Kellogg Biological Station LTER Site as a Potential Member of the USDA LTAR Network: Response to LTAR Request for Information of December 1, 2012

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KBS LTER Response to a Request for Information (RFI) from the USDA Long-Term Agro-ecosystem Research (LTAR) Network

The KBS Long-term Ecological Research (LTER) Program

KBS LTER research is focused on row-crop agriculture and is located in southwest Michigan (42^{o} 24’N, 85^{o} 23’W; 288 m elevation; Fig. 1), in the northern portion of the North Central Region in the upper Midwest. Since its inception in 1987, KBS LTER research has sought to better understand the ecology of intensive row-crop agriculture, with an emphasis on the corn, soybean, wheat, and alfalfa crops that dominate the NCR (Gage et al. 2013). These crops have a correspondingly huge impact on human and environmental welfare. In anticipation of the eventual importance of cellulosic bioenergy crops KBS LTER also studies hybrid poplar since 1987 and more recently switchgrass, miscanthus, and mixed-species grassland communities including restored prairie. These diverse crop ecosystems are compared to replicated native forest and unmanaged successional communities nearby.

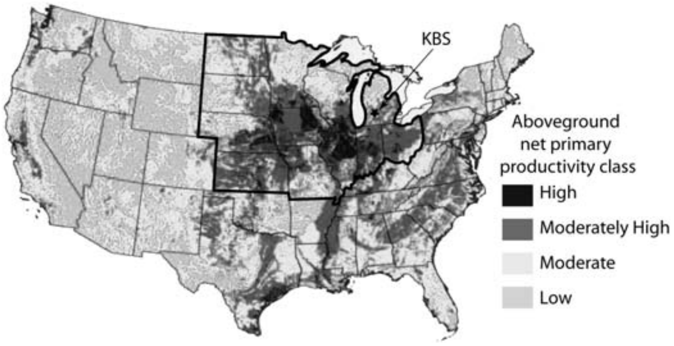

Fig. 1. Location of the Kellogg Biological Station (KBS) in relation to estimates of U.S. net primary productivity. The area outlined in black is the USDA’s North Central Region and includes the U.S. corn belt (Gage et al. 2013). Base map is from Nizeyimana et al. (2001).

Our global hypothesis is that agronomic management based on ecological knowledge can substitute for management based on chemical inputs without sacrificing the high yields necessary for human welfare. A corollary is that the delivery of other ecosystem services—including environmental benefits—will be concomitantly enhanced.

Many of our specific hypotheses have been addressed using the experimental design of our Main Cropping System Experiment (MCSE) established in 1988 to reflect the range of ecosystem types typical of row-crop landscapes in the upper Midwest. Replicated ecosystems along a management intensity gradient include four annual cropping systems, two perennial crops, and both early- and late-successional unmanaged ecosystems (Figs. 2, 3). The annual cropping systems are corn–soybean–wheat rotations ranging in management intensity from conventional to biologically based (the latter are USDA certified organic systems without added compost or manure). Perennial crops include alfalfa and hybrid poplar trees. Successional treatments range in age from early succession (recently abandoned farmland) to late successional (never-cleared) deciduous forest. Additional experiments added since 1988 include crops for cellulosic biofuels as well as scale-up fields as described later.

The Conceptual Basis for KBS LTER Research

Research at KBS LTER has steadily grown in scope and complexity since 1988 when the site was initiated. It is now guided by a conceptual model that integrates both ecological and social perspectives and explicitly addresses questions about the ecosystem services delivered by agriculture. This model (Fig. 4) is derived from the press-pulse disturbance framework for social-ecological research developed by the national LTER community (Collins et al. 2011). The model represents coupled natural and human systems, highlighting relationships between human socioeconomic systems and the cropping systems and landscapes in which they reside. This approach reflects the need to balance attention between both human and natural elements and to understand their interacting linkages. This need is especially acute in agricultural landscapes, where human decisions affect almost every aspect of ecosystem functioning and ecological outcomes strongly affect human and environmental well-being.

Farming for Services

Ecosystem services (Millennium Ecosystem Assessment 2005) provide a framework for examining the dependence of human welfare on ecosystems. Food, fiber, and fuel production are vital provisioning services provided by agriculture, and increasingly society is recognizing the potential for other services such as improved water quality, the protection and enhancement of biodiversity, climate stabilization including carbon sequestration, and social amenities such as verdant landscapes and agrotourism (Robertson and Swinton 2005, Power 2010, Swinton et al. 2013). Agriculture also produces disservices (Swinton et al. 2007): undesirable effects such as erosion, nitrate pollution (e.g. Syswerda et al. 2012), and emissions of greenhouse gases such as nitrous oxide (Gelfand et al. 2013a). Mitigation services provided by alternative practices or other parts of the agricultural landscape can thus also be considered services provided by agriculture (Swinton et al. 2007). We can refer in general to the alteration of agricultural practices to improve the delivery of ecosystem services as "farming for services."

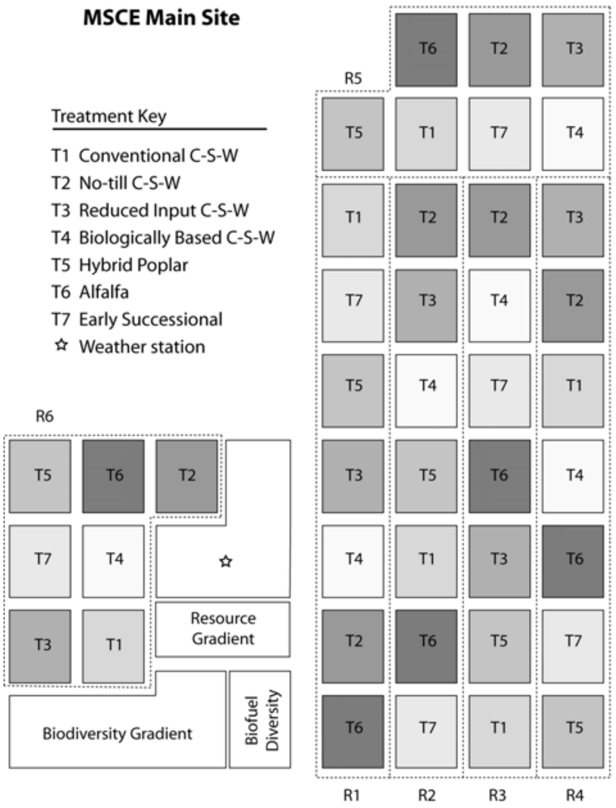

Fig. 2. Experimental layout for seven treatments of the KBS LTER Main Cropping System Experiment (MCSE): four annual cropping systems (T1–T4), Alfalfa (T6) and hybrid Poplar (T5) perennial systems, and the Early Successional community (T7). All are replicated as 1-ha plots in six replicated blocks (R1–R6). C-S-W = corn-soybean-winter wheat rotation. Other MCSE treatments are located as noted in Figure 3. See text for treatment details.

Agriculture is typically subject to a complex set of drivers, including shifts in climate, commodity markets, human population and land use, and social and regulatory environments, as well as to new developments in agricultural technology such as genetically improved crop varieties and new tillage practices. Drivers of change that affect both human and natural systems occur on scales from local to landscape to global, and operate under variable time scales. Conceptually, we can view these drivers as disturbances to the biophysical or social systems (Fig. 4). They can be broadly classified into either "pulse" or "press" disturbances, depending on whether they occur as discrete events or as gradual change over a more protracted period, respectively (Collins et al. 2011). They can be further grouped into those that are direct management interventions vs. those that are unintentional.

Most KBS LTER research to date has emphasized developing an ecosystem-level understanding of ecological structure and function—the right hand portion of Figure 4. Biotic structure includes organisms and their adaptations, population and community assemblages, and the physical organization of different ecosystem habitats. Ecosystem function includes the processes carried out by organisms as mediated by the abiotic environment—e.g., the cycling of carbon, nitrogen, and other nutrients, energy capture and flow, and hydrologic dynamics. Linkages between ecological structure and function largely define the mechanisms that support the production of ecosystem services.

Also important to consider is how the ability of row-crop systems to provide services is affected by factors at scales beyond the field level. Watershed position and landscape complexity can affect many of the connections between ecological structure and function, ranging from the potential movement of organisms, nutrients, and water between and among ecosystems to the spatial patterns of soils and microclimates.

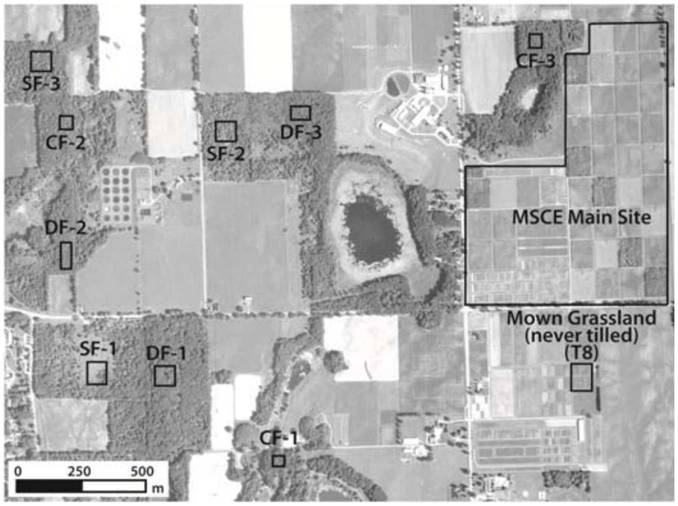

Fig. 3. Location of mid-successional and forested sites of the KBS LTER Main Cropping System Experiment (MCSE). Included are the Mown Grassland (never tilled) site (T8), and three Coniferous Forest (CF), Mid-successional (SF), and mature Deciduous Forest (DF) sites. See Figure 2 for MCSE Main Site details and text for further description. Aerial photo background is from August 2011.

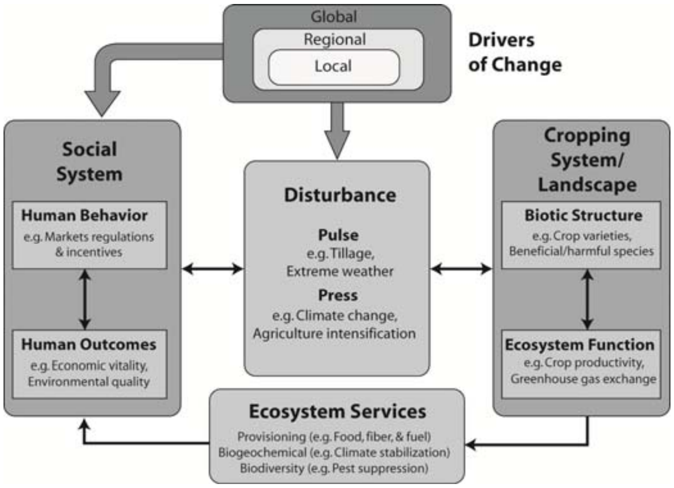

Fig. 4. Conceptual model currently guiding KBS LTER research.

Organisms and their Interactions

The main groups of organisms providing biological structure in the row-crop ecosystem include (i) plants as they consume resources both above and below ground (Gross et al. 2013) and regulate the hydrologic cycle (Hamilton 2013); (ii) microbes as they control organic matter turnover (Paul et al. 2013), nutrient availability (Millar and Robertson 2013; Snapp et al. 2013), and greenhouse gas fluxes (Schmidt and Waldron 2013; Gelfand et al. 2013a); (iii) insects and pathogens as they respond to changes in the plant community and affect plant productivity (Landis and Gage 2013); and (iv) humans as they intentionally and unintentionally create biophysical and chemical disturbance (Swinton et al. 2013). Each of these groups is a focal area of KBS LTER research, and—together with research on watershed biogeochemistry (Hamilton 2013) and regionalization (Gage et al. 2013)—constitute the core research areas of KBS LTER. Understanding the interactions and integration among these core areas is crucial for generating a comprehensive understanding of the drivers and dynamics of the coupled human-natural system we call agriculture.

The KBS Experimental Setting

The KBS LTER Main Cropping System Experiment (MCSE)

The KBS LTER Main Cropping System Experiment (MCSE) is an intensively studied factorial experiment (Figs. 2, 3) that is the focus of much of the biophysical research at KBS LTER. It includes 11 treatments that span different agricultural and unmanaged ecosystems replicated along a management intensity gradient ranging from high-intensity row-crop cultivation to unmanaged late successional forest, as noted earlier. Each treatment is intended to represent a model ecosystem relevant to agricultural landscapes of the region (Gage et al. 2013). They are not intended to represent major regional crop × management combinations—to do this would require scores of additional experimental treatments. However, as model systems arranged along a management intensity gradient, interactions will differ in ways that can be understood, predicted, modeled (Basso and Ritchie 2013), and extended to row-crop ecosystems in general.

The four annual KBS LTER cropping systems are corn–soybean–winter wheat rotations managed to reflect of gradient of chemical inputs:

- The Conventional treatment (T1) represents the management system practiced by most farmers in the region: standard varieties planted with conventional tillage and with chemical inputs at rates recommended by university and industry consultants. Crop varieties are chosen on the basis of yield performance in state variety trials (e.g., Thelen et al. 2011). Beginning in 2009 (for soybean) and 2011 (for corn), we have used varieties that have been genetically modified for glyphosate resistance and (for corn) resistance to European corn borer (*Ostrinia nubilalis*) and root worm (*Diabrotica* spp.). Prior to this we had used the same seed genetics in all treatments. Fertilizers (primarily nitrogen, phosphorus, and potassium) and agricultural lime (carbonate minerals that buffer soil acidity) are applied at rates recommended by Michigan State University (MSU) Extension following soil tests. No crops are irrigated. Herbicides and other pesticides are applied to all three crops as prescribed by integrated pest management (IPM) guidelines for Michigan (e.g., Difonzo and Warner 2010, Sprague and Everman 2011). Tillage for corn and soybean includes spring chisel plowing followed by secondary tillage to prepare the seed bed. Tillage for fall-planted winter wheat usually involves only secondary tillage. Crop residues are either harvested for animal bedding (wheat) or left on the field (corn, soybean).

- The No-till treatment (T2) is managed identically to the Conventional treatment except for tillage and herbicides. A no-till planter is used to drill seed directly into untilled soil through existing crop residue, i.e., without primary or secondary tillage. When prescribed by IPM scouting, additional herbicide is used to control weeds that would otherwise be suppressed by tillage.

- The Reduced Input treatment (T3) differs from the Conventional treatment in the amounts of nitrogen fertilizer and pesticides applied, post-planting soil cultivation (prior to 2008), and winter plant cover. During corn and soybean phases of the rotation a winter cover crop is planted the preceding fall and plowed under prior to planting corn or soybean the following spring. A cover crop is not planted during wheat years because winter wheat is planted in the fall, immediately following soybean harvest. Nitrogen fertilizer is applied at reduced rates relative to the Conventional treatment: at 22% of the rate applied to Conventional corn and at 56% of the rate applied to Conventional wheat, for a full-rotation reduction to 33% of the Conventional treatment rate. Reduction in nitrogen inputs from Conventional management is expected to be made up through atmospheric N_2 fixation by legumes in the rotation: a winter cover crop of red clover (*Trifolium pratense* L.) precedes corn, and soybean precedes wheat. A non-leguminous winter cover crop of fall-planted annual rye grass (*Lolium multiflorum* L.) precedes soybean.

The Reduced Input treatment thus has five species in the rotation: corn $_{\text{ryegrass}}$ – soybean – winter wheat $_{\text{red clover}}$, so a crop is present at all times of the year during the entire three-year rotation cycle. Crop varieties are the same as those used in the Conventional treatment, including genetically modified varieties since 2009.

Prior to 2008, weed control in corn and soybean phases of this treatment was provided by applying herbicides at label rates only within rows (banding), so overall application rates were one-third of the amount applied in the Conventional treatment. Additional weed control was provided by mechanical means—rotary hoeing and between-row cultivation several times post-planting. Since the planting of glyphosate-resistant varieties was initiated in 2009, weed control for corn and soybean now relies on herbicide (glyphosate) as in the Conventional treatment. Weed control in wheat is provided solely by narrow row spacing (19 cm [7.5 inches]) with no additional tillage or herbicide.

- The Biologically Based treatment (T4) is similar to the Reduced Input treatment except that neither nitrogen fertilizer nor pesticides are applied in this system and no genetically modified crop varieties are used. The system is entirely dependent on leguminous N_2 fixation for external nitrogen inputs, which supplements the 6–8 kg N ha^{-1} yr^{-1} received by all treatments in rainfall (Hamilton 2013). Weed control is provided by rotary hoeing and cultivation post-planting. This treatment is certified organic by the USDA, but differs from more typical organic systems in the United States because it receives no manure or compost. This creates a system that is reliant as possible on internal, biologically-based nitrogen inputs.

In addition to four annual cropping systems, we have three perennial cropping systems, one herbaceous and two woody:

- Alfalfa represents a perennial herbaceous biomass treatment (T6). Alfalfa is grown in a 6–8 yr rotation with the duration defined by plant density: when the stand count declines below a recommended threshold the stand is killed with herbicide and replanted. Because alfalfa re-establishment can be inhibited by autotoxicity, a break year is needed in the rotation and a small grain such as no-till oats or winter wheat is grown for one season in between alfalfa cycles. Alfalfa is commonly harvested three times per growing season for forage. Fertilizer (mainly phosphorus, potassium, and micronutrients such as boron and molybdenum) and lime applications follow MSU Extension recommendations following soil tests. Varieties are chosen on the basis of MSU yield trials.
- The Poplar treatment (T5) represents a short-rotation woody biomass production system. In 1989 hybrid poplar clones (*Populus* × *canadensis* Moench 'Eugenei' ([*Populus deltoides* × *P. nigra*], also known as *Populus* × *euramericana* 'Eugenei') were planted as 15-cm stem cuttings on a 1 × 2 m row spacing, with nitrogen fertilizer applied only in the establishment year (60 kg N ha^{-1}). A cover crop of red fescue (*Festuca rubra* L.) was planted in 1990 for erosion control. Trees were allowed to grow for 10 yr then harvested in February 1999 when the trees were without leaves and frozen soil prevented undue soil disturbance. For the second rotation, trees were allowed to coppice (regrow from cut stems) and harvested in the

winter of 2008. After a fallow break year during which coppice growth, red fescue, and weeds were killed with glyphosate, in May 2009 trees were replanted as stem cuttings on a 1.5 × 2.4 m (5 ft x 8 ft) row spacing. For this third rotation, the variety *Populus nigra* × *P. maximowiczii* 'NM6' was planted and there is no cover crop; weeds are controlled with herbicides applied in the first two years of establishment and fertilizer is applied once, in the third year of the rotation, at 156 kg N ha^{-1}.

- The Coniferous Forest (CF) includes three small long-rotation tree plantations established in 1965. One of the three sites is dominated (>10% biomass; http://lter.kbs.msu.edu/datatables/134) by red pine (*Pinus resinosa* Aiton); a second is a mixture of Norway spruce (*Picea abies* (L.) Karst), red and white (*Pinus strobus* L.) pines, and now with significant black cherry (*Prunus serotina* Ehrh.) and large-tooth aspen (*Populus grandidentata* Michx.); and the third is dominated by white pine. The conifer stands have been periodically thinned and understory vegetation removed by prescribed burning as recommended by MSU Extension Forestry personnel.

Four successional ecosystems, either minimally managed or unmanaged, provide reference sites for comparisons of specific processes and populations:

- Early Successional communities (T7) were allowed to establish naturally on land abandoned from row-crop agriculture in 1989 and have been left unmanaged but for annual spring burning (begun in 1997) to prevent tree colonization. Currently dominant plant species (>10% proportional biomass; http://lter.kbs.msu.edu/datatables/237) include Canada goldenrod (*Solidago canadensis* L.), red clover (*Trifolium pratense* L.), timothy grass *(Phleum pratense* L.), and Kentucky bluegrass (*Poa pratensis* L.).

- A Mown Grassland (never tilled) community (T8) that has never been in agriculture was established naturally following the removal of trees from a 10 ha woodlot in 1959. The site has been mown annually in the fall since 1960 to inhibit tree colonization, with biomass left to decompose on site. At times between 1960 and 1984 the site may have received manure additions during winter months. Because the site has never been plowed, it retains an undisturbed, pre-settlement soil profile. Plant community dominants (>10% of total biomass; http://lter.kbs.msu.edu/datatables/140) include smooth brome grass (*Bromus inermis* Leyss.), tall oatgrass (*Arrhenatherum elatius* L.), and blackberry (*Rubus allegheniensis* Porter). Sampling occurs within 4 replicated 15 x 30 m plots randomly located within a portion of the field.

- Mid-successional communities (SF) occupy three sites that were abandoned from agriculture in the 1950s. Since that time they have been allowed to undergo succession, which is occurring at different rates across the replicates. One site (SF-1) has limited overstory growth and is dominated (>10% of total biomass; http://lter.kbs.msu.edu/datatables/40) by tall oatgrass, Canada goldenrod, quackgrass (*Elymus repens* L.), timothy grass and Kentucky bluegrass. Transition to forest is well underway in the remaining two sites; overstory dominants reflect nearby mature deciduous forests and understory dominants include the invasive shrubs oriental bittersweet (*Celastrus orbiculatus* Thunb.) and glossy buckthorn (*Rhamnus frangula L.*).

- Mature Deciduous Forest (DF) comprise the end-point of the management intensity gradient. Soils of these three hardwood forests have never been plowed. Overstory dominants (>10% of total biomass; http://lter.kbs.msu.edu/datatables/134) are the native trees red oak (*Quercus rubra* L.), pignut hickory *(Carya glabra* Mill.), and white oak (*Q. alba* L.); also present are

> black cherry (*Prunus serotina* Ehrh.), red maple (*Acer rubrum* L.), and sugar maple (*Acer saccharum*). Understory vegetation is patchy in nature and includes a variety of native forbs as well as some exotic species such as the shrubs honeysuckle (*Lonicera* spp. L.) and common buckthorn (*Rhamnus cathartica* L.), the woody vine oriental bittersweet (*Celastrus orbiculatus* Thunb), and the increasingly invasive forb garlic mustard (*Alliaria petiolata* M. Bieb.). Two of the three replicate sites have never been logged, while one was cut prior to 1900 and allowed to regrow.

All MCSE treatments and communities are replicated and most are within the same 60-ha experimental area (Fig. 2); others, which for historical or size reasons could not be included in the main layout, are on the same soil series within 1.5 km of the other plots (Fig. 3). Within the MCSE main site are all annual cropping treatments, the Alfalfa and hybrid Poplar perennial crop systems, and the Early Successional community. All are replicated as 1-ha plots in six blocks of a randomized complete block design (Fig. 2), with blocks determined on the basis of an initial analysis of spatial variability in soils across the site (Robertson et al. 1997).

The Mown Grassland (never tilled) community is located about 200 m to the south of the MCSE main site (Fig. 3); four replicated 15 × 30 m plots are located within a larger 1-ha area of the 10-ha former woodlot. The planted Coniferous Forests, the Mid-successional communities, and the mature Deciduous Forests are each replicated three times in the landscape around the main experimental site (Fig. 3). Within each replicated system, a 1-ha sampling area provides a plot size equivalent to those in the main experimental site.

Plot sizes for MCSE treatments in the main experimental site (Fig. 3) are large (90 × 110 m = 1 ha) relative to plot sizes in most agronomic field experiments (Robertson et al. 2007). By adopting a 1-ha (2.5-acre) plot size we encompass more of the spatial variability encountered in local landscapes (Robertson et al. 1997). This provides greater assurance that patterns discovered are relevant for more than a single landscape position and avoids statistical problems associated with spatial autocorrelation. Large plots also (i) allow the use of commercial-scale rather than plot-scale farm equipment, helping to ensure that agronomic practices are as similar as possible to those used by local farmers; (ii) help to ensure the integrity of long-term sampling by avoiding the danger of sampling the same locations multiple times years apart; and (iii) avoid some of the scale effects associated with biodiversity questions for different taxa—for example, seed banks and non-crop plant diversity would not be well represented in 0.01 ha or smaller plots commonly studied in agricultural research, although even the KBS LTER 1-ha plots are insufficient for research on more mobile taxa such as vertebrates and many arthropods.

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

Regular measurements for all treatments in the MCSE include (i) plant species composition, above-ground net primary productivity, litterfall, and crop yield; (ii) predaceous insects, in particular coccinellids (lady beetles); (iii) microbial biomass and abundance; (iv) soil moisture, pH, bulk density, carbon, inorganic nitrogen, and nitrogen mineralization; (v) NO_3^- concentrations in low-tension lysimeters installed at a 1.2-m depth (Bt2/C horizon) in replicate plots of all treatments; and (vi) a number of weather variables. Precipitation chemistry is monitored as part of the National Atmospheric Deposition/National Trends Network at a replicate weather station 2 km away to avoid contamination by agricultural activities on site. Soil carbon is measured to 1-m depth at decadal intervals in all treatment plots. The soil seed bank is sampled on a 6-yr cycle.

The KBS LTER Scale-up Experiment

The need to understand how findings from our 1-ha MCSE treatments scale up to commercial sized fields motivated the establishment of the LTER Scale-up Experiment (Fig. 5). In 2006 we installed three of the four MCSE annual cropping treatments on KBS fields managed commercially as part of the W.K. Kellogg Biological Station dairy farm. Although larger than most agronomic research plots, the 1-ha MCSE plots may still suffer from artifacts related to plot size. For example, because plots are managed for research, agronomic operations may not be as influenced by labor issues as they might be on a commercial farm. The frequency and timing of operations such as mechanical weed control and planting date may affect weed densities and yields, and a commercial operator will have less flexibility for optimal scheduling due to labor constraints.

Additionally, our 1-ha plots are embedded in a matrix of other plots with different plant communities that could provide insect refugia or seed sources not typically available in farm-scale fields. Farm-scale fields, on the other hand, will more often be bordered by larger successional areas or woodlots, important overwintering habitats for both insect herbivores and their natural enemies (Colunga-Garcia and Gage 1998, Landis and Gage 2013).

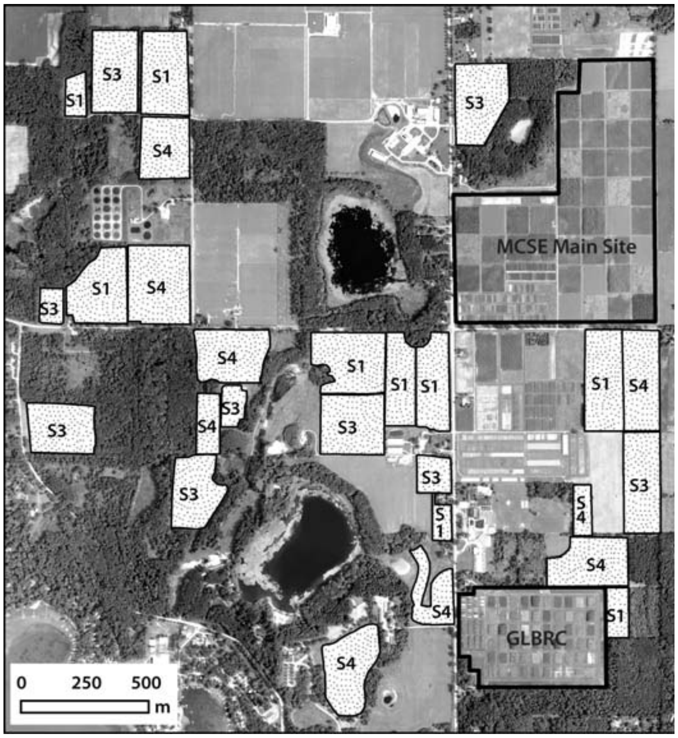

Fig. 5. KBS LTER scale-up fields (n=27) managed to address questions related to the scalability of results from the Main Cropping System Experiment (MCSE) depicted in Figure 2. S1 management follows that of the MCSE Conventional Treatment (T1); S3, the MCSE Reduced Input treatment (T3); and S4, the MCSE Biologically Based treatment (T4). Also shown is the location of the intensive experimental site for the Great Lakes Bioenergy Research Center (GLBRC) at KBS. Aerial photo background is from August 2011.

In Fall 2006, twenty-seven fields managed by the Kellogg Farm were assigned to one of three annual crop management regimes in the MCSE treatments: Conventional, Reduced Input, or Biologically Based. Each was also assigned to one of three rotation entry points—corn, soybean, or wheat—and to one of three replicate blocks. This provides three replicate fields for each treatment × entry point combination (3 treatments × 3 entry points × 3 replicates). Fields range in size from 1 to 7.5 ha, adjoin a variety of different habitat types, and have a variety of perimeter complexities. To date, regular sampling activities in these fields have included agronomic yields; agronomic inputs are also recorded.

Ancillary Experiments

In addition to the experiments described above, several long- and shorter-term ancillary experiments address specific questions. In some cases these are subplots nested within the plots of the MCSE and in others they are independent experiments. Here we describe the most important of these.

Biodiversity Gradient Experiment

The Biodiversity Gradient Experiment was established on the MCSE main site (Fig. 2) in 2000 to investigate the effect of plant species diversity across a gradient ranging from bare ground to 1, 2, 3, 4, 6 and 10 species. Small plots (9 × 30 m) are within four randomized complete blocks and are managed much like the Biologically Based MCSE treatment (i.e., no external chemical inputs). This experiment reveals how crop identity and diversity affect yield, weed competition, soil biogeochemical processes, and other variables (Gross et al. 2013).

Resource Gradient Experiment

The Resource Gradient Experiment was established on the MCSE main site (Fig. 2) in 2003 to investigate nitrogen and water constraints on crop yield. MCSE annual crops (either corn, soybean, or wheat) are nitrogen-fertilized at 9 different rates and either irrigated or rainfed. Fertilizer rates differ by crop; for corn the range has been 0 to 292 kg N ha^{-1} and for wheat 0 to 180. Prior to 2012 soybeans were not fertilized. Irrigation is sufficient to meet plant water needs as predicted by weather and a crop growth model that estimates evapotranspiration. A linear move irrigation system applies water 0–3 times per week during the growing season depending on recent rainfall and crop need. In addition to crop yield, greenhouse gas exchange between soils and the atmosphere are measured in the experiment (Millar and Robertson 2013).

Living Field Lab Experiment

The Living Field Laboratory (LFL) was established in 1993 to investigate the benefits of leguminous cover crops and composted dairy manure in two integrated systems compared to a conventional and an organic agricultural system. The term "integrated" in this case refers to targeted, banded applications of herbicide, reduced tillage, and stringent accounting of nitrogen inputs using the pre-side-dress nitrate test (PSNT) or nitrogen analysis of composted dairy manure. During the past 15 years, a crop rotation of corn-corn-soybean-wheat was compared to continuous corn where every entry point of the rotation was present each year. A number of soil and crop variables were measured at the LFL from 1993-2003 (Snapp et al. 2010); since 2006 the LFL has initiated new studies including a perennial wheat project (Snapp et al. 2013).

Bioenergy Crop Experiments

The DOE Great Lakes Bioenergy Research Center (GLBRC) Intensive Experimental site was established in 2008 south of the MCSE (Fig. 5) to compare the productivity and environmental performance of alternative cellulosic biofuel cropping systems and to ask fundamental questions about their ecological functioning. Eight different cropping systems were established in a randomized complete block design (5 replicate blocks of 30 × 40 m plots) that includes, in order of increasing plant diversity, continuous corn, a corn-soybean-canola rotation, switchgrass, miscanthus, hybrid poplar, mixed-species native grasses, successional vegetation, and restored prairie. In 2012 the corn-soybean-canola system was removed and a corn-soybean and corn-soybean cover crop system were established. Regular measurements at the GLBRC plots are similar to those made in the MCSE, but also include time domain reflectrometry (TDR) soil water profiles and automated chamber measurements of soil-atmosphere greenhouse gas exchanges.

In addition, larger biofuel scale-up fields of continuous corn, switchgrass, and restored prairie were established on both existing cropland and on land that had been in the USDA Conservation Reserve Program (CRP) for 20 years. These sites are about 10 km distant. The GLBRC scale-up fields have eddy covariance flux towers to measure carbon dioxide and water exchange at the whole-ecosystem scale, and are also sampled for yield and a variety of soil biogeochemical and insect diversity attributes.

Cellulosic Biofuels Diversity Experiment

The Cellulosic Biofuels Diversity Experiment provides a range of treatments to test the long-term impact of plant diversity on the delivery of ecosystem services from cellulosic biofuel systems. The experiment is located within the MCSE main site (Fig. 2). Twelve different cropping systems vary in species composition and nitrogen input. Treatments include continuous corn, corn-soybean, two varieties of switchgrass fertilized differently, a C3 and C4 grass plus legume mix, and four different prairie restorations with 6, 10, 18, or 30 different species at establishment. Treatment plots are 9 × 30 m replicated in 4 randomized blocks, established in 2008.

The Regional Setting - Landscape and Regional Observations

As noted earlier, certain important ecosystem services that may not be evident at the field scale emerge at the scale of landscapes. Prominent examples include biodiversity-mediated services that require landscape-level habitat configurations (Gardiner et al. 2009) and recreational / aesthetic services that emerge from a landscape of varied vegetation and topography (Bolund and Hunhammar 1999, Swinton et al. 2013). Likewise the provision of high-quality water is an important service delivered by well managed agricultural landscapes.

Experiments and observation networks designed to address landscape-level questions are by necessity specialized and do not lend themselves to a one-size-fits-all design (Robertson et al. 2007). Biogeochemical questions, for example, may require a diversity of flow paths and discrete watersheds (e.g., Hamilton et al. 2007). In contrast, questions about insect biodiversity may require a multi-county region that includes a variety of landscape patterns, crop rotations or intensities (e.g., Landis et al. 2008, Landis and Gage 2013). And KBS LTER economic questions may require a social or market setting that encompasses scales from the regional (e.g. Jolejole 2009, Chen 2010, Ma et al. 2012) to the national (e.g. James et al. 2010) and international.

Consequently, there is no single landscape that is the focus for KBS LTER landscape-level research. Rather, the KBS LTER landscape research setting expands outward from MCSE sites to local fields (e.g. Gelfand et al. 2011); local watersheds (e.g. Hamilton 2013); southwest Michigan (e.g. Rudy et al. 2008); the state of Michigan (e.g. Ma et al. 2013); the Great Lakes states (e.g. Landis et al. 2008): and the U.S. Midwest (Gelfand et al. 2013b, Grace et al. 2011) as the questions under investigation require.

How large a landscape might KBS LTER research represent? Michigan is among the 12 states that produce most (80%) of the nation’s corn, and is thus included in the USDA’s designated North Central Region, also known as the U.S. corn belt. Included are the states of Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, and Wisconsin. Though there are many caveats, KBS LTER research has been extended to the North Central Region by biogeochemical modeling used to forecast potential soil carbon sequestration (Grace et al. 2006) and N_2O fluxes (Grace et al. 2011), as well as by crop modeling to develop regional crop stress indicators (Gage et al. 2013).

Criteria for Evaluating a Site's Potential for LTAR Candidacy

1. *Productivity*

Since its inception in 1987, the KBS LTER research program has produced 446 journal articles, 140 books/book chapters, and 96 theses and dissertations (http://lter.kbs.msu.edu/citations). Additionally, we have made major progress on our first site synthesis volume and are on schedule for a 2013 submission to Oxford University Press. Over the last five years we have averaged annually ~32 journal articles, 6 books/book chapters, and 5 theses and dissertations. In addition to our core LTER funding (~$1M per year), some 26 projects funded with non-LTER funds (~$42M total) are currently active on site, not including a major DOE Bioenergy Research Center ($125M) for which KBS LTER is the principal field site. In 2011-2012 the project supported in part or in whole the research training of 26 graduate students, 18 undergraduate students (mainly REU type interns), 24 postdoctoral scholars, and 9 high school teachers (RET).

2. *Infrastructure Capacity*

The KBS LTER program is part of MSU's W.K. Kellogg Biological Station (KBS). The Station is MSU's largest off-campus educational facility and is one of the oldest and prominent US inland field stations, with 13 faculty in year-round residence. KBS is located northeast of Kalamazoo, MI, and about 60 miles southwest of the main MSU campus in East Lansing. Facilities at KBS include modern laboratories (http://www.kbs.msu.edu/research/research-facilities/instrumentation), computer labs (http://www.kbs.msu.edu/research/research-facilities/computer-labs) and classrooms plus a conference center that provides overnight and longer term housing (http://www.kbs.msu.edu/visit/conference-center/visiting-researcher-rates).

3. *Data Richness*

Several hundred data sets produced and managed by the KBS LTER project are available on-line via the KBS LTER server (http://lter.kbs.msu.edu/datatables). Recent additions include enhancements to databases for weather, net primary production, agronomic yields, soil properties (chemical, physical, and biological), biodiversity (plants and insects in particular), and trace gas fluxes.

4. *Data Availability (Accessibility)*

Our priority for data management is to curate and distribute accurate research data from the site in a consistent, timely, and accessible manner. We serve information to local, LTER Network, and community-based users, and strive to do so in a way that facilitates interdisciplinary research. Our primary goals are 1) to ensure the long-term integrity of KBS databases, 2) to allow data to be retrieved easily, 3) to facilitate the inclusion of data collected by site investigators, and 4) to provide metadata sufficient to allow appropriate analyses and interpretation by future investigators.
Scope -- Data collected as part of KBS research activities are managed locally on PostgreSQL and PostGIS open-source, object-relational, scalable database systems that run in a Linux environment on our database servers. The servers are mirrored on campus, 60 miles distant, via a Gigabit fiber connection to the National LambdaRail. A local telecom company provides a 10Mb/s backup link.

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

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

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

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

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

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

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

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

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

Contributions to LTER Network and community activities. We consistently contribute data to the LTER Network databases ClimDB and HydroDB and have contributed 55 datasets to EcoTrends (excluding the 359 economic datasets from non-KBS sources).

5. Geographic Coverage at Various Scales

Given the broad range of landscape-level questions that are addressed by the KBS LTER project (e.g. watershed-level biogeochemistry, insect biodiversity, economic analyses), as noted above there is no single landscape scale that is the focus for KBS LTER research. As a result, the KBS LTER research program increases in scale from the plot-level in MCSE sites to (1) local fields (e.g. scale-up experiment); (2) local watersheds; (3) southwest MI; (4) the Great Lake states; (5) the U.S. Midwest; and (6) the 12 state North Central Region as necessitated by specific questions. The KBS LTER site is located within the Northern Crescent Farm Resource Region, the Great Lakes Domain (5) of NEON and the Great Lakes (04) hydrologic region. This important agricultural region is not currently represented within the LTAR network.

6. Partnerships

MSU AgBioResearch. MSU AgBioResearch (formerly the Michigan Agricultural Experiment Station) partners with KBS LTER to provide funding for research facilities including field research sites and instrumentation, as well as salary support for faculty and staff investigators.

Michigan State University Extension. MSUE extension faculty and educators partner with KBS LTER to provide education and research related to project outreach activities.

Local K-12 Schools. Gull Lake Community Schools; Plainwell Community Schools; Vicksburg Community Schools; Martin Public Schools; Gobles Public Schools; Hastings Area School System; Olivet Community Schools; Lawton Community Schools; Delton-Kellogg Community Schools; Harper Creek Community Schools; Comstock Community Schools; Galesburg-Augusta Community Schools; and Parchment School District partner with KBS LTER with teachers who participate in the KBS K-12 Partnership for Science Literacy.

Education and Outreach

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

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

University Students. A number of educational programs affiliated with KBS, MSU, and nearby colleges and universities continue to use the LTER site for formal teaching activities, including classes from MSU (both KBS and campus-based courses) and the University of Michigan. We have also supported REU and other undergraduate interns to work on site to gain hands-on research experience with support from NSF, DOE, and other sources. Graduate students are actively encouraged to participate in all aspects of LTER research and outreach activities, including All Scientist Meetings. We have also contributed LTER data to the Ecological Society's *Teaching Issues and Experiments in Ecology* series on climate change and agriculture (Wilke and Kunkle 2009).

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

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

Policy Makers and Media. We place significant value on efforts to educate and inform national and state decision makers. In 2005 we participated in a congressional briefing on broader impacts of LTER research, sponsored by AIBS; in 2007 we participated in a congressional briefing on ecosystem services from agriculture co-sponsored by the Ecological (ESA) and Agronomy (ASA) Societies; in 2008 we participated in briefings on the sustainability of cellulosic biofuels, sponsored by ESA; and in 2009 we participated in an international briefing on the ecological management of nitrogen sponsored by NSF. In 2006 we organized a AAAS symposium on ecosystem services in agriculture that attracted national media attention, and in 2008 participated in a national web seminar on ecosystem services in agriculture sponsored by ESA and the Council on Food, Agricultural and Resource Economics. In 2009 we also participated in a climate change and agriculture briefing to the Michigan state legislature, which was followed by a field tour for legislative staff, and a follow-on request to host a field visit for all members of the Michigan House Agriculture Committee. Other state and federal legislative staffers have visited KBS on an ad hoc basis. Also at the national level, we have co-authored 3 recent Policy Forum pieces in *Science*, and the policy value of KBS LTER results were specifically highlighted in a fourth *Science* article in 2009 (Richter & Mobley 2009).

7. Institutional Commitment

MSU places a high value on the continued success of the KBS LTER. The University's cost-share commitment is $480k per year. This represents a substantial portion of total project costs and illustrates the importance that the University attaches to this project, even in very challenging economic times. Although not guaranteed after the current LTER funding cycle (2011-2016), MSU cost sharing is provided in the following five forms:

1. Land Base. In addition to research access to habitats at KBS in general, the University continues to commit 179 acres of tillable land to the LTER project for as long as the project continues. The costs to the Station for this land are considerable as the land base would otherwise be available to supply feed for the KBS dairy herd.

2. Annual Operational Expenses. The University is underwriting all of the expenses required to farm the MCSE plots. This includes support for salaries, transportation, equipment, and supplies and services.

3. Data Management. The University is providing support for a systems/data analyst and a half-time web and database programmer.

4. Project Support Specialists. The University is providing support for two LTER coordinator positions. These academic specialists will have responsibility for research coordination and education and outreach coordination.

5. Graduate Support. The University is providing support for an annual appointment of an MSU graduate student to conduct LTER-related research, including funds to cover stipend support, tuition and fees, and professional development. Additionally, the University is providing funds for two summer research fellowships for MSU enrolled graduate students to initiate and conduct LTER-affiliated research.

References

Basso, B. and J. T. Ritchie. 2013. Simulating crop response and biogeochemical fluxes to the environment as a tool for assessment of sustainability. Pages xx-xx *in* S. K. Hamilton, J. E. Doll, and G. P. Robertson, editors. The ecology of agricultural ecosystems: research on the path to sustainability. Oxford University Press, New York, New York, USA.

Bolund, P. and S. Hunhammar. 1999. Ecosystem services in urban areas. Ecological Economics 29:293-301.

Chen, H. 2010. Ecosystem services from low input cropping systems and the public's willingness to pay for them. Thesis. Michigan State University, East Lansing, Michigan, USA.

Collins, S. L., S. R. Carpenter, S. M. Swinton, D. E. Orenstein, D. L. Childers, T. L. Gragson, N. B. Grimm, J. M. Grove, S. L. Harlan, J. P. Kaye, A. K. Knapp, G. P. Kofinas, J. J. Magnuson, W. H. McDowell, J. M. Melack, L. A. Ogden, G. P. Robertson, M. D. Smith, and A. C. Whitmer. 2011. An integrated conceptual framework for long-term social-ecological research. Frontiers in Ecology and the Environment 9:351-357.

Colunga-Garcia, M. and S. H. Gage. 1998. Arrival, establishment, and habitat use of the multicolored Asian lady beetle (Coleoptera: Coccinellidae) in a Michigan landscape. Environmental Entomology 27:1574-1580.

DiFonzo, C. and F. Warner. 2010. Insect, nematode and disease control in Michigan field crops. Michigan State University Extension Bulletin E1582, East Lansing, Michigan, USA.

Gage, S. H., J. E. Doll, and G. R. Safir. 2013. Production agriculture in the North Central Region of the United States: Why we farm where we farm. Pages xx-xx *in* S. K. Hamilton, J. E. Doll, and G. P. Robertson, editors. The ecology of agricultural ecosystems: research on the path to sustainability. Oxford University Press, New York, New York, USA.

Gardiner, M. M., D. A. Landis, C. Gratton, C. D. DiFonzo, M. O'Neal, J. M. Chacon, M. T. Wayo, N. P. Schmidt, E. E. Mueller, and G. E. Heimpel. 2009. Landscape diversity enhances the biological control of an introduced crop pest in the north-central USA. Ecological Applications 19:143-154.

Gelfand, I., G. P. Robertson, and S. K. Hamilton. 2013a. Mitigation of greenhouse gases in agricultural ecosystems. Pages xx-xx *in* S. K. Hamilton, J. E. Doll, and G. P. Robertson, editors. The ecology of agricultural ecosystems: research on the path to sustainability. Oxford University Press, New York, New York, USA.

Gelfand, I., R. Sahajpal, X. Zhang, C. R. Izaurralde, K. L. Gross, and G. P. Robertson. 2013b. Sustainable bioenergy production from marginal lands in the US Midwest. Nature. doi:10.1038/nature11811.

Gelfand I., T. Zenone, P. Jasrotia, J. Chen, S. K. Hamilton, and G. P. Robertson. 2011. Carbon debt of Conservation Reserve Program (CRP) grasslands converted to bioenergy production. Proceedings of the National Academy of Sciences USA 108: 13864-13869.

Grace, P., G. P. Robertson, N. Millar, M. Colunga-Garcia, B. Basso, S. H. Gage, and J. Hoben. 2011. The contribution of maize cropping in the Midwest USA to global warming: a regional estimate. Agricultural Systems 104:292-296.

Grace, P. R., M. Colunga-Garcia, S. H. Gage, G. P. Robertson, and G. R. Safir. 2006. The potential impact of agricultural management and climate change on soil organic carbon of the North Central Region of the United States. Ecosystems 9:816-827.

Gross, K. L., S. Emery, A. S. Davis, R. G. Smith, and T. M. P. Robinson. 2013. Plant community dynamics in managed and natural ecosystems. Pages xx-xx *in* S. K. Hamilton, J. E. Doll, and G. P. Robertson, editors. The ecology of agricultural ecosystems: research on the path to sustainability. Oxford University Press, New York, New York, USA.

Hamilton, S. K. 2013. Changes in water quality as water moves through agricultural landscapes. Pages xx-xx *in* S. K. Hamilton, J. E. Doll, and G. P. Robertson, editors. The ecology of agricultural ecosystems: research on the path to sustainability. Oxford University Press, New York, New York, USA.

Hamilton, S. K., A. L. Kurzman, C. Arango, L. Jin, and G. P. Robertson. 2007. Evidence for carbon sequestration by agricultural liming. Global Biogeochemical Cycles 21:GB2021.

James, L. K., S. M. Swinton, and K. D. Thelen. 2010. Profitability analysis of cellulosic energy crops compared with corn. Agronomy Journal 102: 675-687.

Johnson, J. C., R. R. Christian, J. W. Brunt, C. R. Hickman, and R. B. Waide. 2010. Evolution of collaboration within the US Long Term Ecological Research Network. BioScience 60:931-940.

Jolejole, M. C. B. 2009. Trade-offs, incentives, and the supply of ecosystem services from cropland. Thesis. Michigan State University, East Lansing, Michigan, USA.

Landis, D. A. and S. H. Gage. 2013. Arthropod diversity and pest suppression in agricultural landscapes. Pages xx-xx *in* S. K. Hamilton, J. E. Doll, and G. P. Robertson, editors. The ecology of agricultural ecosystems: Research on the path to sustainability. Oxford University Press, New York, New York, USA.

Landis, D. A., M. M. Gardiner, W. van der Werf, and S. M. Swinton. 2008. Increasing corn for biofuel production reduces biocontrol services in agricultural landscapes. Proceedings of the National Academy of Sciences USA 105:20552-20557.

Ma, Y. C., X. W. Kong, B. Yang, X. L. Zhang, X. Y. Yan, J. C. Yang, and Z. Q. Xiong. 2013. Net global warming potential and greenhouse gas intensity of annual rice-wheat rotations with integrated soil-crop system management. Agriculture, Ecosystems and Environment 164: 209-219.

Ma S., S. M. Swinton, F. Lupi, and C. B. Jolejole-Foreman. 2012. Farmers' willingness to participate in Payment-for-Environmental-Services programmes. Journal of Agricultural Economics 63: 604-626.

Millar, N. and G. P. Robertson. 2013. Agricultural nitrogen: boon and bane. Pages xx-xx *in* S. K. Hamilton, J. E. Doll, and G. P. Robertson, editors. The ecology of agricultural ecosystems: research on the path to sustainability. Oxford University Press, New York, New York, USA.

Millennium Ecosystem Assessment. 2005. Ecosystems and human well-being: synthesis. Island Press, Washington, D.C., USA.

Nizeyimana, E. L., G. W. Petersen, M. L. Imhoff, H. R. Sinclair, S. W. Waltman, D. S. Reed-Margetan, E. R. Levine, and J. M. Russo. 2001. Assessing the impact of land conversion to urban use on soils with different productivity levels in the USA. Soil Science Society of America Journal 65:391-402.

Paul, E. A., A. Kravchenko, A. S. Grandy, and S. Morris. 2013. Soil organic matter dynamics: controls and management for ecosystem functioning. Pages xx-xx *in* S. K. Hamilton, J. E. Doll, and G. P. Robertson, editors. The ecology of agricultural ecosystems: research on the path to sustainability. Oxford University Press, New York, New York, USA.

Power, A. G. 2010. Ecosystem services and agriculture: tradeoffs and synergies. Philosophical Transactions of the Royal Society B: Biological Sciences 365:2959-2971.

Robertson, G. P., V. G. Allen, G. Boody, E. R. Boose, N. G. Creamer, L. E. Drinkwater, J. R. Gosz, L. Lynch, J. L. Havlin, L. E. Jackson, S. T. A. Pickett, L. Pitelka, A. Randall, A. S. Reed, T. R.

Seastedt, R. B. Waide, and D. H. Wall. 2008. Long-term agricultural research: a research, education, and extension imperative. BioScience 58:640-643.

Robertson, G. P. and P. M. Groffman. 2007. Nitrogen transformations. Pages 341-364 *in* E. A. Paul, editor. Soil microbiology, ecology, and biochemistry. Academic Press, Burlington, Massachusetts, USA.

Robertson, G. P., K. M. Klingensmith, M. J. Klug, E. A. Paul, J. R. Crum, and B. G. Ellis. 1997. Soil resources, microbial activity, and primary production across an agricultural ecosystem. Ecological Applications 7:158-170.

Robertson, G. P. and S. M. Swinton. 2005. Reconciling agricultural productivity and environmental integrity: a grand challenge for agriculture. Frontiers in Ecology and the Environment 3:38-46.

Rudy, A.P., C. K., B. J., Thomas, M. R. Worosz, S. C. Kaplan , and E. C. O'Donnell. 2008. The political ecology of Southwest Michigan Agriculture, 1837-2000. Pages 152-205 *in* C. L. Redman, and R. R. Foster, editors. Agrarian landscapes in transition. New York, New York, USA: Oxford University Press.

Schmidt, T. M. and C. Waldron. 2013. Microbial diversity in agricultural soils and its relation to ecosystem functions. Pages xx-xx *in* S. K. Hamilton, J. E. Doll, and G. P. Robertson, editors. The ecology of agricultural ecosystems: research on the path to sustainability. Oxford University Press, New York, New York, USA.

Snapp, S. S., L. E. Gentry, and R. R. Harwood. 2010. Management intensity - not biodiversity - the driver of ecosystem services in a long-term row crop experiment. Agriculture, Ecosystems and Environment. 138:242-248.

Snapp, S. S., R. G. Smith, and G. P. Robertson. 2013. Agronomic lessons from KBS: field crop performance in the LTER and living field lab. Pages xx-xx *in* S. K. Hamilton, J. E. Doll, and G. P. Robertson, editors. The ecology of agricultural ecosystems: research on the path to sustainability. *This volume*. Oxford University Press, New York, New York, USA.

Sprague, C. and W. Everman. 2011. Weed control guide for field crops. Michigan State University Extension Bulletin E0434, East Lansing, Michigan, USA.

Swinton, S. M., K. L. Gross, D. A. Landis, and W. Zhang. 2013. Ecosystem services afforded by agriculture and their economic value. Pages xx-xx *in* S. K. Hamilton, J. E. Doll, and G. P. Robertson, editors. The ecology of agricultural ecosystems: research on the path to sustainability. Oxford University Press, New York, New York, USA.

Swinton, S. M., F. Lupi, G. P. Robertson, and S. K. Hamilton. 2007. Ecosystem services and agriculture: cultivating agricultural ecosystems for diverse benefits. Ecological Economics 64:245-252.

Syswerda, S. P., B. Basso, S. K. Hamilton, J. B. Tausig, and G. P. Robertson. 2012. Long-term nitrate loss along an agricultural intensity gradient in the Upper Midwest USA. Agriculture, Ecosystems and Environment 149:10-19.

Thelen, K., B. Widdicombe, and L. Williams. 2011. Michigan corn hybrids compared. Michigan State University Extension Bulletin E0431, East Lansing, Michigan, USA.