed us to evaluate the overall greenhouse gas impact of agriculture (e.g. Robertson et al. 2000). In addition, we are working to define the role of individual processes and microbial populations in controlling these fluxes (e.g. Cavigelli and Robertson 2000, 2001; Bergsma et al. 2002), and we have investigated the effects of land management on specific fluxes (e.g. Suwanaree 2003). Our long term sampling results (trace gas fluxes from all treatments measured regularly since 1992) are available in our data catalog.

1.7 Regionalization

Our regionalization efforts, begun in 1998, have focused on the analysis of historical maize productivity patterns in the 12-State North Central Region (Fig. 1) and development of a modeling and analysis framework to explore future scenarios. Our general intent is to test the hypothesis that productivity can be predicted by temperature, precipitation, and soil water-holding capacity, and to then build on these relationships to better understand how changes in climate and cropping systems will affect regional NPP, soil carbon storage, and the fluxes of various greenhouse gases. We use a variety of models integrated with the MASIF modeling framework that we developed in collaboration with the San Diego Supercomputer Center. MASIF (Fig. 13) allows us to process effectively and visually the massive amount of spatially-explicit information required and produced by regional scale simulations, and allows one to use a variety of existing ecosystem-level models for these regional estimates.

We have used MASIF to reliably simulate 3 decades of corn yield in the region using the MAIZE crop model (Muchow et al. 1990) adjusted for northern soil temperatures. We used daily weather observations in 1055 counties to characterize the distribution of drought patterns in the region, and showed that major regional crop losses due to drought were due to the occurrence of severe plant stress during May and June. Using a monthly heat-precipitation ratio we developed an accurate crop stress index (Gage 2003), and have recently used the MASIF environment to model regional NPP, N_2O, and CH_4 fluxes with the daily version of the Century model (Fig. 14), and to predict changes in soil carbon across the region under different climate and crop management scenarios using the Socrates soil carbon model (Grace et al. 2004).

1.8 Publications and Published Datasets

Publications credited to the KBS LTER site are listed in Supplementary Table S1. Datasets are listed in Table S2, together with a 2003 traffic analysis in Table S3.

2.0 Proposed Research

2.1 Overview

The long-term core hypothesis of the KBS LTER (Fig. 2) can be recast as two questions:

1. what are the ecological relationships in row-crop ecosystems that can be managed to provide ecosystem services typically provided by external inputs such as fertilizers and pesticides; and
2. to what extent can the current environmental impact of agriculture be minimized without losing the high crop yields needed to feed a burgeoning global population?

Over the first 15 years of LTER research we have learned much about the organisms and processes responsible for the high productivity of our row crops, mostly by field experimentation and comparisons with nearby unmanaged sites in different stages of secondary succession. We have also learned quite a bit about the environmental consequences of different management strategies, at scales ranging from individual fields to the regional watershed. Our results continually reinforce our view that row crop ecosystems, despite aboveground simplicity, are as ecologically complex as many other early successional ecosystems. We have also demonstrated ways that biological management can largely replace chemical inputs without penalizing yields, and also that these low-input cropping systems can be as biogeochemically open as their chemical-based counterparts.

For this next period of research at KBS we will maintain our core, long-term examination of ecological interactions in row crop agriculture and how these systems impact the environment by focusing on understanding the mechanisms that underlie patterns that have emerged in the project's first 15 years. We now have a more holistic view of our system and the forces that shape it, both internally and externally, ecologically and socially. And we have a more realistic view of the expertise needed to address the critical questions that emerge from this more integrative view of the agricultural ecosystem.

Our new conceptual model (Fig. 15) organizes our ecosystem-level understanding into two components: ecological structure (organisms and their adaptations, population and community assemblages, and habitat structure), and ecological functions (biogeochemical processes, energy capture and flow, and hydrologic dynamics). Linkages between ecological structure and function largely define the mechanisms that underlie the production of ecosystem goods and services: those products that provide the economic and social rationale for farming. Food production is by far the most important 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, carbon sequestration, and even social amenities such as verdant landscapes. The ability of row-crop systems to provide these services is affected greatly by factors at scales greater than the ecosystem: 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 environments. The former includes climate, weather, and geomorphology; the latter includes product and input prices, transportation and communication infrastructure, and ethics and values as they shape public policy and other human institutions. Both of these environments can greatly affect the system's capacity to produce services.

This new model is an expansion of our earlier models that were organized around biological taxa; organisms and their interactions remain an important organizational construct 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 is a focal area of research, and together with watershed biogeochemistry and regionalization, which we added in 1998, constitute the 6 core research areas of the KBS LTER. In this renewal we are focusing more effort on interactions and integration among these core areas as their effects, particularly in agricultural ecosystems, are so closely intertwined.

Changes to Our Experimental Design

With one exception, the research we propose will be performed largely in the context of our existing experimental design:

a) the **main site experiment** with its 6 cropping systems and 5 successional or forested sites (Figs. 3 and 4) has been in place for 15 years and provides the context for most core research on site; embedded in many of these sites are 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;

b) the **biodiversity plots** established as part of our 1998 renewal proposal (Fig. 16) 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 3 crop rotations with 2 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 succession treatments, one tilled in fall and the other in spring, and a no-plant (bare soil) treatment; and

c) the **nitrogen fertilizer gradient** (Fig. 17) established in 1999 allows us to test how monotonic changes in N availability (from 0 – 294 kg N ha^{-1}) affect ecosystem processes in continuous corn; in 2003 we added an irrigated block to remove water as a growth limiting factor.

In 2005 we will establish our low-input treatment (T3; see Fig. 3) and conventional input (T1) treatments on a larger portion of the KBS landscape. Half of 18 fields ranging in size from 1 to 12 ha (90 ha total) currently used to produce feed and forage for the KBS dairy herd will be converted to low-input, biologically-based management (T3); the other half of each field will be converted to our standard chemical input treatment (T1). These **T3 scale-up fields** will allow us to better test hypotheses related to landscape position such as plant and insect dispersal and some biogeochemical fluxes.

2.2 Plant Community Dynamics

The view that agricultural production systems need to be designed and managed as high productivity monocultures to be economically profitable is being increasingly challenged (e.g. Matson et al. 1997, Tilman 1999, Robertson et al. 2004). Paralleling this is a growing body of experimental evidence that there is a positive (and causal) relationship between the diversity and ecosystem functioning of a community (e.g. Tilman et al. 2001). Although almost none of the recent explosion of experimental work exploring the relationship between diversity and ecosystem function has been performed in agricultural systems, there is evidence that there is unexploited potential for biological diversity to provide ecosystem services in agricultural systems. Recent studies that have shown that lower chemical input and organic systems also can be competitive in crop yield and value (Matson et al. 1997, Reganold et al. 2001), and this has raised the awareness among ecologists and agronomists that incorporating diversity may be an important aspect of managing lower chemical input systems. The challenge remains to determine how to incorporate diversity into agricultural ecosystems in a way that provides ecosystem services and profitability.

Our work on weed community dynamics in response to different management and cropping systems suggests that compositional and diversity differences among weed communities may be as important as weed biomass in regulating crop yields (Fig. 7). In this renewal proposal we plan to continue our work on weed community response to variation in cropping system and management by continuing to sample weed communities annually and weed seedbanks sexennially (next in 2008). In addition, we plan to expand our work to consider explicitly how cropping system diversity, independent of chemical inputs, can influence crop yield and the interactions between weeds. This work will complement (and in some cases be done in collaboration with) studies on arthropod predation and the dynamics of herbivore (Section 2.4) and soil microbial communities (Section 2.3). We also plan to continue our work on plant community dynamics and responses to perturbations (fertilization and tillage) as this work has provided us with opportunities to both address fundamental ecological hypotheses (e.g. Huberty et al. 1998, Gross et al. 2000, Gough et al. 2000) and to participate in cross-site collaborations (e.g. Drake et al. 2004, Chalcraft et al. 2004, Cleland et al. 2004, Wilsey et al. 2004)

Weed Diversity in Response to Agricultural Management

Biodiversity Experiment. Our main experimental plots provide unique opportunities to address a number of hypotheses regarding how different cropping systems affect diversity and ecosystem functions in row-crop ecosystems. For example, we have shown that differences in chemical inputs have significant effects on the composition and diversity of both the emergent and seedbank weed communities (Menalled et al. 2001). An important finding of that work was that although high chemical input systems have lower weed biomass, weed community composition is less predictable than in the low and zero-chemical input systems. A more recent analysis has shown that differences in weed biomass among these treatments may have little effect on crop yields. In corn, for example, crop yield is generally independent of weed biomass, species richness, and diversity (Fig. 7).

However, in our main site treatments it is difficult to identify what features of a cropping system are important for determining differences in crop yield or other system function (e.g. soil N availability, beneficial and herbivorous insect abundances) because multiple factors such as tillage, chemical inputs, and cover crops are manipulated at the same time. As noted above, in spring 2000 we established a set of biodiversity plots (Fig. 16) that have allowed us to focus on the effect of plant diversity on ecosystem processes in cropping systems. The design of this experiment is unique because there are no chemical inputs, so the only variables that differ among treatments is the number of crops, cover crops, and tillage time. Although these treatment plots are still young, results to date have shown that 1) crop rotational diversity strongly influences weed diversity, 2) the inclusion of wheat (a winter annual in our rotation) results in shifts in weed community composition that are attributable to tillage time (fall vs. spring; Fig. 18), and (3) the antecedent crop has a significant effect on the composition of both the soil seed bank and emergent community in a given year.

Most exciting to us is the observation in 2003 that crop yields in corn are significantly related to cropping system diversity (Fig. 19). We are currently examining possible causal correlations for this pattern by including in this analysis weed biomass, diversity, and species composition. Other mechanisms that could account for these differences are variation in soil nutrients (most likely N) and insect communities (both pest and predators). We plan to explore both of these mechanisms during the renewal period. We will also use these plots to tease apart the role of cover crops (present or not) and weed community diversity and composition and with appropriate manipulations (e.g. additional weeding of experimental plots) determine how these factors interact to determine pest and predator numbers, and the impact of intra-guild predation on pest populations (see Section 2.3). This will allow us to test more mechanistic hypotheses on the main plots about how these factors may interact to account for the observed differences in aphid/pest abundance and the response of predatory insects.

Seed Bank Dynamics. We have sampled the soil seed bank in our main agricultural treatments every 3 years since 1990 and have used both direct germination and elutriation methods (Gross and Renner 1989, Gross 1990) to characterize the weed community composition in these treatments. Plot are sampled in early spring (late March or early April) and either split to allow assessments of viable seeds (by direct germination) and total weed seed numbers (using elutriation) or processed only by elutriation. We have sampled both the upper (0-5 cm) and deeper (10-15cm) seed bank, but now focus our efforts only on the upper soils. These studies on the main site have been complemented by smaller scale sampling on Living Field Lab (Smith et al., in prep.) and biodiversity plots (Smith and Gross, in prep.) Our most recent sampling in 2002 confirms Menalled et al.'s (2001) finding that weed seed banks shift in response to agricultural management. In particular, the abundance of grass weed seeds differs among treatments, and both tillage (conventional vs. no-till) and nitrogen source (synthetic vs. cover crop) can account for differences (Fig. 20). Although the weed seed banks in these treatments are dynamic and interesting, the resources required for seed bank sampling and our desire to pursue new hypotheses limits our ability to sample as frequently as in the past. With this renewal we extend our sampling interval to every 6 yrs (still following wheat, going into corn) and to focus efforts on agronomic treatments. This will allow us to maintain our long-term record of the temporal dynamics of seed banks although at a coarser scale.

Community Dynamics: Successional Fields

Our successional treatments were established to provide reference communities for comparisons of how our different agronomic treatments function relative to native communities. They have provided important insights into how soil processes (e.g. Robertson et al. 2000, Bergsma et al. 2002), microbial communities (e.g. Phillips et al. 2000, Buckley and Schmidt 2003), and insect communities (e.g. Colunga-Garcia and Gage 1998) respond to the abandonment of management. Our successional treatments have also provided us with the opportunity to test hypotheses that address plant successional dynamics (Huberty et al. 1998, Foster and Gross 1999), patterns of diversity at different spatial scales (Gross et al. 2000, Mittelbach et al. 2001), and the response of communities to resource manipulations (Huberty et al. 1998, Gough et al. 2000). A growing number of cross-site collaborations and synthesis activities have also utilized these treatments (e.g. Symstad et al. 2003), including several sponsored by NCEAS (e.g. the Knowledge Network for Biodiversity project, http://knb.ecoinformatics.org).

During the coming renewal period we plan to continue our experimental manipulations of disturbance and N addition to document responses of plant populations to resource manipulations and disturbance, and to extend these to focus on 1) how species traits affect their response to fertilization and 2) how both species and community traits such as biomass and dominance affect invasion and diversity of our communities. A recent observation illustrates the importance of these long-term studies for understanding the responses of communities to perturbations such as chronic nitrogen inputs: Over the first 12 years of our fertilization experiment we saw no effect of nitrogen addition on species richness or on any other measure of plant diversity (Huberty et al. 1998, Gross, unpublished), despite a consistent stimulation of above-ground production (30-50% increase; Huberty et al. 1998, Gough et al. 2000). Over the past 3 years, however, there has been a consistent decline in species richness (Fig. 21) and an associated change in species evenness. Whether this is a result of a time lag in the response of the system as a consequence of species traits or site (e.g. initial fertility) or community characteristics (e.g. magnitude of the production response) will be a focus of our future work and involvement in an LTER-sponsored cross-site synthesis, FertSyn.

A previous cross-site analysis (Gough et al. 2000) found no relationship between initial productivity and the magnitude of response to fertilization experiments across sites. Our longer-term data, together with data from on-going long-term fertilization experiments at other sites, is allowing us to explore alternative mechanisms for why sites differ in response to fertilization (Fig. 22). Our present focus is on testing hypotheses about why sites differ in the degree of species loss, focusing first on how dominance rankings change (Fig. 22) and what traits are favored. Our most recent analysis has shown that across all sites, tall clonal perennial species increase in response to fertilization (Fig. 23). At the KBS site, all of the dominant species have these traits and this may explain the delay in species extinctions in response to fertilization. As part of the FertSyn network (SEV, KNZ, ARC, NWT, GCE, CRP, SGS, and CDR) we will continue to address these important community-level questions collaboratively.

2.3 Microbes: Linking the Structure and Function of Microbial Communities

Soils constitute a huge reservoir of microbes whose activities have a profound impact on global warming potentials, on crop productivity, and on soil fertility and biogeochemistry. The magnitude and diversity of the microbial community in soils is staggering: one gram of soil contains up to 10^{10} microbes representing at least 4,000 different microbial species (Torsvik et al. 1990). The prospects of understanding the structure and function of these microbial communities is further complicated by the fact that the vast majority of these microbes remain uncultured, so our understanding of their ecology is meager. However, the challenges associated with studying microbial communities are not unique to soil, and fortunately a suite of techniques has been developed to study natural communities that can be readily applied to soil.

Efforts to characterize the diversity and dynamics of microbes at KBS are well-established and continue today. Groups for which we have significant information include nitrifiers (e.g. Bruns et al. 1998), basidiomycetes (e.g. Thorn et al. 1996), endomycorrhizae (e.g. Johnson et al. 2003), denitrifiers (e.g. Stres et al. 2004), alpha proteobacteria (e.g. Buckley and Schmidt 2003), and 2,4-D degrading prokaryotes (e.g. Ka et al. 1995), among others. In this renewal we plan to couple this knowledge and expertise to our expertise in trace gas biogeochemistry (see Section 2.5) and focus specifically on the components of microbial communities that influence the production and consumption of greenhouse gases. We will focus on the three major biogenic gases: CH_4, N_2O, and CO_2, for all of which agriculture plays a major global role (Robertson 2004) and for all of which agriculture has a significant capacity for mitigation (Caldiera et al. 2004).

Methane

Methane (CH_4) is an important greenhouse gas that is ~30 times more efficient at trapping heat than CO_2 and its atmospheric mixing ratio has been increasing at a rate of ~1% per year (IPCC 2001). Unsaturated soils typically consume methane, with the rate of methane consumption varying dramatically among different soils. At KBS the rate of methane consumption is similar among cropped sites but is dramatically higher in native forest soils (Robertson et al. 2000). High rates of oxidation in the forest soils can be attenuated by high rates of nitrogen addition, but agricultural soils are not similarly affected, nor does removing nitrogen from agricultural soils increase oxidation (Suwanwaree 2003). Because oxidation of methane is catalyzed by methanotrophic bacteria, it is reasonable to posit that variations in methane consumption reflect underlying differences in the composition of the microbial communities in soil. We plan to focus efforts on identifying the active methanotrophs in soils at KBS and to understand the environmental parameters that influence their distribution in the landscape.

The main question to be resolved with this research is: What bacteria constitute the dominant methanotrophs in soils? The identity of active methanotrophs in soils remains uncertain since none of the cultured methanotrophs display methane uptake kinetics consistent with the rates observed in soil (Dunfield and Conrad 2000). Using stable isotope probing (SIP), a technique that allows for tracking the microbial assimilation of ^{13}C from CH_4 into taxon-specific biomolecules, we propose to identify the dominant methanotrophs in native and agricultural soils at KBS. Once identified, we will determine their population dynamics and niche preference through enumeration and localization and through the physiological characterization of isolates. The resulting profiles will provide a framework for exploring the possibility of increasing the rate of methane consumption in agricultural sites through agricultural management strategies.

We will add $^{13}CH_4$ to soil cores from native and historically cultivated sites collected and pooled at the time of maximal differences between methane consumption rates (as determined during routine monitoring of methane fluxes). DNA will be purified from aliquots of incubated soil and separated using cesium chloride density centrifugation. The origin of the ^{13}C DNA will be determined by PCR-based analysis of the respective DNA fractions. While SIP is a relatively new technique (Radajewski et al. 2003), it is a powerful and effective approach that has been applied successfully to determine the members of complex microbial communities that use a variety of labeled substrates (Manefield et al. 2002, Radajewski et al. 2002, Padmanabhan et al. 2003).

Culturing strategies will be derived from both classical techniques for methanotrophs (Whittenbury et al. 1970) and more recently developed approaches using low methane concentrations and co-cultures (Dunfield et al. 1999). Cultures of the dominant methanotrophs (as determined with stable isotopes and nucleic acid probes – see below) will be characterized for growth parameters including kinetics of CH_4 oxidation, pH and temperature optima, and requirements for cofactors that might limit the growth or activity of certain taxa. Community structure will be resolved both by analyzing extracted RNA and using 16S rRNA-targeted fluorescent in situ hybridization (FISH), used routinely in the Schmidt lab. The 16S rRNA-targeted oligonucleotide probing will follow the methods of Buckley and Schmidt (2003), and will serve to identify the abundance of methanotrophs. In the event that a probe's target rRNA is less than 1% of the total RNA (limit of detection), quantitative PCR will be utilized (Suzuki et al. 2000).

Nitrous Oxide

The flux of nitrous oxide from soils at KBS represents the greatest source of global warming potential (GWP) in all but one of the KBS LTER treatments, and is three times higher in agronomic sites receiving nitrogen than from poplar plots or unmanaged successional sites (Robertson et al. 2000). We propose to investigate the structure of microbial communities in these sites as it relates to differences in the flux of N_2O, with the ultimate goal of being able to understand and manage agricultural treatments in a manner consistent with minimizing nitrous oxide emissions.

Although populations of both nitrifying and denitrifying bacteria can contribute to differences in N_2O flux, recent studies at KBS revealed no shifts in the composition of the nitrifier community associated with N_2O flux (Phillips et al. 2000), while differences in the denitrifier community have been suggested both by cultivation based studies (Cavigelli and Robertson 2000, 2001) and analysis of denitrification genes present in native and cultivated treatments (Stres et al. 2004). Therefore we will focus on denitrification as a source of N_2O. Denitrification is carried out by a phylogenetically diverse group of bacteria that reduce nitrate in a step-wise manner: first to nitrite by nitrate reductase (*nar*), then to nitric oxide by nitrite reductase (*nirK* or *nirS*), then to nitrous oxide by nitric oxide reductase (*nor*), and finally to dinitrogen gas by nitrous oxide reductase (*nos*).

Primers suitable for PCR-based recovery of these various denitrification genes from environmental samples have been designed and tested in a variety of environments. We propose to use these primers, coupled with large-insert genomic libraries (generated from a complementary project at KBS undertaken by J. Breznak and Schmidt) to test the hypothesis that nitrite reductase expressed from *nirK* of the alpha proteobacteria is the dominant form of the enzyme expressed in native fields, while N-amended agricultural fields are dominated by expression of nitrite reductase from *nirS*.

Nitrite reductase is widely considered to be the key enzyme of the denitrification pathway, producing the first gaseous intermediate in the pathway, nitric oxide. There are two functionally equivalent but evolutionarily distinct genes that code for this enzyme: *nirK* codes for a copper-containing nitrite reductase, whereas *nirS* encodes for a cytochrome cd1-containing enzyme. Denitrifying bacteria contain either *nirK* or *nirS*, but the presence of either gene does not map precisely onto an organismal phylogeny (Philippot 2002). One reasonable explanation for the lack of congruence between organismal phylogenies and the occurrence of *nirK* or *nirS* is that selection for one or the other is based on the ecological strategies of different denitrifying populations. Since *nirK* is common in the alpha proteobacteria (Philippot 2002) and alpha proteobacteria are typically oligotrophic (Klappenbach et al. 2000) and constitute a majority of bacteria in soil (Buckley and Schmidt 2003), we propose that the alpha proteobacteria will be the primary denitrifiers in native soils. *NirS* may be more commonly associated with 'r-selected' bacteria that occupy habitats characterized by variable resource availability. We will also explore the possibility that sites fertilized with nitrogen are dominated by r-selected bacteria containing *nirS*. There are examples of nitrogen amended sites, e.g. estuarine sediments (Nogales et al. 2002), where the *nirS* transcript appears to be the primary nitrite reductase expressed. We will use two complementary approaches to assess nitrite reductase genes in various LTER treatments: (1) PCR sequencing of extracted DNA (Zhou et al. 1996, Suzuki et al. 2000) using primers for *nir*K and *nir*S, with analysis by LIBSHUFF (Singleton et al. 2001) to assess community structure, and (2) a simultaneous screen of a fosmid library (ca. 30 Kb inserts) made from total community DNA for *nos* and *nir* genes to identify clones that are likely to contain the genes encoding for denitrification. These genes will be sequenced and analyzed independently of the PCR libraries to provide an additional view of denitrifier diversity in the selected soils.

Carbon Dioxide

Metabolism of organic compounds by the soil microbiota is a key process in the global carbon cycle, influencing the balance between carbon sequestration and carbon dioxide emission from soils. Community-wide measures of respiration, such as the respiratory quotient (mole CO_2 evolution per mole of O_2 consumption; Dilly 2003), have been used in an effort to understand factors that influence microbial respiration in soil, but the size and metabolic complexity of soil microbial communities has hindered experimental approaches to isolate the factors that influence the balance between sequestration and respiration. Based on a model recently developed from research with bacterial isolates from KBS (Klappenbach et al. 2000), we propose to explore the underlying metabolism of bacteria that influence the relative production of CO_2 versus incorporation of carbon into biomass. In particular, we plan to test the hypothesis that slow growing bacteria exhibit a higher efficiency of growth (C incorporated into macromolecules per C emitted as CO_2) than fast growing bacteria.

Fundamental differences in the metabolic efficiency of bacteria with different ecological strategies would help to explain factors that influence carbon sequestration versus carbon dioxide emission in soils. Treatments that routinely redistribute carbon in the soil, e.g. tillage, may increase the relative abundance of fast growing bacteria in soil and this could influence the proportion of carbon respired as carbon dioxide as opposed to incorporation into microbial biomass.

A collection of 12 phylogenetically paired bacterial isolates from soil, one with fast and one with slow growth rates, and representing the major phyla of bacteria in soil, have been isolated and are routinely cultivated in Schmidt's laboratory. We propose to develop a defined medium for each isolate and then to use uniformly ^{14}C-labeled substrates to determine the proportion of carbon respired as CO_2 versus incorporated into macromolecules. The same basic approach will be employed in soil microcosms, measuring efficiency in addition to standard measurements of respiratory quotient (Dilly 2003). Soil samples for these experiments will be collected to span a range of soil respiration rates determined routinely as part of the KBS baseline trace gas collection. Correlations between growth rate and efficiency (pure culture experiments) or between efficiency and respiratory quotient (microcosm experiments) will be used to develop a mathematical model for the fraction of carbon respired versus that sequestered in microbial biomass in fast and slow growing bacteria.

2.4 Arthropod Community Dynamics

Our insect consumer work to date has concentrated on the long-term dynamics of selected insect predator communities, primarily coccinellids and ground-dwelling beetles (e.g. Clark et al. 1997, Colunga-Garcia *et al.* 1997, Colunga-Garcia and Gage 1998). With this renewal we propose to build on these investigations to include plant-herbivore and herbivore-predator interactions. We will build on existing long-term datasets and with new experiments examine population and community-level impacts of insects as invaders in agricultural landscapes. We propose investigations in three areas: 1) population regulation of a new invasive herbivore, 2) impact of intraguild predation on parasitoids, and 3) invasion-facilitated displacement of native coccinellids.

Invasive species present one of today's most important global environmental challenges and are among the leading causes of biodiversity loss and ecosystem change worldwide (Wilcove et al. 1998). Estimates of the economic costs of non-native invaders to the US exceed $137 billion/yr (Pimentel et al. 2000). Some have suggested that the presence of one invasive species may predispose habitats to colonization by additional invaders, a phenomenon termed invasional meltdown (Riccardi 2001, Simberloff and Von Holle 1999). Such phenomena may be common in agricultural landscapes that often contain a high proportion of non-native species. For example, the recent invasion of the soybean aphid (*Aphis glycines*) into North America appears to have been facilitated by the prior invasion of its overwintering host common buckthorn (*Rhamnus cathartica*) in a fashion consistent with the meltdown notion (Fox et al. *2004*). In contrast, a previous invader such as the multicolored Asian lady beetle (*Harmonia axyridis*) may act to limit establishment and growth of a new invader such as *A. glycines* (Fox et al. *2004*) or, alternatively, enhance their survival by limiting the establishment and impacts of aphid parasitoids through intraguild predation (Costamagna and Landis unpub. data, Brodeur and Rosenheim 2000). Finally, the increased resources provided by a new invader such as *A. glycines* may enhance *H. axyridis* populations and potentially increase their detrimental impact on native coccinellid communities (Koch 2003).

Understanding the varied impacts of multiple antagonists on each other, their shared prey, and subsequent cascading effects through food webs has emerged as a central question in insect ecology (Polis and Strong 1996, Rosenheim 1998, 2001, Sih et al. 1998, Polis et al. 2000, Schmitz et al. 2000, Denno et al. 2003, Graton and Denno 2003, Rosenheim and Corbet 2003, Borer et al. 2003). Brodeur and Rosenheim (2000) suggested that intraguild predation might significantly limit the effectiveness of aphid parasitoids as biocontrol agents. Subsequent field studies have shown that intraguild predation on immature aphid parasitoids in agroecosystems can be intense (Colfer and Rosenheim 2001). In previous studies we have demonstrated that generalist natural enemies are abundant (Fox 2002, Rutledge et al. 2004) and play a key role in suppressing *A. glycines* populations in soybean (Fox and Landis 2003, Fox et al. *2004*).

Soybean Aphid Population Regulation

The soybean aphid *Aphis glycines* Matsumura (Homoptera: Aphididae) is a major new invasive pest of soybean in North America. First discovered in July 2000, it is currently distributed in 21 US states and parts of Canada (Fig. 24). In 2003, over 50 million acres of US soybean were infested and over 7 million acres were treated with insecticides to control *A. glycines* (Landis et al. 2003). *A. glycines* overwinters on buckthorn (*Rhamnus* spp.) before migrating to soybean in the spring where it produces multiple summer generations (Wang et al. 1962). Common buckthorn (*R. cathartica*), itself highly invasive in woodland and wetland ecosystems, is the primary overwintering host for *A. glycines* in Michigan (Difonzo and Hines 2002). Generalist predators dominated the natural enemy community of *A. glycines* in US soybeans from 2000-2002 (Fox 2002, Fox and Landis 2003). Recently, the role of generalist predators in biological control has received increased attention (Settle et al. 1996, Snyder and Wise 2001, Symondson et al. 2002).

While generalist predators are often not as effective *per capita* as specialized predators, this limitation may be overcome by their earlier presence in the habitat when pest densities are low and specialist predators are scarce (Chang and Kareiva 1999). In previous studies we have demonstrated that generalist predators play a key role in regulating early-season aphid populations in field crops (Landis and van der Werf 1997).

In 2003 we investigated the relative strength of top-down (predation) versus bottom-up (plant host quality) regulation of soybean aphid at the KBS LTER site. Three of our soybean treatments (Conventional, No-till, and Zero-Input) resulted in varied plant quality for aphids. Conventional and no-till treatments received standard levels of nutrients and herbicide inputs, varying only in tillage method (chisel plow versus no-till). The organic-based zero-input treatment received no fertilizer or other chemical inputs and used cultivation for weed control. In each treatment we established three levels of natural enemy exclusion in 1 m^3 cages to study top-down effects: 1) total predator exclusion, 2) sham cages with openings to allow predator entry but control for cage effects, and 3) no-cage control (methods modified from Fox et al. *2004*). We removed all predators and aphids from the plots and re-infested with 110 aphids/m^2 to mimic the surrounding field population. Aphid populations were assessed at 7 and 14 days after infestation.

Aphid populations were 3-7 fold greater in the predator exclusion versus the sham or no cage treatments indicating a strong top-down effect (Fig.25a). Slicing among treatments in the exclusion cages revealed a weaker (1.5-2x) bottom–up effect, with aphid populations greater in the conventional than zero input treatment. Field populations of *A. glycines* were generally held below the economic threshold until mid August (Fig. 2b). In contrast, in plots where predators were excluded beginning on July 14, aphid populations rapidly exceeded the economic threshold. The natural enemy community responsible for aphid suppression (Fig. 25c) was primarily comprised of the predators *C. septempunctata*, *H. axyridis* and *Orius insidiosus*.

We will repeat this trial again in 2006 and 2009 when soybeans are present in the LTER main plots to further test the hypotheses that 1) *A. glycines* population growth does not differ due to bottom-up effects of agronomic treatments, and 2) *A. glycines* populations are strongly influenced by top-down effects of predator communities.

Intraguild Predation and Aphid Parasitoids

Generalist natural enemies may also affect biological control though intraguild predation and these interactions are vital to understanding herbivore population regulation (Rosenheim 1998). In terms of biological control, intraguild predation can reduce (Hindayana et al. 2001, Finke and Denno 2002, Snyder and Ives 2003, Lang 2003), fail to influence (Venzon et al. 2001), or have varying effects on herbivore control (Snyder and Wise 2001). In particular, asymmetrical intraguild predation interactions can disrupt biocontrol when an effective natural enemy is negatively affected by an intraguild predator that is itself a less effective natural enemy of their shared herbivore. Highly asymmetrical interactions can result in the apparent exclusion of certain natural enemies by the more effective intraguild predator (Michaud 2001, 2002). However, habitat complexity (Finke and Denno 2002) or source-sink dynamics (Rosenheim 2001) may alter such interactions by providing spatial or temporal refuges for victimsof intraguild predation.

To identify the parasitoid species attacking *A. glycines* in Michigan, sentinel *A. glycines* were exposed on soybean plants in soybean and alfalfa fields at the KBS 3 times during the 2003 field season (late June, early Aug, mid Sept). We detected three native parasitoids: *Lysiphlebus testaceipes, Aphidius colemani, Diaeretiella rapae* (Hymenoptera: Braconidae); and two previously introduced exotic parasitoids *Aphelinus albipodus* and *A. asychis* [Hymenoptera: Aphelinidae]. These parasitoids appear to be adapting to *A. glycines*. *Lysiphlebus testaceipes* was most abundant and present in soybeans in approximately equal numbers on all sample dates. *Aphidius colemani* also occurred at KBS on all sample dates, however, 75% of the detections were in the August sample. *Aphelinus asychis* and *A. albipodus* were detected only during August (Brewer and Noma 2003).

We will evaluate the impacts of intraguild predation on *L. testaceipes* and *A. albipodus* and their ability to establish and impact A. glycines population growth. Treatment impacts on *A. glycines, L. testaceipes*, and *A. albipodus* population growth will be examined using predator exclusion cages and controls (Fig. 26) as used earlier (Fox et al. *2004*). In several previous field studies using exclusion cages we have observed large differences in *A. glycines* populations when predators have been excluded (Fox, 2002, Fox et al. *2004*), and in 2003 we obtained preliminary evidence for intraguild predation against *L. testaceipes* in the field. We thus anticipate that the existing predator assemblages will have an impact on *L. testaceipes* and *A. albipodus* via intraguild predation (Fig. 27) as well as *A. glycines* population growth. Three specific hypotheses will be tested with this design: 1) that *L. testaceipes* and *A. albipodus* both reduce *A. glycines* population growth, 2) that intraguild predation reduces parasitoid survival in the field, and 3) that biological control of *A. glycines* is reduced by intraguild predation. Experiments will take place in the Biodiversity and T3-Scaleup fields where soybeans are present every year.

Competitive Displacement of Native Coccinellids

Harmonia axyridis is an exotic coccinellid from Asia that established in the US in 1988 (Chapin and Brou 1991). In Asia, *H. axyridis* is a common predator of aphids in Japan (Osawa 2000) and specifically of *A. glycines* in China (Han 1997). In many north central states *H. axyridis* has become the dominant coccinellid in a number of crops (Brown and Miller 1998) and successional habitats (Colunga-Garcia and Gage 1998), and it emerged as the dominant natural enemy of soybean aphid in soybeans during 2000-03 (Fox 2002, Fox et al. *2004*, Rutledge et al. 2004). *Harmonia axyridis* is a well-known intraguild predator (Koch 2003, Sato et al. 2003) and has been implicated in the decline of several competing coccinellids (Colunga-Garcia and Gage 1998, Yasuda et al. 2001, Michaud 2002).

Our preliminary observations indicate that long term *H. axyridis* population dynamics are likely to be related to *A. glycines* outbreaks. Densities of *H. axyridis* as high as 7 adults and up to 46 larvae/m^2 have been recorded in soybean fields during *A. glycines* outbreaks (Fox 2002). The increased resources provided by this new invader may increase *H. axyridis* fecundity, survival, and facilitate an extra generation in some years. This may, in turn, enhance *H. axyridis'* detrimental impact on native coccinellid communities.

Our long-term sampling of 15 coccinellid species (since 1988) will continue in the main site plots in order to characterize community response to this new and abundant food source. We will use this dataset to address two specific hypotheses about the long-term interaction of a new invader, *A. glycines,* on the interactions of *H. axyridis* and the native coccinellid community: 1) that *H. axyridis* population dynamics will exhibit a long-term shift with *A. glycines* populations as a primary driver, and 2) that the arrival of *A. glycines* will accelerate the decline in native coccinellids observed following the initial arrival of *H. axyridis.*

2.5 Biogeochemistry: Watershed Dynamics and Trace Gas Fluxes

Watershed Hydrogeochemistry

Research on watershed hydrogeochemistry at KBS is occurring on several fronts, each of which contributes to a holistic understanding of our two central questions: how current and future land use and landscape patterns affect the fluxes of water and nutrients from upland areas to lakes, streams and wetlands, and how these fluxes are altered in transit. Our extensive measurements of lakes, streams, wetlands, and soil and ground waters described earlier (see Section 1.6) have provided a detailed picture of the diversity and variability of hydrochemistries in our landscape. We intend to continue this measurement program during the coming phase of LTER research, although we now have sufficient data to appropriately reassess our distribution of sample sites and will reorganize our network for optimal efficiency. We have also examined how wetlands affect nutrient fluxes (Whitmire and Hamilton, in review), and the ongoing LINX stream experiments are revealing how small streams alter N export from watersheds of different land use. These more specific biogeochemical studies complement our abundant data on nutrient concentrations throughout the hydrologic system and will facilitate the eventual extrapolation of our results to the overall landscape.

Our measurements of soil water chemistry have led to a new research direction that we intend to pursue during the renewal period: What is the fate of inorganic carbon in agricultural lime amendments? This question is relevant to both field-scale agronomy and to regional and global biogeochemistry: Lime is an input added to counteract the continuous production of soil acidity during crop production, and whether its liberated carbon ends up as bicarbonate in ground and surface waters or as CO_2 in the atmosphere can affect surface water quality, atmospheric chemistry, and national carbon inventories. This is a good example of how agricultural land use is linked to landscape flows of materials via water movement and how agriculture can affect greenhouse gas fluxes in a way that heretofore has been little considered.

The periodic addition of lime, usually carbonate minerals, to neutralize acidity that would otherwise render soils infertile is a foundation of intensive agriculture in humid regions – over 17 Tg of limestone are mined for agricultural use each year in the U.S. (USGS 1997). Lime is usually applied as calcite ($CaCO_3$) or dolomite ($CaMg(CO_3)_2$) and represents an anthropogenic transport of carbon from geologic deposits to an actively cycling form. In earlier work we found agricultural liming to be second only to N_2O release with respect to sources of global warming potential in conventional annual crop systems (Robertson et al. 2000). Lime added to soils can also affect groundwater quality, which will eventually affect groundwater-fed surface waters. For example, Raymond and Cole (2003) reported that the flux of alkalinity through the Mississippi River system has increased substantially over the past few decades, and that the most highly agricultural subwatersheds appear responsible for this increased flux. We believe agricultural liming is likely to be the source of this enhanced alkalinity export, and Hamilton is collaborating with Raymond to assess this possibility.

Our earlier estimates regarding the importance of lime-derived CO_2 as a source of global warming potential (Robertson et al. 2000) assumed that all of the inorganic carbon in lime eventually becomes CO_2 as the lime is consumed, but we lack direct experimental evidence for this assumption. In moderately acid (pH 5-6.5), neutral, and alkaline soils, most of the dissolution of carbonate minerals can be ascribed to carbonic acid weathering, the major natural process involved in limestone weathering. CO_2 from root and microbial respiration hydrates in water to form the weak acid H_2CO_3, which reacts with solid carbonates as shown here for dolomite:

$$CaMg(CO_3)_2 + 2H_2CO_3 \rightarrow Ca^{2+} + Mg^{2+} + 4HCO_3^-$$

This reaction is actually a *sink* for soil CO_2, because for every mole of lime-derived C that dissolves, 2 moles of HCO_3^- alkalinity are produced and exported to groundwater. Carbonate alkalinity is generally conservative in groundwater and rivers, and therefore represents a long-term (centuries) sink for carbon (Raymond and Cole 2003). On the other hand, lime can be *source* for CO_2 if the carbonate comes into contact with a strong mineral acid; take, for example, dolomite reacting with nitric acid, where a mole of CO_2 is produced for every mole of carbonate that dissolves:

$$CaMg(CO_3)_2 + 4HNO_3 \rightarrow Ca^{2+} + Mg^{2+} + 4NO_3^- + 2CO_2 + 2H_2O$$

This latter reaction becomes important at $pH < 5$ and greatly enhances the rate of dissolution of carbonate minerals. Similarly, if the HCO_3^- produced by carbonic acid weathering subsequently comes into contact with H^+, which may occur after downward transport by infiltration, it will be consumed to yield free CO_2. The net result of these reactions is for the carbon in lime to become a source of free CO_2 in the soil and, ultimately, to contribute to soil-atmosphere CO_2 emission.

Our soil-solution chemistry measurements suggest variable fates for the lime added to KBS soils. The relative concentrations of dissolved Ca^{2+}, Mg^{2+}, and HCO_3^- produced by carbonate dissolution can be depicted as in Fig. 28. Concentrations of these ions in soil solutions beneath cropped plots span the range from nearly complete conversion of the lime carbon to free CO_2 (i.e., points climbing along the y-axis) to sequestration of additional CO_2 in an amount nearly equivalent to the lime carbon that has dissolved (points near the lower-slope 1:1 line).

We hypothesize that differences among agricultural soils with respect to the fate of the lime-derived carbon are mainly due to the variable importance of acidifying reactions, and particularly to differences in rates of nitrification associated with fertilization or nitrogen fixation. An increase in the availability of lime in soil will shift the net carbon balance associated with liming from a CO_2 source to a CO_2 sink, as will a decrease in acidifying reactions. If we can learn the circumstances under which one reaction pathway dominates the other in these soils, and if these circumstances can be manipulated (by, for example, inhibiting nitrifying bacteria or adjusting the source, amount, or placement of nitrogen fertilizers), then new management options for sequestering carbon in agricultural soils could be explored. Such options could entail adding *more* lime rather than less, effectively employing lime to sequester soil CO_2 as HCO_3^- and transport it downward by infiltration to deeper groundwaters.

We will employ three strategies to address this question. First, we will continue our watershed scale sampling and chemical analyses of major solutes to infer the overall fate of lime in various land uses around KBS. Second, we will continue bimonthly measurements of soil water from lysimeters beneath our agronomic treatments (some of which receive lime and some of which do not) and our successional sites to document seasonal and interannual changes in lime fates. Our regular measurements of surface soil properties (e.g. nitrate pools and nitrification and respiration rates) will provide insights into how lime weathering reactions can be affected by variations in acidifying processes in the solum. Third, field and laboratory experiments will allow us to test hypotheses about the effects of specific processes on lime fate. We are seeking funding to establish a set of differentially-fertilized experimental plots to which the same amount of lime will be added; differences in solute chemistry should reflect differences in soil acidification rates and concomitant differences in sequestered carbon. We established a preliminary experiment on the adjacent 56-plot Living Field Lab site (Smeenk et al. 2004) last spring, where we are collecting water samples from gravity lysimeters beneath 14 cropping systems that receive different forms of fertilizer (e.g. compost vs. inorganic N). In the lab we will test the importance of specific processes on inorganic-C fates by, for example, treating microcosms with nitrification inhibitors and measuring the appearance of ^{13}C from added carbonate minerals as either $^{13}CO_2$ or $H^{13}CO_3^-$. These strategies will be further informed by recently-established studies by geochemist L. Walters (UMichigan), who is studying overall mineral weathering in KBS soils (both silicate and carbonate weathering), and by soil chemist J. Reeves (USDA), who is mapping the distribution of carbonates in 1m deep soil cores across the LTER site.

Gas Fluxes

Since 1992 we have measured fluxes of the major biogenic trace gases from our 11 different crop and successional systems at KBS, and have additionally initiated various studies of the processes responsible for differential fluxes across the landscape. These measurements, among the longest term for any sites worldwide, are providing valuable information on interannual variations in fluxes among different land uses. We plan to continue these measurements during the next phase of LTER research, and additionally plan to further explore the relationship between soil nitrogen availability and N_2O production.

Recent research (McSwiney and Robertson, submitted) has shown a nonlinear relationship between added nitrogen and N_2O flux in cropping systems that is counter to accepted wisdom. The usual assumption, embedded in IPCC guidelines for greenhouse gas inventories (IPCC 2001), is that N_2O flux is directly proportional (1.25%) to total N inputs. Our findings, based on 3 years of measurements across our replicated nitrogen fertility gradient (Fig. 17) suggest that there is a fertilizer threshold below which N_2O fluxes are substantially below this proportion (Fig. 29). During the next phase of LTER research we plan to investigate the mechanisms underlying this threshold, and in particular to test the hypothesis that plant uptake is largely responsible for maintaining soil nitrate pools at levels that inhibit N_2O production. Alternative hypotheses include microbial immobilization, denitrification to N_2, and lower N mineralization rates. We will test these hypotheses by following N transformations and sinks along our nitrogen gradient in plots within which we will manipulate plant N uptake. This research also ties into our investigations of the microbes responsible for N_2O flux (Section 2.3) insofar as different resource levels may select for different populations of N_2O producers.

2.6 Humans: The Economic Valuation of Ecosystem Services

We first added a social component to our LTER portfolio at the beginning of the 1998 renewal period. Our aim then was to explore ways in which humans affect ecological interactions in the agricultural landscape, and in particular to explore questions related to 1) the effects of exurbanization on farm practices and 2) the barriers that prevent or slow growers' adoption of environmentally friendly technology. We plan to continue the exurbanization research during the coming years, but primarily with external support. The research on adoption of ecological technology is being integrated into our revised conceptual model (Fig. 15) that identifies ecosystem services as a principal product and driver of human behavior in row-crop agriculture. We now see a greater need to direct resources towards characterizing and quantifying these services, how they can be enhanced in a row-crop landscape, and ultimately how better understanding of such services can affect the farmers' willingness to adopt them and policy makers' desire to create incentives for their adoption. With this renewal, then, we initiate a long-term effort to better characterize and value ecosystem services in row-crop agriculture and to examine how the provision of these services affects (either directly or indirectly) ecosystem structure and function.

The economic value of ecosystem services

Fifteen years of KBS LTER research has produced a large inventory of data on agricultural ecosystem functions. Most of these functions are important and many are critical to the ecological integrity of our ecosystems, but how many of them link to ecosystem services that are valued by society? And apart from the commercial value of farm products, do these services provide added value? At present agricultural ecosystems are explicitly managed to meet private objectives, primarily profitability. But because they are directly managed by humans, these ecosystems are uniquely suited to produce services that could also meet public objectives if suitable incentives could be provided.

Current attempts to characterize and value the non-marketed services provided by cropland ecosystems are largely limited to soil erosion and water quality, with a nascent literature in carbon sequestration (e.g. McCarl and Schneider 2000). There is very little published research on the valuation of cropland services such as water regulation, soil formation, nutrient cycling, pollination, and waste treatment. Our initial efforts towards quantifying services will necessarily start with their identification: We will begin by developing an inventory of ecosystem functions and services based on focus group research conducted with LTER scientists. The inventory will include a bibliographic database of valuation studies on services that will be useful 1) for providing a frame of reference for methods and results of prior valuation efforts, and 2) for exploring the potential to use metadata analysis to transfer nonmarket values from other settings to ours while accounting for some of the factors that may make them vary from one place to another (Brouwer 2000, Morrison et al. 2002, Smith et al. 2002, van den Bergh and Button 1999). These different valuation strategies are depicted in Fig. 30.

Supply-side valuation methods

The replacement cost approach to ecosystem valuation used by some ecologists (e.g. Costanza et al. 1997, Pimentel et al. 1992, 1997) has been criticized for violating microeconomic principles of marginal analysis, budget constraints, and comparison of most feasible alternatives (e.g. Barbier 1998, Bockstael et al. 2000, Pearce 1998). Alternative approaches that avoid these problems exist for marginal changes: From the supply side one can examine how much revenue farmers would have to sacrifice in order to produce more of specified ecosystem services by changing production practices. On the demand side one can explore how much consumers of ecosystem services are willing to pay (WTP) in order to obtain more of specified services.

We focus on the valuation of ecosystem services that are not directly traded in markets because the value of marketed services can be measured by prices. Simulation modeling of producer behavior offers a valid approach to calculating the opportunity cost in foregone revenues for farmers to increase output of ecosystem services. The resulting values can be interpreted as the minimum amounts that these managers of agricultural ecosystems would be willing to accept in order to produce more of a particular service. Apart from their contribution to economic research methods, better measures of ecosystem values may encourage policy makers to create more explicit incentives for land managers to generate more diverse services.

Bioeconomic optimization modeling takes several forms that are useful for farmers' willingness to accept compensation to provide more ecosystem services (Holden 2004). A series of increasingly complicated methods will be applied to develop these values, and we will seek external support to develop this activity beyond a base model. First, KBS LTER data will be analyzed statistically to estimate functional relationships between management practices and the generation of ecosystem services. Second, selected input-output relationships and the production resources they entail will be incorporated into a mathematical programming model, initially for scenario analysis at the whole-farm level. Such a model can capture inter-relationships between resources required for different farming activities in developing estimates of the value of productive resources and requirements for enhanced ecosystem service (Hazell and Norton 1986, Roberts and Swinton 1996, Swinton and Clark 1994). After its initial development we will make the model dynamic and eventually extend it to a regional level.

Demand-side valuation of ecosystem services

The demand-side value of nonmarketed ecosystem services can be estimated by assessing consumer preferences, either as revealed indirectly in existing markets or as stated by consumers in response to survey questions. For land-based ecosystem services, such as soil formation, nutrient cycling, and landscape aesthetics, hedonic analysis of land prices can potentially reveal willingness to pay for a) enhanced soil microbial activity that could ameliorate the impact of agriculture on the broader landscape (e.g. nitrate contamination of groundwater) or global climate (e.g. soil C sequestration), or b) landscapes made attractive by diverse vegetative cover or through provision of wildlife. Prior hedonic analyses of land prices have been applied to valuation of erosion control (Palmquist and Danielson 1989, Ribaudo and Hellerstein 1992). A major challenge to this method is the development of a database of land prices that includes both 1) a variable that is directly related to the ecosystem service of interest and 2) a comprehensive set of additional variables that account for the other factors influencing land value. We will conduct an exploratory study to determine whether a high-quality hedonic land price study is a feasible approach to the valuation of ecosystem services measured at our site.

Expressed preference methods, such as contingent valuation and conjoint analysis have been widely applied to estimate willingness-to-pay (WTP) values for large wildlife, water quality, and other environmental attributes of direct human interest (Bergstrom et al. 2001, Braden and Kolstad 1991, Freeman III 1993, Haab and McConnel 2002, Hanemann 1994). However, these valuation methods may be less suitable for ecosystem services with less obvious direct benefits to consumers such as water regulation, soil formation, nutrient cycling, or waste treatment. The validity of an expressed preference study depends on many factors, but the nature of the hypothetical market and the mechanism by which consumers would pay for the ecosystem service in question are key determinants. This type of survey research is expensive and we will use core funding chiefly to support an initial feasibility study and the planning of additional externally-funded research.

Economic value of biological control of an invasive insect species

The recent invasion of the soybean aphid (*Aphis glycines*; see Section 2.3, above) presents an opportunity to evaluate the economic value of a specific ecosystem service: the biological control of an important crop pest (Landis and Orr 1996, Landis et al. 2000). We propose to undertake this evaluation by developing a bioeconomic model of alternative control mechanisms for soybean aphid via the following steps (Boggess et al. 1985, King et al. 1993):

(1) using explanatory variables for environmental conditions and human-imposed pest control measures, we will statistically estimate functions to predict a) the reproduction rate of the soybean aphid, b) rates of survival to adulthood, and c) rates and patterns of its spatial dispersion;

(2) using explanatory variables for soybean aphid population, soybean plant growth stage, and environmental conditions, we will statistically estimate functions to predict soybean yield loss (Lichtenberg and Zilberman 1986, Pedigo et al. 1986);

(3) we will obtain data on historical soybean prices and costs of alternative soybean aphid controls (including machinery, chemicals, and labor requirements);

(4) we will program a bioeconomic simulation model, linking elements (1-3) above, to predict dynamic profitability outcomes of alternative pest control practices over time (using gross margin over pest control costs as a proxy for profit);

(5) using measures of unexplained variability from the statistical models in (1-3), we will extend the deterministic model in (4) to a stochastic model offering probability distributions of outcomes for profitability, soybean yields, and soybean aphid population trends;

(6) using cost-of-illness data from published studies that include alternative insect control methods included in (1), we will adjust the bioeconomic model to reflect hidden health costs that would otherwise not appear in profitability estimates (Antle and Pingali 1994, Crissman et al. 1998, Maumbe and Swinton 2003, Sunding and Zivin 2000); and

(7) we will extend the model to a regional level, incorporating general-equilibrium price feedback in response to soybean yield effects. This element will capture expected increases in soybean prices in response to yield decline, to the extent that soybean production in other parts of the world does not compensate for reductions in the United States.

Results will provide one of the first comprehensive evaluations for ecosystem services in row-crop agriculture, and will serve as a model for subsequent analyses.

2.7 Regionalization

Effective forecasting of biophysical and ecological processes and attributes depends in part on the development of predictive models of ecological phenomena at landscape to regional scales. Our development of the MASIF (Modeling Applications System Integrative Framework) modeling framework (see Section 1.7) is central to our efforts to scale local LTER knowledge to regional levels, and thus central 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 that is available for subsequent 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 as a consequence of changing climate and agronomic practices (Grace et al., submitted).

We are presently working to incorporate a discrete suite of additional models into the MASIF framework in order to further the analysis of future scenarios. Models for which we have run successful regional simulations include the corn productivity model MAIZE (Muchow et al. 1990), and the daily version of the CENTURY soil organic model (DAYCENT) that also includes trace gas submodels (del Grosso et al. 2002). We are working with model authors to refine the models to allow better representations of changes in NPP and soil carbon under different climate, land use, and economic incentive scenarios, and to incorporate N_2O and CH_4 submodels. DAYCENT can successfully predict annual N_2O fluxes for KBS soils (Fig. 31; del Grosso and Parton, unpublished) and efforts are underway to produce a version to better predict daily values prior to further regional simulations.

In addition, we are currently working on remote sensing estimates of various physical variables such as leaf area index and no-till practices of the region using the new MODIS images from Terra satellite to 1) calibrate and validate these process-based models and 2) improve model predictions in the MASIF environment. Assimilation techniques are being tested to guide model simulation and forecasting using remotely sensed variables such as LAI, fPAR, and crop phenology information.

Over the coming renewal period we will work on three regionalization activities:

Activity 1. Model Formulation: Goals for Prediction and Scale Identification

Modeling developed at a particular spatial scale must be matched by the appropriate temporal scale if results are to make ecological sense (Wiens 1989, Levin 1992). For example, short-term studies over large areas will likely predict non-perceptible changes, whereas long term studies in a reduced area will likely over- or under-predict change when applied to the larger area. One of our challenges, then, is to assure that a) we have an appropriate spatial scale (e.g. Fig. 32) and b) that our spatial scale is matched by an appropriate temporal scale when modeling (Fig. 33).

We have chosen 3 processes for initial model development: crop productivity, soil carbon change, and trace gas flux. To these we will later add insect dispersal, and in particular the dispersal of the ladybird beetles (Coccinellidae) and its prey the invasive soybean aphid *Aphis glycine* (see Section 2.4), and as we generate more information on the fate of carbon in agricultural lime amendments we will employ the model framework to extrapolate these results to the region (see Section 2.5). We will identify the appropriate scale for which each variable can be effectively modeled, based on climate, soil, and socioeconomic considerations.

Activity 2. Model Calibration and Validation

Our biggest technical challenges are to appropriately parameterize, calibrate, and validate each model. Climate data needs are common to all models and we believe our present database (1055 counties with daily records since 1972) meets current weather parameterization requirements. Our soils data are derived from the USDA/NRCS STATSGO database, which has been sufficient for modeling regional NPP and soil carbon change (Grace et al., submitted). Our need for verifiable land use and land cover data is not as easily met with existing databases, however, and we will in the coming period use remote sensing imagery to better characterize land use and land cover in the region. We have had substantial success with our initial efforts to differentiate between tilled and no-till cropland using Landsat satellite imagery (South et al. 2004), and we expect to use these new algorithms together with established methods for differentiating among crop types to build a historical and contemporary crop land use and land cover database for the region. KBS investigators are part of the NASA Upper Midwest Regional Earth Science Applications Center (RESAC), a consortium comprised by MSU, the University of Wisconsin, and the University of Minnesota, and we are tapping this collaboration for this effort.

Calibration and validation is an equal challenge. All of the variables that we have chosen to regionalize have been measured at KBS for at least 12 years. Our calibration and validation strategy is thus to first test models against our existing data, and then against information from other sites in the region for which long-term data are available. We also test regional model output against historical trends for those variables with historical records. Historical crop yield data, for example, are available at the resolution of individual counties in the USDA/ERS databases; harvest indices can be easily applied to transform yield to aboveground NPP. Our tests of MASIF/MAIZE against this database (see Section 1.7) showed a lack of concurrence until we incorporated a soil temperature algorithm to override the influence of air temperature during early corn growth. To test our soil carbon model estimates (Fig. 34 and 35; Grace et al., submitted), we compared model output for the region in 1990 (4.7 Pg C in upper 10 cm) against an estimate derived from soil surveys specific to the region (5.4 Pg C; Franzmeier et al. 1985).

Activity 3. Model Synthesis

To effectively forecast ecological change requires that we integrate our models with other change forecasts derived from trend analysis and other types of models. Econometric, population, land use, and climate projections are particularly important to include as they will affect (and in some cases be affected by) changes in agronomic activities. Initially we have focused on climate change as the principal driver of change in our models. However, as our models develop and are appropriately validated, we will begin to incorporate additional change agents and explore ways to include these models directly in the MASIF framework. We anticipate that the usefulness of our models for policy analysis will depend on identifying and modeling specific economic and environmental scenarios, and part of our effort in the coming period will be devoted to the incorporation and (as needed) development of these scenarios.

We are also committed to synthesizing our activities with regional modeling efforts elsewhere in the network. As a site, we (in particular SHG) have helped to organize and lead the three network-level workshops on regional modeling held at the San Diego Supercomputer Center since 1998. As this effort progresses we expect to incorporate new models and approaches into our own modeling efforts.

Ultimately this work will take us in the direction of one of the goals of LTER research – to be able to apply the knowledge developed from years of study of representative sites to the broader regions that they represent.

2.8 Synthesis

Over the past 15 years we have addressed most of the major ecological factors that underlie the productivity and environmental impact of the intensively managed, high-productivity row-crop ecosystem 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 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. We propose two strategies for achieving this during the upcoming renewal phase.

The first strategy is the adoption of a conceptual model (Fig. 15) that better integrates key properties and processes in the row-crop ecosystem and identifies the major factors that influence their interactions. A focus on ecological interactions within the ecosystem – among structural properties such as community composition and functional properties such as nutrient loss – provides a localized understanding of the system within the constraints of particular biophysical and socioeconomic contexts. Scaling this understanding to the broader watershed or landscape scale with its concomitant variation in both the biophysical environment (e.g. geomorphology and landscape position) and socioeconomic environment (e.g. market prices, infrastructure, and ethics and values) requires a further degree of integration. And scaling still further to a regional focus allows a better understanding of regional-scale drivers, feedbacks, and consequences such as the impact of regional climate change, farm commodity price changes, or changes in national farmland conservation or greenhouse gas policies. We expect this model, especially as it suggests priority areas for cross-project research (below), will significantly promote integration.

The second strategy is a more focused effort on cross-project and cross-site investigations that contribute directly to our conceptual model. Research in any single part of the project is expected to a) address fundamental questions about the ecology or value of row crop ecosystems and b) tie into research elsewhere in the project. All of our core research is designed to address a specific portion of our conceptual model and where possible to relate directly to research addressing other parts of the model. In this way we have attempted to ensure that the model is as completely addressed as possible. Our plant research, for example, ties directly into research on the diversity and dispersal of arthropods and nutrient availability. Our microbial research ties directly into research on trace gas fluxes, nutrient availability, and soil structure, and all of these areas intersect with the hydrogeochemical research.

Two core components are particularly integrative: (1) Research on the valuation of ecosystem services requires knowledge from all other aspects of the project, and as it develops to consider the design of ecosystems for optimal services it will likely influence the direction of biophysical research. And (2) our regionalization efforts depend mainly on modeling that at first will integrate knowledge of soil carbon change, trace gas fluxes, and coccinellid population dynamics; as model development proceeds, however, it will pave the way to build in other aspects of the row-crop system of interest for regional integration. Further, our involvement in diverse cross-site comparisons is helping to provide an understanding of how a predominantly agricultural landscape compares with other ecosystems of divergent climate and biota, as well as how agricultural practices affect the environment in different landscapes.

Taken together, we are hopeful that these strategies will combine to effectively direct our efforts towards a more complete understanding of the row-crop ecosystem, and in particular will help us better produce research results that elucidate ways in which ecological structure and function interact in row crops at multiple scales. Without this understanding we are unlikely to make effective progress towards relieving our economic and environmentally costly reliance on chemical inputs in the high-productivity row crop ecosystem.

2.9 Figures

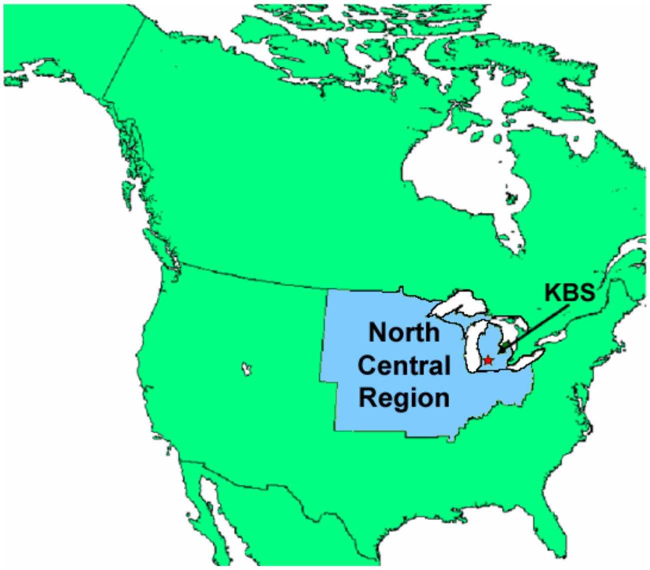


Figure 1. Location of KBS. The North Central Region is the USDA's nomenclature for what is commonly known as the corn belt, and which we have identified as the region best represented by the KBS LTER site. Annual rainfall at KBS averages 890 mm y-1 with about half falling as snow; mean annual temperature is 9.7 °C.

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.

Figure 2. The KBS LTER global hypothesis formulated in 1987 for our field-scale research. For 2004 the corollaries have been expanded to include the interactions and human dynamics depicted in our revised conceptual model (Fig. 15).

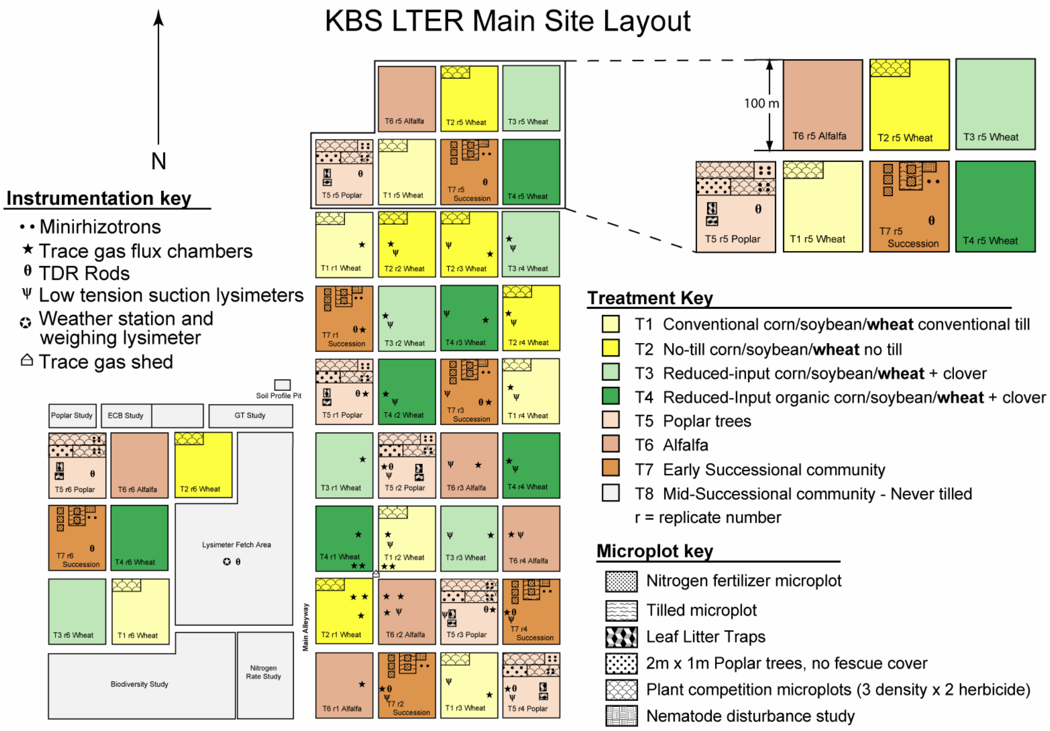


Figure 3. Experimental layout of the main set of cropping systems at the KBS LTER site. Block 5 (of 6 total blocks) is expanded at upper right to show plot details. In addition to the seven treatments shown here are 1-ha plots in three older successional fields (40 - 60 years since abandonment), in three conifer plantations (40 – 70 years since establishment), and in three old-growth deciduous forest stands. Four small plots on a cropped but never tilled soil profile comprise another midsuccessional treatment (T8), for a total of 11 types of replicated communities on the same soil series.

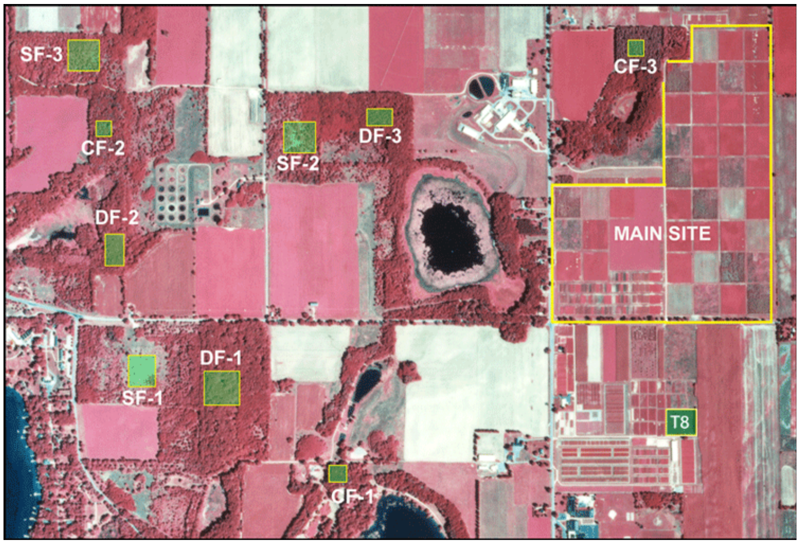


Figure 4. Aerial infrared photograph of KBS showing locations of the main LTER site (See Figure 3) and (in green) the mid-successional communities and forest stands. SF = mid successional fields abandoned from cropland ca. 1950, CF = conifer-dominated forest stands, and DF = deciduous forest sites.

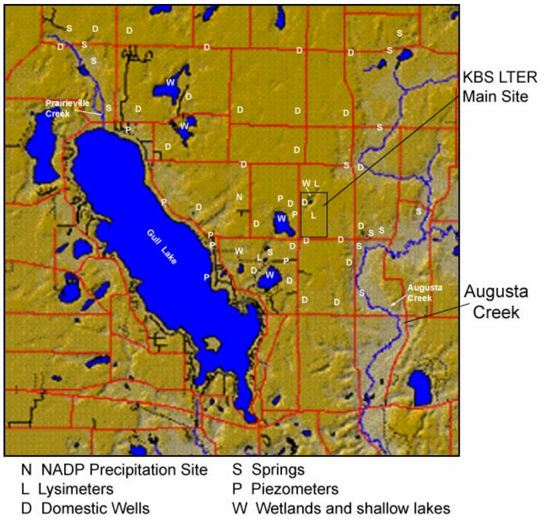


Figure 5. Digital elevation map of the KBS watershed study area. Symbols denote water sampling sites. The area is bounded by Gull Lake on the west and Augusta Creek on the east. Red lines are roads.

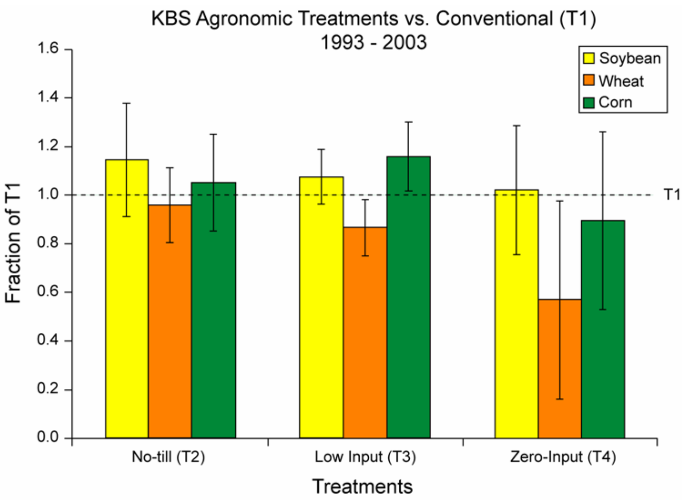


Figure 6. Yields in our no-till (T2), low-chemical input (T3), and zero-chemical input (T4) treatments relative to yields in our conventional (T1) management treatment (dashed line). Values are mean yields for 3 full rotation cycles (1993-2003). Average T1 yields are 2.3 MT ha^{-1} y^{-1} for soybeans, 3.5 MT ha^{-1} y^{-1} for wheat, and 5.8 MT ha^{-1} y^{-1} for corn.

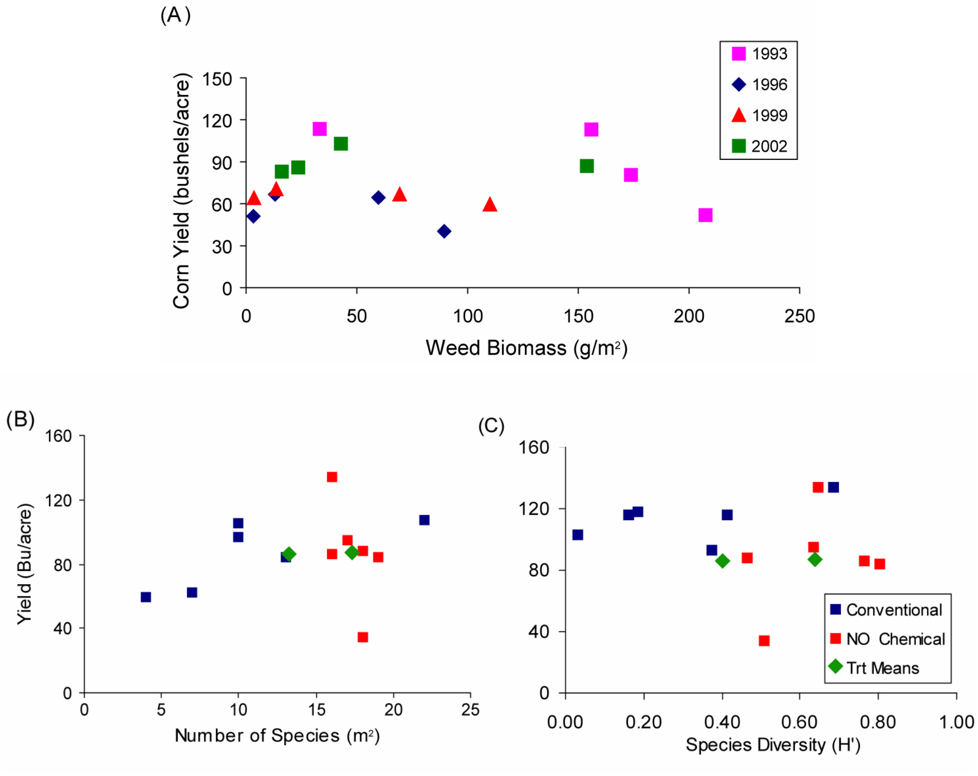


Figure 7. Corn yields in relation to (A) weed biomass and (B) weed species richness across years (1993-2002) and (C) diversity in 2002 at the KBS LTER site. Variation in weed community characteristics had no effect on corn yield.

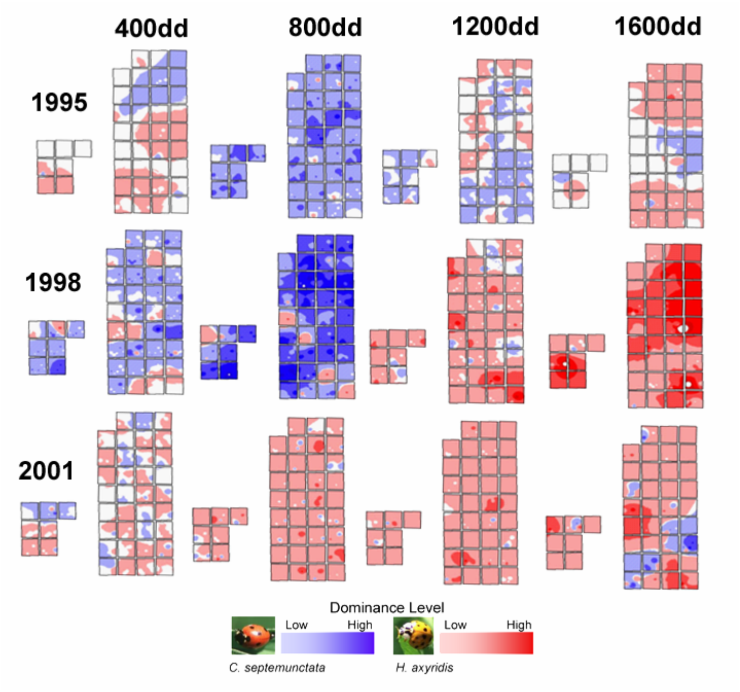


Figure 8. Spatial comparison showing the dominance level of two main exotic species of ladybird beetles in the KBS LTER during winter-wheat years at four degree-day intervals. Color gradients indicate the intensity of dominance by either *Harmonia axyridis* (red gradient) or *Coccinella septempunctata* (blue gradient).

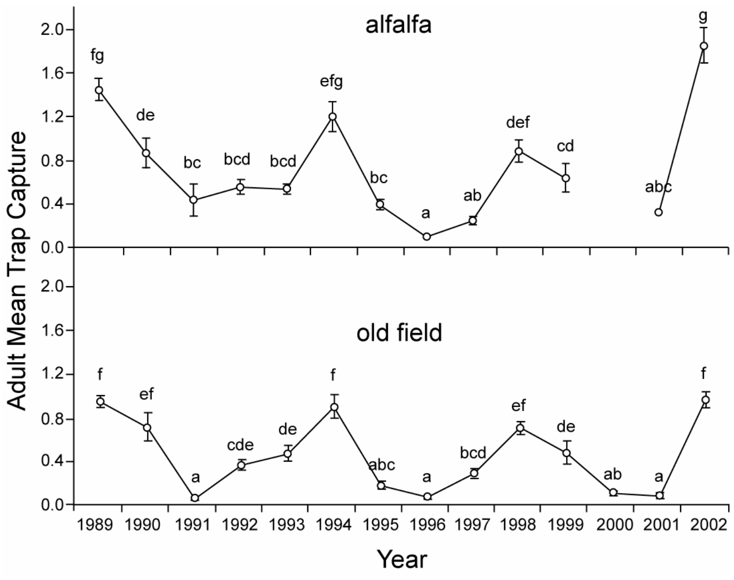


Figure 9. Abundance-activity of the ladybird beetle *C. septempunctata* on alfalfa and old-field succession habitats from 1989-2002. Values within the same habitat followed by different letters indicate years where observations were significantly different (Turkey P=0.05).

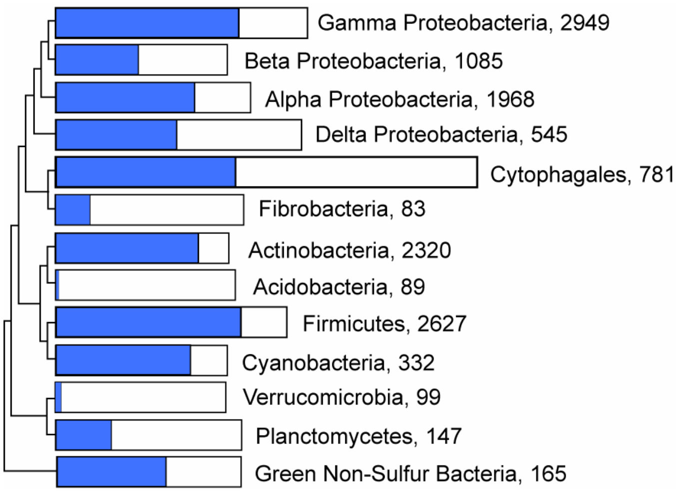


Figure 10. Phylogenetic tree of the microbial groups most commonly recovered from soils. The length of each box is a measure of the extent of sequence variation in the 16S rRNA encoding genes for organisms in that phylogenetic group; the shaded regions portray the proportion of the sequences derived from cultivated strains.

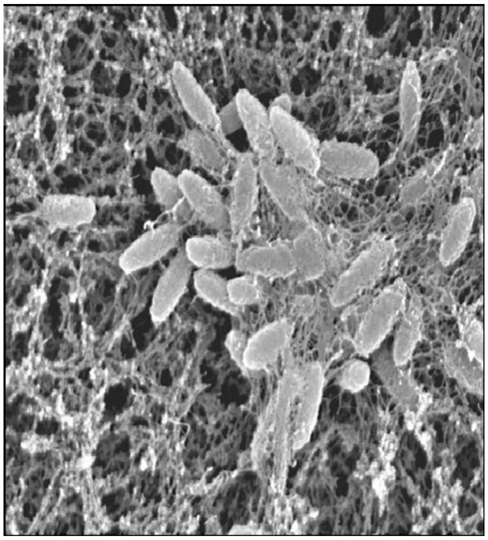


Figure 11. Scanning electron micrograph of Acidobacterium strain KBS89, isolated from the KBS-LTER site.

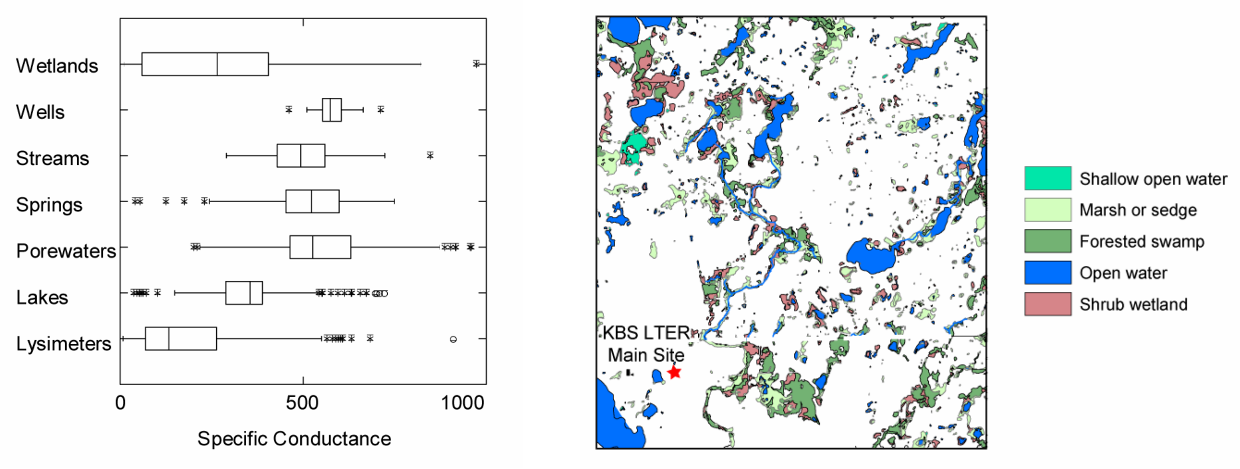


Figure 12. Specific conductance of surface and ground waters sampled in the vicinity of KBS (left) and surface waters in the landscape just northeast of the site (right). Wetlands and lakes are abundant and biogeochemically diverse, making this landscape ideal for comparative studies.

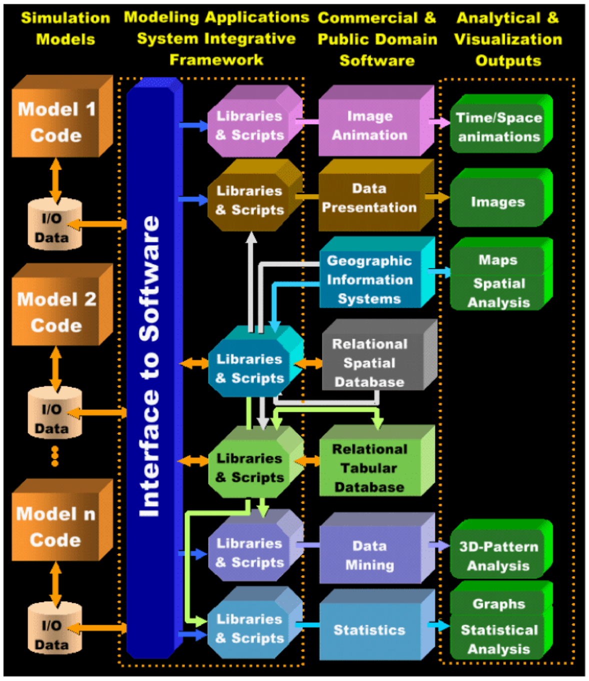


Figure 13. Integration of software elements for the analysis and visualization of simulation models via MASIF (Modeling Applications System Integrative Framework), developed in partnership with the San Diego Supercomputer Center.

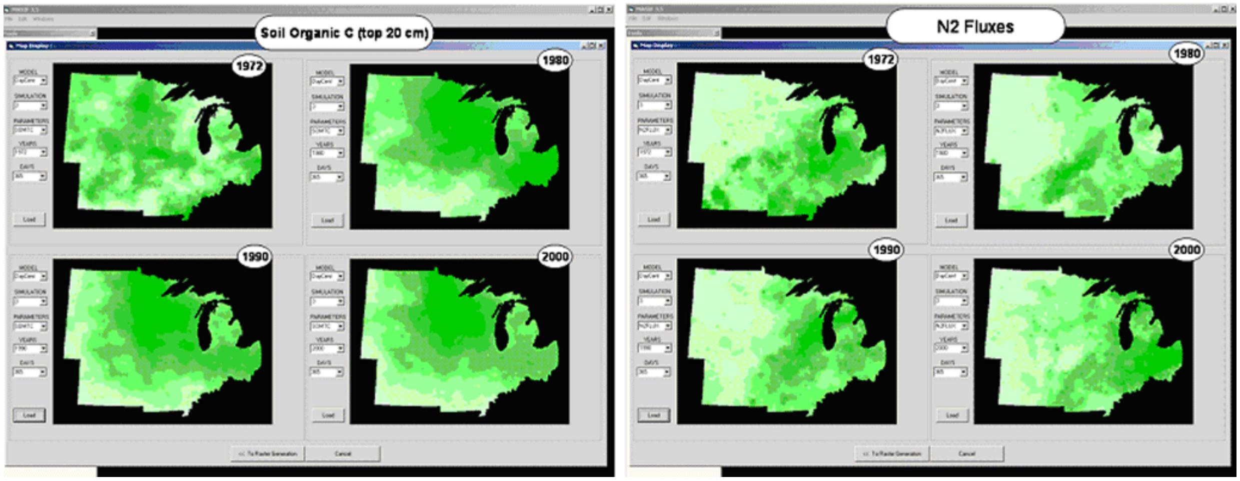


Figure 14. MASIF/DAYCENT outputs for soil organic carbon (left) and denitrification-N_2 fluxes (right) across the North Central Region for four periods : 1972 (upper left), 1980 (upper right), 1990 (lower left), and 2000 (lower right) of each panel. From del Grosso et al. (in prep).

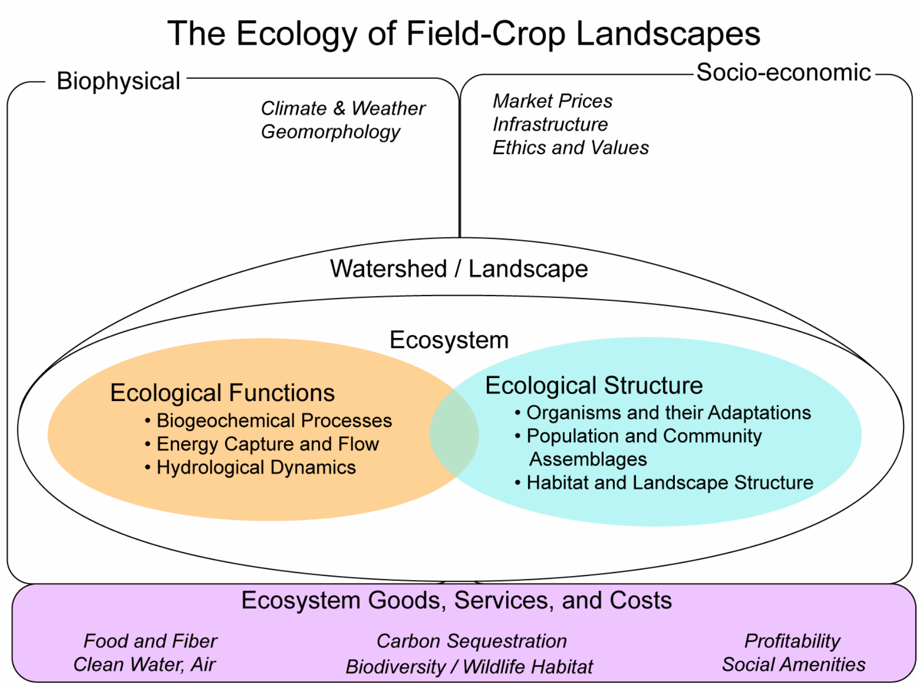
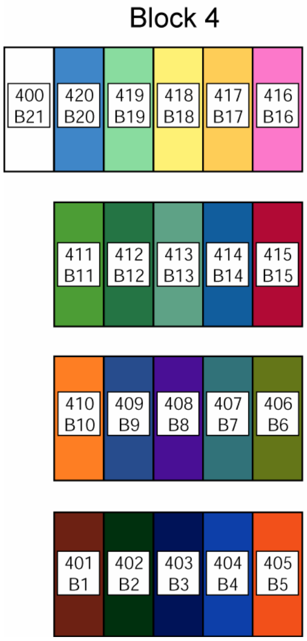
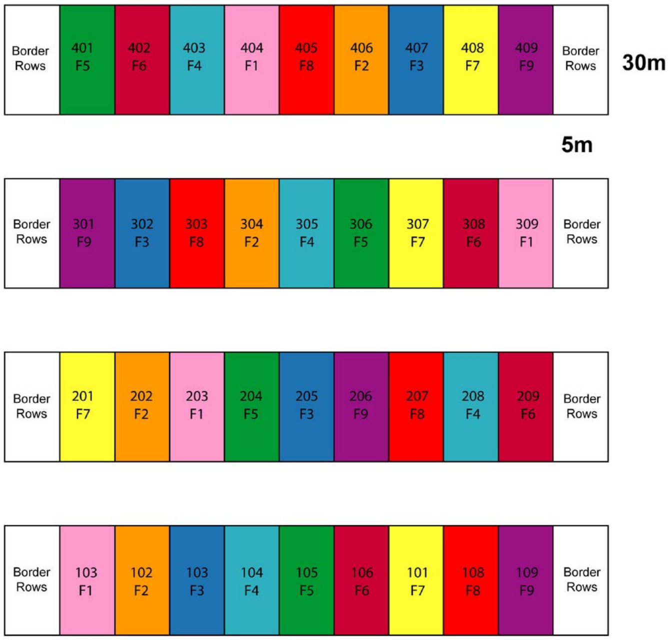


Figure 15. Conceptual model for the next phase of KBS LTER research. Linkages between ecological structure and function within the crop ecosystem largely determine the production of ecosystem goods and services. The capacity of a system's production, however, is greatly influenced by the biophysical and socioeconomic contexts in which interactions occur, and which largely govern crop management decisions.



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

Figure 16. Layout of the Biodiversity experiment 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.



Legend

Treatment	F1	F2	F3	F4	F5	F6	F7	F8	F9
N(lb/a)	0	30	60	90	120	150	180	220	260
N(kg/ha)	0	34	67	101	134	168	202	246	291

Figure 17. Layout of the nitrogen fertilizer gradient experiment on the LTER main site (n=4 replicate blocks). Fertilizer is applied to continuous corn at 9 rates ranging from 0 to 290 kg N ha^{-1} (best management practice usually calls for ca. 134 kg N ha^{-1}). Each plot is 5 x 30 m. A second set of irrigated plots adjacent to and otherwise identical to this set was established in 2003.

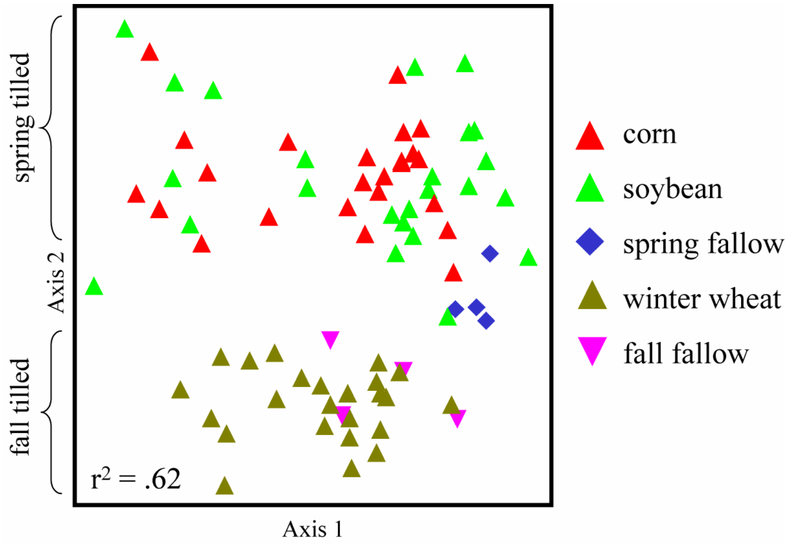


Figure 18. Non-metric multidimensional scaling ordination of weed species communities in 2002 on the KBS biodiversity plots. Tillage time, rather than crop type, rotational diversity, or sequence, is the primary determinant of weed community composition.

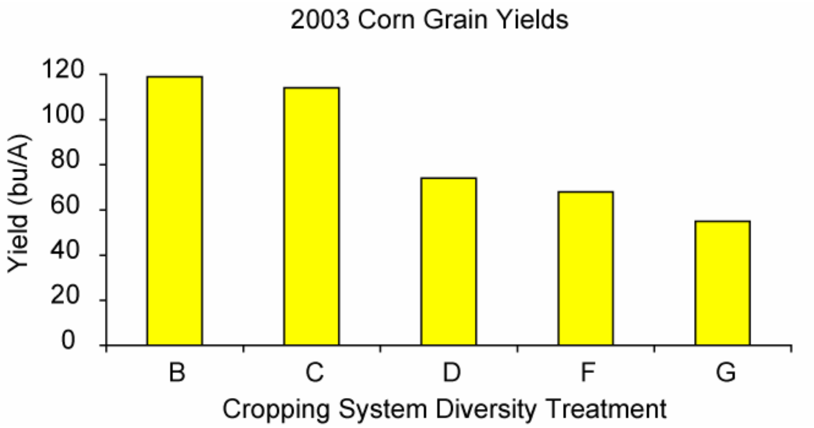
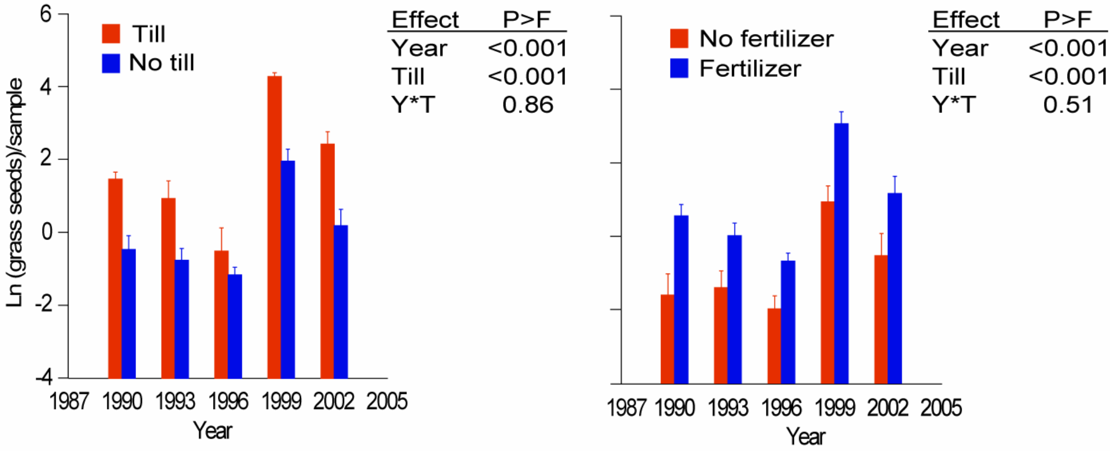


Figure 19. Corn in relation to crop diversity treatments in the KBS biodiversity plots: B=high diversity, 3-crop rotation with 2 cover crops; C=3-crop rotation with 1 cover crop; D=3-crop rotation with no cover crop; F=continuous corn, with cover crop; G=continuous corn, no cover crop.



Effect	P>F
Year	<0.001
Till	<0.001
Y*T	0.86

Effect	P>F
Year	<0.001
Till	<0.001
Y*T	0.51

Figure 20. Single degree of freedom contrasts examining effects of a) tillage and b) synthetic N fertilizer on abundance of grass seeds in the soil seedbank.

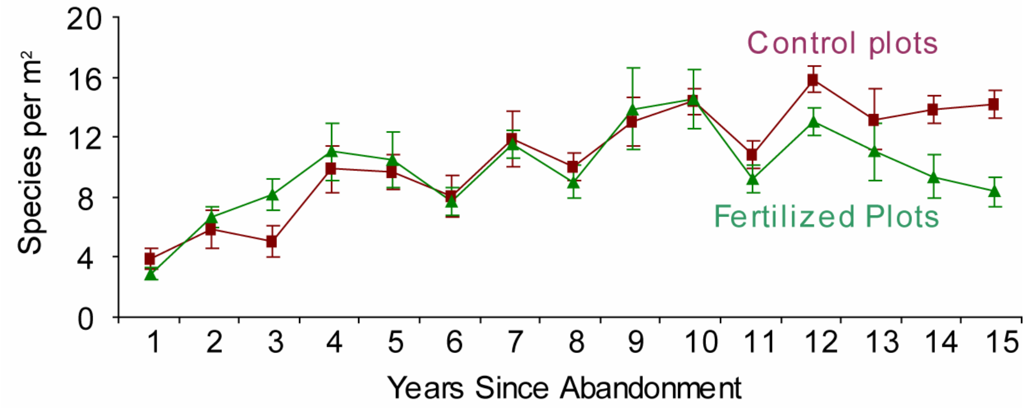


Figure 21. Temporal dynamics in plant species richness in successional fields (T7) in response to fertilization from 1989-2003.

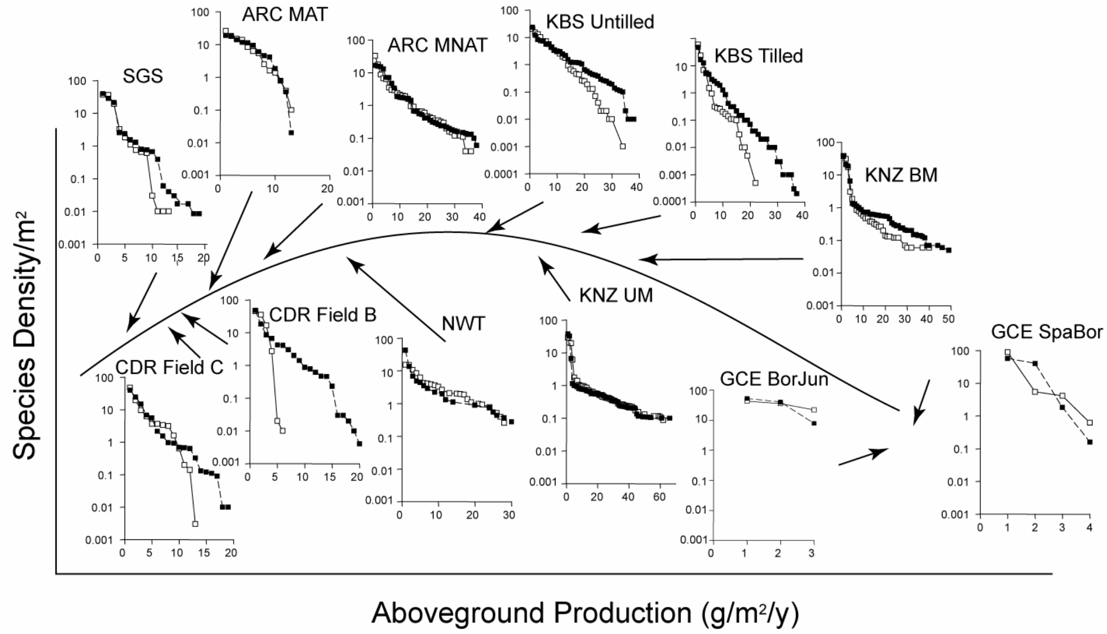


Figure 22. Grasslands at LTER sites differ in the magnitude of response to fertilization, including species loss and changes in dominance. Inset graphs are rank abundance plots for fertilized and control plots from 12 communities at 8 LTER sites; arrows indicate site location on the curve describing the overall relationship between productivity and diversity.

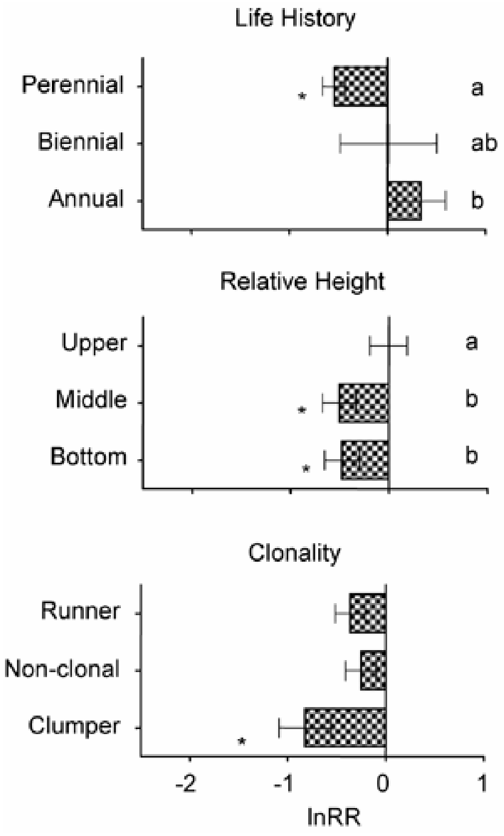


Figure 23. The relationship between functional traits (y-axis) and species' relative response to nitrogen fertilization (lnRR) for all species records in the FertSyn database. Negative values indicate that a group decreased in relative abundance due to fertilization, positive values indicate that the species increased in relative abundance. Asterisks indicate the relative responses of species functional group that significantly differed from zero, and different letters indicate significant differences among functional traits.

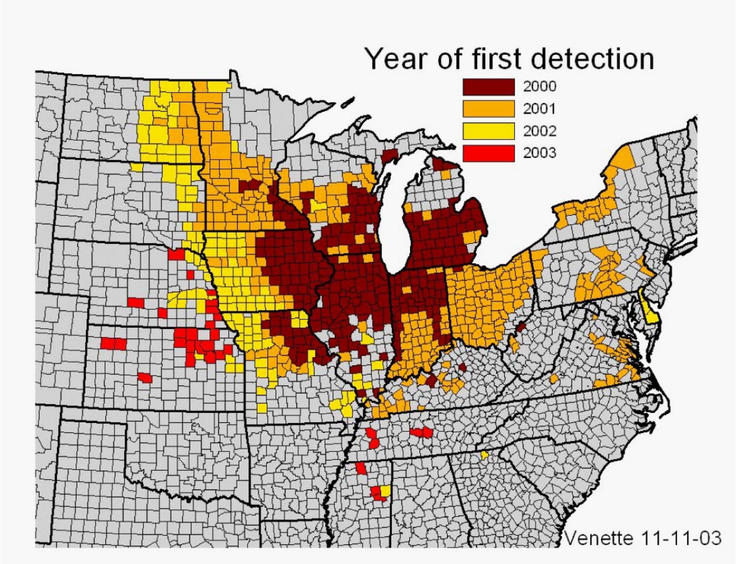


Figure 24. Spread of *Aphis glycines* (2000-2003) (from R. Vennette, unpubl.).

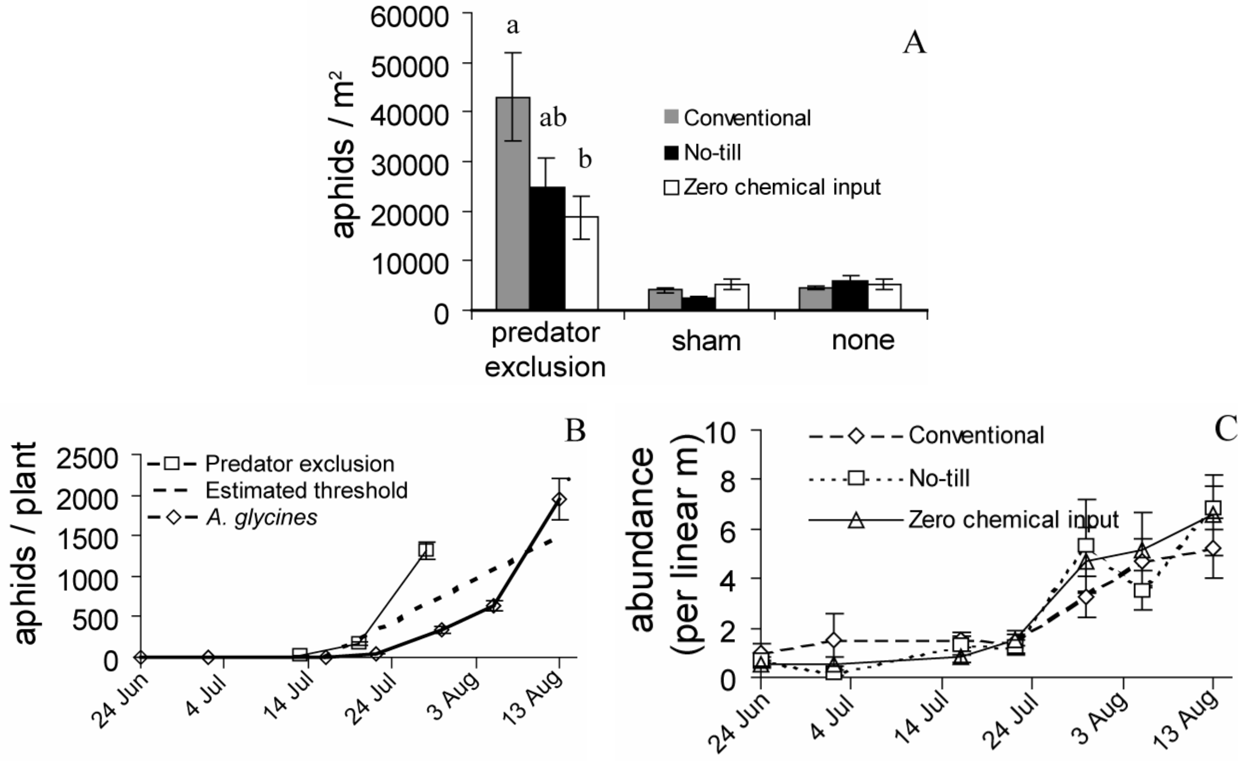


Figure 25. Soybean aphid populations in predator exclusion trials (A), natural population versus predator exclusion trial and estimated treatment threshold (B), and predator populations in season long trials (C), KBS 2003.

Figure 26. Complete predator exclosure (left) and sham cage (right). Plastic on sham cage is raised 10 cm above soil line to allow entry by soil dwelling predators.

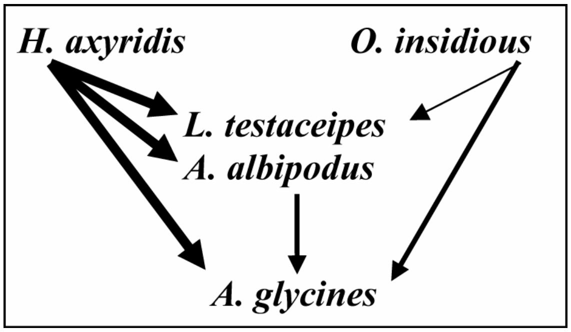


Figure 27. Predicted intraguild interaction in the A. *glycines* system. Arrows point towards the victim and thickness indicates the strength of the interaction.

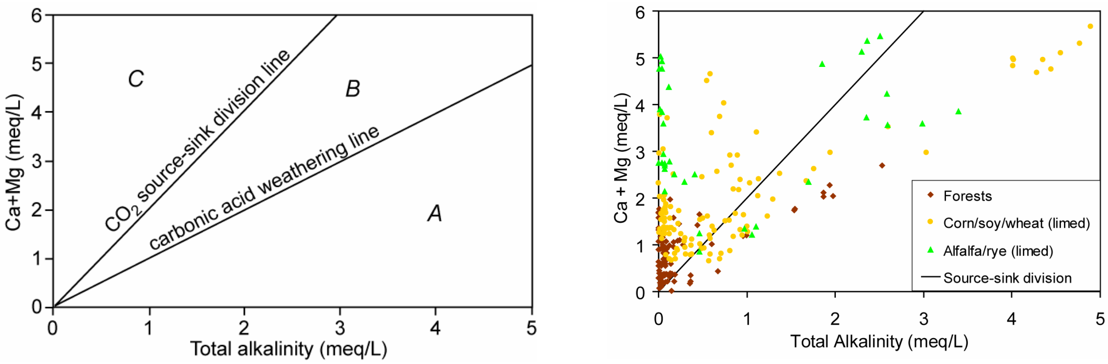


Figure 28. Left: Conceptual model of carbonate dissolution in soils. The carbonic acid weathering line depicts the expected 1:1 ratio of dissolved Ca^{2+} + Mg^{2+} to HCO_3^- measured as alkalinity. The CO_2 source-sink division line" represents the elemental stoichiometry in the lime (calcite or dolomite). Carbonate dissolution alone does not produce samples plotting in area A. Solutions plotting in area B represent dissolution of lime plus sequestration of soil CO_2, while solutions plotting in area C represent dissolution of lime and conversion of at least some of the carbonate-carbon to free CO_2, thereby representing a source of soil CO_2. Right: Infiltrating soil waters from LTER treatments sampled with low tension lysimeters span areas C and B, showing that liming can be either a sink or source of CO_2 to the atmosphere.

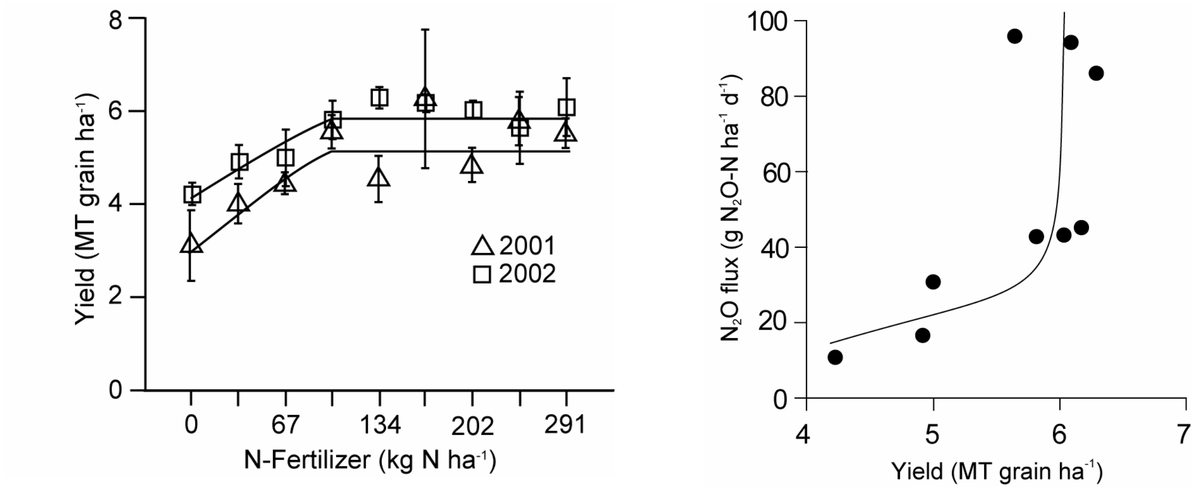


Figure 29. Yield response to N-fertilizer levels (left) and non linear relationship of N_2O flux and yield in continuous corn (right).

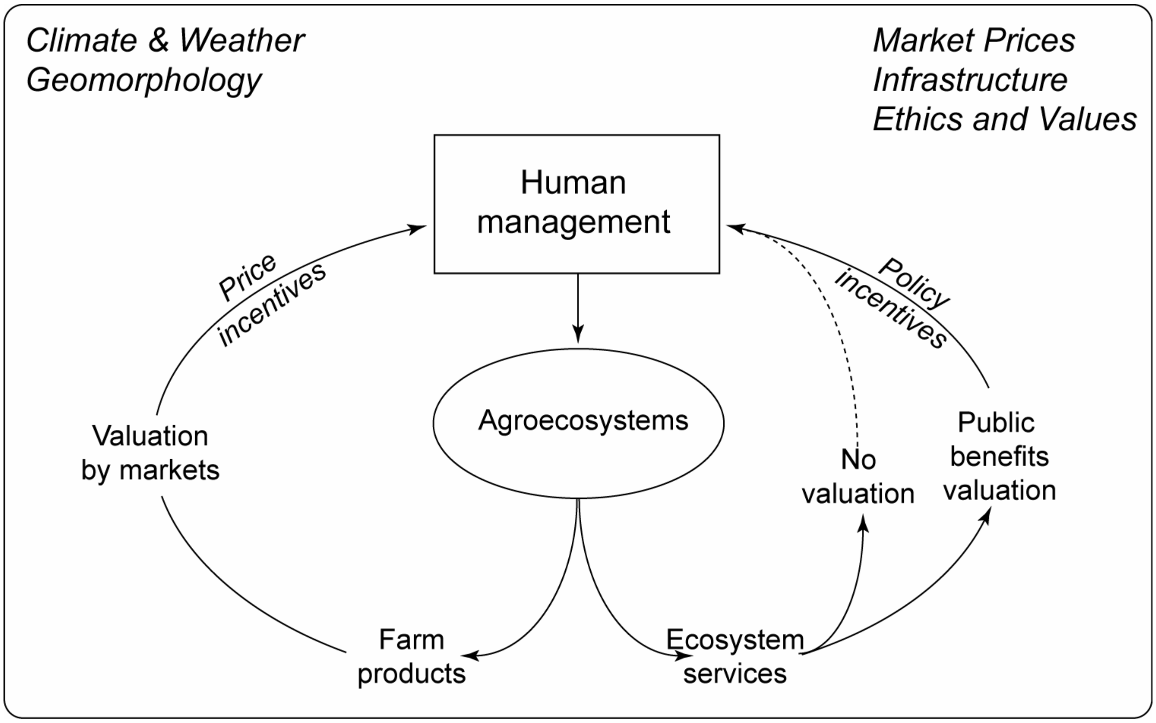


Figure 30. Different valuation strategies for services provided by agricultural ecosystems. On the left side are those services such as farm products that are valued by markets and for which price incentives drive human management decisions. On the right side are those services (such as conservation set-asides) that are publicly valued and for which policy incentives drive management decisions. Other services (such as the provision of private recreation) may be only privately valued so that their provision via human management is not rewarded by markets or policy. Compare with overall conceptual model in Figure 15.

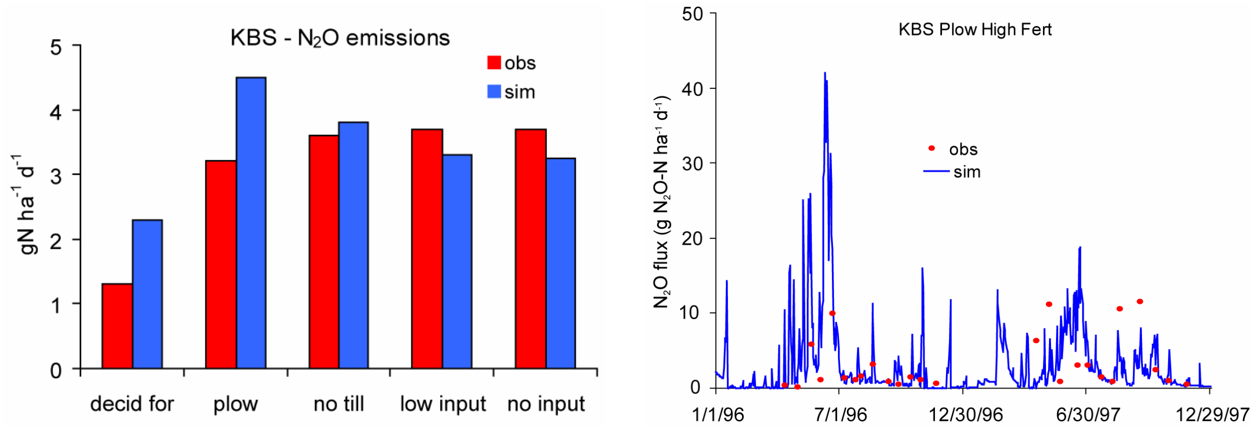


Figure 31. Seasonal (left) and daily N_2O flux at KBS simulated by DAYCENT. Measured observations appear as red (left-hand) bars on the left graph and as red circles on the right graph. Blue bars and lines represent simulated fluxes. From del Grosso and Parton (unpublished).

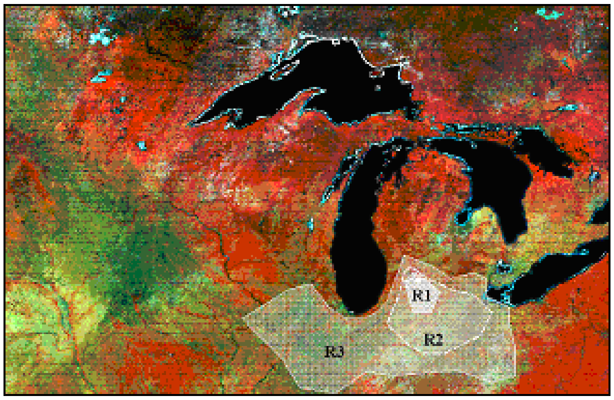


Figure 32. Concept of regionalization – definition of a region in the terms of ecological / biological / social / geographic variables. KBS is embedded in semirural area R1, which is nested within the larger Grand Rapids - Kalamazoo - Detroit metropolitan region R2, which is nested within the Toledo - Detroit - Chicago - Milwaukee region R3.

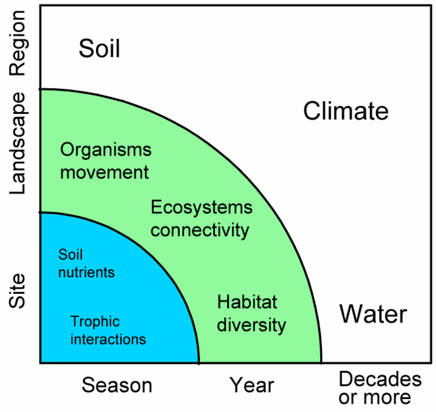


Figure 33. Ecological driving variables of agricultural systems at different temporal and spatial scales.

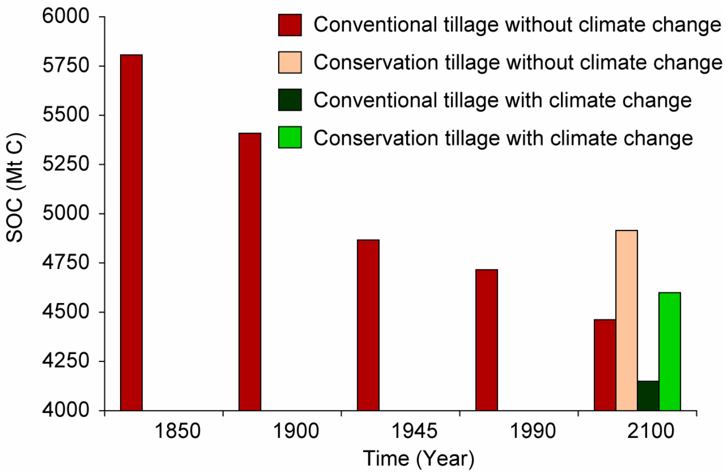


Figure 34. Soil organic carbon (0-10 cm) in the North Central Region from 1850-2100 as simulated by MASIF/SOCRATES. (red single bars at each time period). For year 2100, bars represent left to right): (1) conventional tillage without climate change, (2) conservation tillage without climate change, (3) conventional tillage with climate change, and (4) conservation tillage with climate change. Scenario (4) is visually depicted if Figure 35. (From Grace et al., submitted).

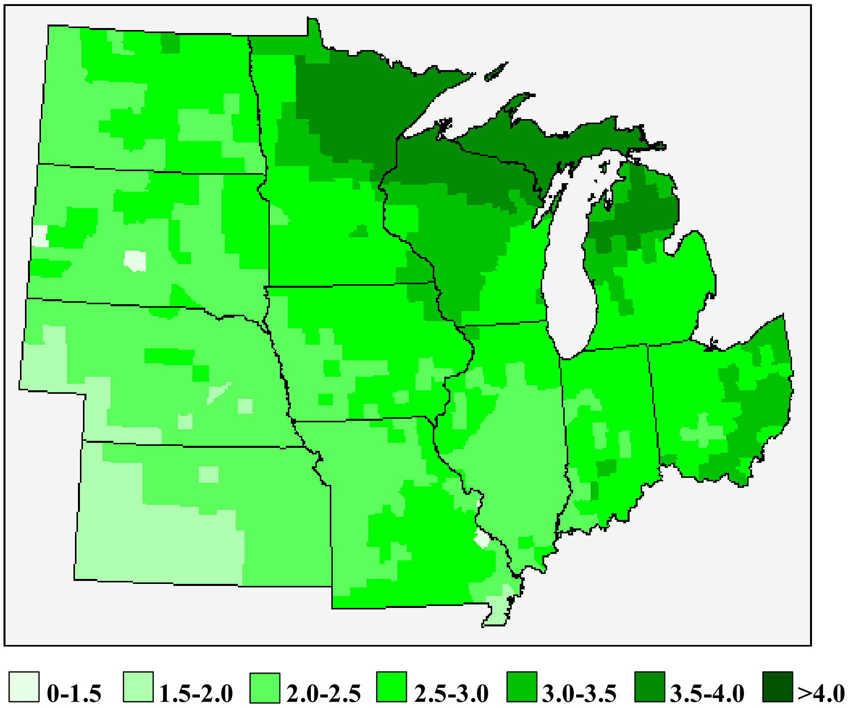


Figure 35. Predicted soil organic carbon concentrations (kg/m^2) across the North Central Region in 2100 as simulated by MASIF/SOCRATES. This scenario assumes an average regional increase in temperature of 3.9°C, a doubling of atmospheric CO$_2$ concentration, and the complete adoption of conservation tillage across the region by the end of the 21st century (Grace et al., submitted).

3.0 Site Management

The KBS LTER Project is led by an Executive Committee (EC) chaired by Lead PI Phil Robertson. Serving on the Executive Committee are project co-PIs Stuart Gage, Kay Gross, Steve Hamilton, Doug Landis, Tom Schmidt, and Scott Swinton, as well as the chair of our Agronomy Committee Kurt Thelen (see below). The EC meets bimonthly or more often as needed. Members of this committee have specific responsibilities:

Robertson as PI and chair of the EC provides overall project leadership; he is the principal project contact for NSF, the LTER Network Office, the University, and collaborating scientists, and has overall responsibility for coordinating sampling activities, data management, site promotion, and most baseline soil and plant analyses; shared responsibility for agronomic management and outreach activities; prepares annual reports and supplement proposals; and attends semiannual Network Coordinating Committee meetings.

Each co-PI actively participates in all decisions regarding project coordination, management, and scientific direction (via email and regular EC meetings); 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 as appropriate; and prepares or coordinates workgroup data for incorporation into the site database.

Additionally, each co-PI leads specific research topic areas:

- Plant Dynamics (Gross)
- Microbial Dynamics (Schmidt)
- Insect Dynamics (Landis)
- Human Dynamics (Swinton)
- Watershed (Hamilton) and Field-Scale (Robertson) Biogeochemistry
- Regionalization (Gage)

As chair of our Agronomy Committee, co-investigator Kurt Thelen is also a member of the EC. The Agronomy Committee meets as needed, but at least once per year in February. This committee is comprised of MSU agronomists with expertise in crop, weed, and soil management and who provide specific advice about the agronomic management of our cropped treatments. Our agronomic manager Joe Simpson confers with Thelen and other members of the committee throughout the growing season.

Core project staff include a Project Coordinator / Lab Manger (Andrew Corbin) who is responsible for most core sampling activities including analyses, and who reports to Robertson. Corbin supervises the laboratory staff that includes a research technician (Starr Shelton), and 2-3 seasonal employees. Our full-time Information Manager (Sven Bohm) also reports to Robertson and is responsible for data management as described in Section 4, below.

Co-investigators 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. Annually the project also hosts an all-scientist meeting, usually an overnight meeting at

KBS that involves research presentations, posters, and discussion groups. Our 2003 meeting had 58 participants (http://lter.kbs.msu.edu/Meetings/2003_All_Inv_Meeting/Abstracts/Index.htm).

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 1998-2003 we have had some 43 non-LTER funded research projects active on site, ranging from $5k doctoral dissertation improvement grants to several >$1M/y larger collaborations. Funding agencies include USDA (NRI, Sustainable Agriculture, NCR Regional Project, and Special Grants programs), the Michigan Dept. of Environmental Quality, the Dept. of Defense, NSF (Ecology, Ecosystems, Dissertation Improvement, RTG, EHR, ICEB, Biocomplexity, and STC programs), Dept. of Energy (Global Change), Canada's NSERC/CRSNG, the Mott Foundation, and the Michigan Agricultural Experiment Station. At present there are at least 6 pending proposals to use the site beginning in 2004; four of these are from researchers not now associated with MSU.

Site Access

As for 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/SiteUse/SiteUsePolicy.html). For researchers conducting on-site experiments (as opposed to using samples collected by our research staff), we now require submission of a formal site use request (via a form available at the web address above) that is reviewed and approved by the PI and EC.

Leadership Change

Since the beginning of the last renewal period we have had significant turnover of senior personnel, and a normal level of co-investigator turnover. Robertson, Gage, Gross, and Hamilton were co-PI's in 1998 and continue with this renewal; Landis, Schmidt, and Swinton are new in 2004. Dick Harwood and Eldor Paul retired in 2002 and are no longer co-PIs. Also absent is co-PI Chris Vanderpool, whose untimely death in 2001 was a great personal and professional loss.

The addition of Landis, Schmidt, and Swinton add considerable strength to the project. Landis' leading our insect research allows Gage to focus primarily on regionalization, a new area in which we are making significant progress. Schmidt provides fresh leadership for our microbial work, and Swinton, new to the project this year, joined us to provide the economics expertise necessary to address questions about the valuation of ecosystem services.

We are hopeful that we will regain missing strength in agronomy, soil biology, and sociology when faculty positions are filled to replace Harwood, Paul, and Vanderpool, respectively. We address this issue in our letter of response to the mid-term site review.

4.0 - Information Management

Overview

The priority for data management at the KBS LTER is to ensure that data from the site is accurate and accessible. It is our goal to have all datasets associated with the core hypotheses available on-line. We have adopted a fairly liberal data access policy with very limited restrictions (see below) that is consistent with the "Data Access Policy for the LTER Network" adopted at the Fall 1997 Network Coordinating Committee Meeting. Our policy relies on professional and 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 accession other than counting numbers of visitors to various pages.

Our official policy (available at http://lter.kbs.msu.edu/Data/dataUsePolicy.html) states that: "Data in the KBS LTER core database may not be published without written permission of the lead investigator or project director. These restrictions are intended mainly to preserve the primary investigators' rights to first publication and to ensure that data users are aware of the limitations that may be associated with any specific dataset. These restrictions apply to both the baseline dataset and to the datasets associated with specific LTER-supported subprojects."

We also place a priority on ensuring that all posted datasets have associated meta-data available on-line that is accurate, concise and sufficiently detailed to allow the use by a broad community of scientists. We have followed closely the recommendations for meta-data standards developed as part of ESA's Future of Long-term Ecological Data Committee report, chaired by KBS co-PI Kay Gross (see Michner et al. 1997). Former data manager Tim Bergsma helped to develop the EML meta-data language, which is being fully implemented at KBS. In fact KBS is one of the first sites to demonstrate the feasibility of a custom solution for dynamic EML 2.0 generation, helping to expand the pool of models for full EML implementation within the LTER network.

Until 1998 our data were stored and served principally as flat files, a strategy justified by the relative simplicity of our data bases and a desire to keep data management simple and transparent. With the 1998 renewal we hired a full-time professional database manager and began the transition to relational databases. We now have all databases on an MS-Access-based system and have begun the transition to MS-SQL to provide quicker content delivery and remove some redundancy. Data delivery has also evolved; we have now moved from static HTML pages to dynamic server pages, using Java-based technology that is likely to survive changes in platforms. The current information system consists of a small, robust set of JSP's that retrieve information from the relational databases as an XML data stream. The XML data is further transformed to HTML, EML, DTOC, ClimDB, or plain text through the use of style sheets. The relational database system, web server, and JSP container are all hosted on a PC running Windows NT with a RAID subsystem. Backups are done weekly by the KBS network staff and rotated off-site for safety. Raw data (voucher files) and snapshots of the databases are archived once per year to CD's.

KBS is an active participant in network-level common database efforts. We submit weekly updates to ClimbDB and sponsor two gauging stations for HydroDB. We also participate in the DTOC (Data Table of Contents) activity, and as noted above have played an active role in the development of network metadata standards.

Quality assurance and control

Investigators have primary, ultimate responsibility for the QA/QC of LTER data. Data generated by the core laboratory is screened initially by Project Coordinator Andrew Corbin, who reviews data with the appropriate co-PI and then transfers it to the Information Manager, Sven Bohm. Individual investigators are responsible for QA/QC of their own data, though a secondary review by the Project Coordinator or Information Manager has at times caught early errors. The Information Manager 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 for long-term congruency.

Information Manager

Data management at the KBS LTER is supervised by a full-time Data Manager (Sven Bohm) who coordinates the data-related activities of Andrew Corbin (responsible for QA/QC, synthesis, and summary of most core datasets, protocols, and metadata updates), Suzanne Sippel (responsible since 2003 for GIS programming), and Barbara Fox (responsible for managing the KBS LTER web site; and maintaining the NT server and backups). This model has been in place since January 1997 and has worked well.

Data Use

We installed traffic analysis software on our web site in late 2002, and can report (Supplement Table S2) that for 2003 we had on average about 20 different non-MSU visitors to our data tables per day, from a variety of domains (.edu, .gov, .org, .com). The best measure of data use is the number of publications from the site (Supplement Table S1) – many make reference to our soils and weather databases, in particular.

Recent Changes

Our mid-term site review identified four areas for strengthening, and we have implemented recent changes in response to these comments as well as others from users.

1. *Broaden the information perspective.* With supplemental funding beginning last year we are redeveloping our GIS and spatial databases. We collect a substantial amount of georeferenced data on site, ranging from yield-monitoring (our combines are equipped with GPS-based yield sensors) to insect and soil sampling. Professional GIS analyst Suzanne Sippel is working part-time to update and implement our GIS plan; we have included partial salary support in our renewal budget to continue this work. We are also beginning to collect audio and video data on-site, and our data management model has been enhanced to recognize images as an explicit data type, pioneering a mechanism for associating any digital object with a particular dataset.

2. *Improve linkages.* By porting our data/metadata stores from html pages to an integrated relational system, we have enabled low-maintenance scripting of linkages. For example, we have implemented linkages between the datasets and the investigator database and have started to link publications (citations and abstracts). We contribute to DTOC and will contribute to Metacat, which will allow for more focused cross-site discovery of embedded datasets. Search engines regularly index our site; between 5-15% of our pages

are viewed as a result of a search. We expect to implement a "bread-crumb" site navigation aide this spring.

3. *Work to develop scalable systems for data and metadata management.* We have made substantial progress in making our information management system scaleable. By deploying a relational database system, the addition of new datasets and data has been simplified. We have developed a web-based editing facility that allows authenticated users to enter and correct their own data and metadata. Our investment in compliance with network standards leaves us poised to adopt community-developed metadata editing tools when available.

4. *Work to develop structured metadata.* With the exception of our legacy spatial variability data, all of our metadata is currently structured and we are close to having all of it accessible as EML 2.0 by invoking the metadata-eml.xls style sheet. Attribute level metadata including units and definitions are most structured. Methods, protocols, and descriptions have less structure due to the more varied nature of these data. Text descriptions are marked up using a subset of docbook xml compatible with eml-TextType, and the document sections are stored separately in the database to improve retrievability.

We anticipate continued progress in information management during this next renewal period as our databases are ported to SQL servers and metadata standards are further developed.

5.0 - Outreach

We place a high value on outreach activities 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. We detail below activities in specific areas.

5.1 Educational Activities

Informal Education

Our focus on agriculture and the location of KBS in a semi-rural region of southwest Michigan provide ample opportunities for informal education and outreach to a variety of audiences: other scientists (both national and international), extension agents, farmers, teachers, university and K-12 students, government officials, and the general public. Since 1998 we have hosted more than 90 formal tours and presentations to a variety of groups, including, for example, various farmer groups, Great Lakes environmental journalists, senior officers from the Chinese Academy of Sciences, participants of an International Earthworm Conference, a delegation of agriculture ministers from Egypt, participants of the USDA North Central Weeds Conference, and World Bank administrators. We also provide general visitors to the KBS Conference Center exposure to LTER science via outreach posters and brochures.

Agricultural Extension

The 1998 publication of *Michigan Field Crop Ecology* (Cavigelli et al. 1998) represents one of our major professional outreach activities, and its ongoing success illustrates the impact of LTER science on regional agriculture. This effort, led by LTER co-PI Dick Harwood and former LTER grad student Michel Cavigelli, was undertaken to provide Michigan farmers and extension agents greater access to the science being conducted at KBS. The 92-page full color publication is designed to promote an ecologically-based understanding of field crop systems for growers. All but one of its chapters were written by KBS LTER scientists, and all draw heavily on research conducted at KBS. It has won national Extension awards, is being used in professional development and undergraduate education in other states and Canada, and has spun off a companion volume *Michigan Field Crop Pest Ecology and Management* (Cavigelli et al. 2000), and volumes for other commodities (fruit crops, turf) are in press or under development. *Michigan Field Crop Ecology* is now in its 5th printing.

Largely due to the participation of extension faculty in the project, and in particular to Harwood's efforts, KBS is known by many leading producers and extension professionals in the state. Last June, for example, we were asked by a major sugar beet concern to host a KBS short course in soil organic matter management, and this January (2004) we were asked by producers to participate in two 1-day short-courses on soil quality at Frankenmuth (140 farmers) and KBS (30 farmers). By actively partnering with MSU Extension we have substantially broadened the impact of LTER science, and we expect to continue this partnership into the renewal period.

Undergraduate and Graduate Education

A number of educational programs affiliated with KBS, MSU, and nearby colleges and universities have used the site for formal teaching purposes. Each summer undergraduate and graduate students enrolled in courses at KBS use the site for field trips or research; courses that regularly use the site include the upper-level undergraduate courses Plant Systematics, Ecology, and Biogeochemistry and the graduate-level course Advanced Field Ecology and Evolution.

We also host visiting courses. A University of Michigan Agroecology course has used the site several times in the past 6 years, and an MSU International Agroecology course annually spends 2 days at KBS and visits the LTER site to learn about agricultural ecology. This latter course was begun 9 years ago with funding from international development agencies and attracts 12-24 participants (mostly early or mid-career agricultural professionals and policy makers) from all over the developing world.

We also host a number of REU students working on site. For 2 of the past 6 years the Biological Station has had an REU site program and a number of students have chosen to conduct their research in LTER communities. We also directly sponsor 1-2 students per year. During the past grant period 16 undergraduate interns, mostly from institutions other than MSU, have been formally associated with the LTER (see http://lter.kbs.msu.edu/Data/Investigators.jsp). A number of them present their research at regional meetings; in 2003, for example, one of our REU interns won the MSU Undergraduate Research Award, a significant achievement at a place the size of MSU. A number of undergraduate students taking summer field classes at KBS also assist with field and laboratory activities as paid laboratory assistants.

We encourage graduate student participation in all aspects of LTER activities, including workgroup and all-investigator meetings as well as site reviews. More than 25 students are currently pursuing dissertation research on site (listed at the url above); 21 additional students have received their degrees in the 1998-2003 period of the current award (Supplemental Table S1). Part of our strategy for encouraging graduate research on-site is to offer small graduate-student grants to help defray research expenses. We typically have 3-4 students per year apply for and receive travel and supplies funding (to $1,500) for thesis work on site.

K-12 Educators and Students

K-12 students occasionally visit the site as part of class field trips or summer camp activities. A biology class from the Kalamazoo Area Math and Science Center annually visits to conduct a CO_2 field experiment, and a local MSU-sponsored day camp (Youth Exploring Science) visits the site in summers. However, we have found that our time is most effectively spent educating K-12 teachers, and since 1998 we have partnered with area K-12 science teachers and MSU College of Education faculty to promote better K-12 science teaching.

Our efforts started in 1998 with supplemental (Schoolyard) funding for six 1-day workshops for middle school science teachers from the 4 school districts around KBS. In 2001 we sought and received funding from the NSF-EHR Teacher Retention and Renewal Program ($1.3M for 3 years) to expand the partnership to additional districts and teachers. The partnership now provides 80 science teachers from 14 districts around KBS in-depth exposure to ecological science topics and in-depth training to teach Science for Understanding (Blythe et al. 1998).

Elements of the program (http://www.kbs.msu.edu/K12_Partnership/Index.htm) include six school-year workshops, two summer science institutes, and advanced KBS PhD students assigned to buildings as teacher resources. Each of the school-year workshops has a science content component based on LTER core areas provided by KBS scientists, and a science teaching and leadership component provided by MSU science education faculty Jim Gallagher and Andy Anderson. The workshops are designed to provide teachers a deeper knowledge of how science is conducted and how hands-on science is best taught. In addition to the school-year workshops are two 1-week Summer Institutes. The first concentrates on science content and teaching methodology, and involves LTER field work. The second is designed to provide teachers a deeper exposure to new science teaching methods plus training in educational leadership. Lead teachers are using this training to coordinate efforts to restructure science teaching in their districts.

5.2 Media Interactions and Policy Implications

Media interest in KBS LTER activities has been cyclical. Over the past renewal period LTER research has been the subject of about 8 local newspaper articles. Our research has also been featured in trade journals, notably Michigan Farmer and the national No-Till Farmer. Radio interviews have featured both our global warming and biodiversity research (including NPR's All Things Considered and two Earthwatch Radio programs). We have also hosted various groups of visiting journalists (e.g. in 2001 the American Association of Agricultural Journalists (50 participants), in 1998 and 1999 the Great Lakes Environmental Journalists (20-30), and in 2001 the Great Lakes Environmental Journalism Training Institute (28)); while these have not (so far as we know) resulted in media pieces, we are hopeful that our participation has resulted in better science reporting.

We have also been involved in modest efforts to educate policy makers. Apart from tour groups that include environmental regulators (e.g. the 20-member Michigan DEQ's Environmental Assistance Division), we have hosted tours for individual congressional staffers in 2003, and two of our co-PI's have informed Congress on issues relevant to LTER science (Harwood and Robertson have testified before the US Senate Agriculture, Forestry and Nutrition Committee as part of Farm Bill deliberations, and Robertson has participated in briefings for the US House Agriculture and House Science Committees).

5.3 Network Level Activities

We have also participated in a number of network-level outreach activities. KBS scientists led the development and publication of the 1999 book *Soils Standardization for Long-Term Ecological Research* (Robertson et al. 1999). In 2002, at the request of Taiwan's LTER Network, we organized a Taiwan workshop to provide advice on starting an agricultural LTER site there. KBS co-PI Stuart Gage has been a lead organizer for three network-sponsored regional modeling workshops at the San Diego Supercomputer Center and National All Scientist Meetings (ASM). And KBS scientists organized 13 workshops at ASM 2000 and 9 workshops at ASM 2003.

We also continue to be active participants in cross-site research. Co-PI Kay Gross is a lead participant in the NCEAS-sponsored examination of NPP and diversity across multiple sites. Co-PI Steve Hamilton was a co-investigator on the LINX project and is now a co-PI on its NSF-ICEB successor, a cross-site examination of in-stream nitrogen cycling. We are also hosting several investigators from other sites who are sampling KBS as part of other cross-site projects.

5.4 Future Plans

We expect to continue to emphasize outreach activities during the next funding cycle. Public interest in agriculture and agricultural policy remains high, and to the extent that we can further our education and outreach objectives we will do so. We do not at present plan any major new initiatives for the next 6 years, but rather expect to strengthen and expand existing efforts as investigator expertise and interests permit and as opportunities for partnerships arise.

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