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Long-Term Ecological Research at the Kellogg Biological Station LTER Site

Conceptual and Experimental Framework

G. Philip Robertson and Stephen K. Hamilton

Over half of the land area of the contiguous United States is in agricultural production, with over half devoted to row crops such as corn (*Zea mays* L.), soybean (*Glycine max* L.), and wheat (*Triticum aestivum* L.) (NASS 2013). These cropping systems thus represent one of the most extensive and important ecosystem types in North America. The vast majority of this cropland is managed intensively with tillage, chemical fertilizers, and pesticides to achieve high yields. And with well-known environmental impacts on soils, watersheds, surface and coastal waters, and the atmosphere (Matson et al. 1997, Robertson et al. 2004, Robertson and Vitousek 2009, Tilman et al. 2011), the environmental consequences of agricultural intensification extend well beyond the boundaries of individual farm fields.

While the catalog of agriculture's harmful environmental impacts is extensive—ranging from biogeochemical pollution to diminished biodiversity to human health risks—many of the benefits are substantial, not the least of which is human well-being from the provision of food and other products. Less well appreciated are agriculture's contributions to a number of other ecosystem services (Swinton et al. 2007, Power 2010)—clean water, flood protection, climate regulation, disease and pest suppression, soil fertility, habitat conservation, and recreational and aesthetic amenities, among others—all of which benefit people.

Also underappreciated is the degree to which agricultural ecosystems are linked to one another and to unmanaged areas of the surrounding landscape such as surface waters, wetlands, woodlots, and abandoned fields undergoing ecological succession. Only recently have we learned the importance of many of these understudied linkages (Robertson et al. 2007). For example, while it has been long known how bacteria in streams and wetlands can transform excess nitrate (NO_3^-) that leaves farm fields into harmless dinitrogen (N_2) gas (Lowrance et al. 1984, Robertson and Groffman 2015), only recently have headwater streams and small wetlands in agricultural landscapes been shown to disproportionately improve water quality (Mulholland et al. 2009, Hamilton 2015, Chapter 11 in this volume). Likewise, relatively small areas of uncropped habitat can disproportionately support biodiversity services via the provision of refugia for pollinators and insect predators important to pest suppression (Gardiner et al. 2009).

How can row crops be managed to balance or reduce the negative impacts of agricultural production? The answer lies in knowing how to manage cropland for an array of ecosystem services, and that area of research remains largely unexplored. Of particular importance is an understanding of how different cropping systems vary in their impacts—environmental, economic, as well as social—and how they interact with unmanaged ecosystems. By fully comprehending the causes and consequences of these impacts and interactions we can identify (1) which components and interactions are important for delivering the services we value and (2) how this knowledge can be used to promote beneficial services and minimize the negative impacts of agriculture at different geographic scales.

Many processes and attributes that provide ecosystem services in agricultural landscapes take decades to occur or become visible. Thus, long-term observations are crucial for detecting change (Magnuson 1990, Scheffer et al. 2009). Some changes are gradual, such as trends in soil organic matter (Paul et al. 2015, Chapter 5 in this volume) and shifts in soil microbial communities (Schmidt and Waldron 2015, Chapter 6 in this volume). Others may be more rapid with clear immediate effects but still have long-term, perhaps subtle consequences. The appearance and persistence of exotic pests and their predators (Landis and Gage 2015, Chapter 8 in this volume) and the adoption of new genomic technologies (Snapp et al. 2015, Chapter 15 in this volume) might fit this description. And still other changes can be highly episodic, such as the outbreak of a pest that affects a dominant competitor or a 20-year drought that affects later plant populations via seed bank changes (Gross et al. 2015, Chapter 7 in this volume). Short-term observations might entirely miss episodic events or lack the temporal context to fully understand events with long-term consequences. Century-long experiments at Rothamsted in England (Jenkinson 1991) and at a few U.S. sites (Rasmussen et al. 1998) have illustrated the importance of long-term observations and experiments for understanding the impact of agriculture on many slowly changing ecosystem attributes (Robertson et al. 2008a).

Understanding the complexity of intensive field–crop ecosystems thus requires a long-term systems perspective: understanding (1) potential ecosystem services and how multiple services can be delivered in synergistic ways; (2) how local, interdependent communities in agricultural landscapes interact across landscapes and regions; and (3) how the component parts of agricultural ecosystems behave and interact over appropriate, often long time scales. Sustainable agriculture depends on this knowledge (Robertson and Harwood 2013). And the prospect of human-induced climate change coupled with increasing demands for agriculture to produce both food and fuel (Robertson et al. 2008b, Tilman et al. 2009) makes the need for long-term agricultural research guided by a systems perspective ever more imperative. This has been, and remains, a primary motivation underlying research at the Kellogg Biological Station Long-Term Ecological Research site (KBS LTER).

Here, we present the context and conceptual basis for the KBS LTER program, including descriptions of the principal long-term experiments, their rationale, and their regional setting. Data collected as part of core KBS LTER research activities are maintained online, in a publicly available database. This includes most of the data used in this and the following chapters. The KBS LTER Data Catalog (http://lter.kbs.msu.edu/datatables) is also incorporated in the LTER Network Information System (https://portal.lternet.edu/nis/home.jsp).

The KBS Long-Term Ecological Research Program

The KBS LTER program is part of a nationwide network of 26 LTER sites representing a diversity of biomes (Robertson et al. 2012). KBS is the only LTER site focused on row-crop agriculture and is located in the USDA's North Central Region in southwest Michigan (42° 24'N, 85° 23'W; 288-m elevation; Fig. 1.1). Since its inception in 1987, LTER research at KBS has sought to better understand the ecology of intensively managed field crops and the landscape in which they reside. The emphasis of our research has been on corn, soybean, wheat, and alfalfa (*Medicago sativa* L.) (Gage et al. 2015, Chapter 4 in this volume)—crops that dominate the North Central Region and have a huge impact on human and environmental welfare. And in anticipation of the importance of cellulosic bioenergy crops over the coming decades, we have also studied hybrid poplar (*Populus* sp.) since 1987 and more

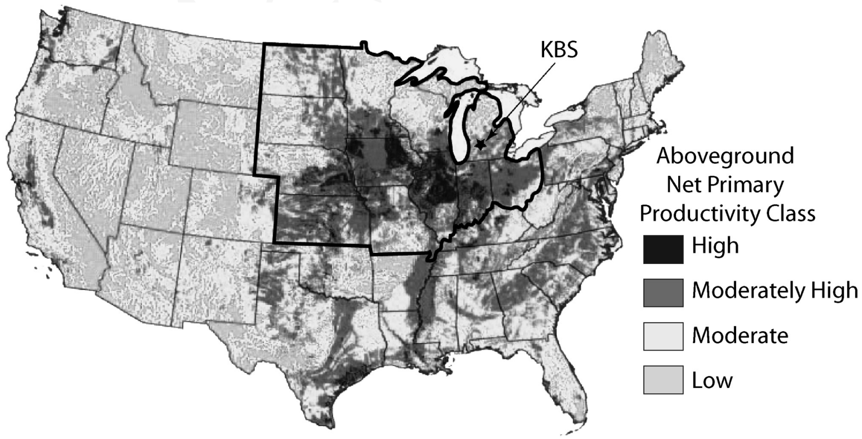

Figure 1.1. Location of the Kellogg Biological Station (KBS) in relation to estimates of U.S. net primary productivity. The area outlined in black is the USDA's North Central Region and includes the U.S. corn belt (Gage et al. 2015, this volume). Base map is modified from Nizeyimana et al. (2001).

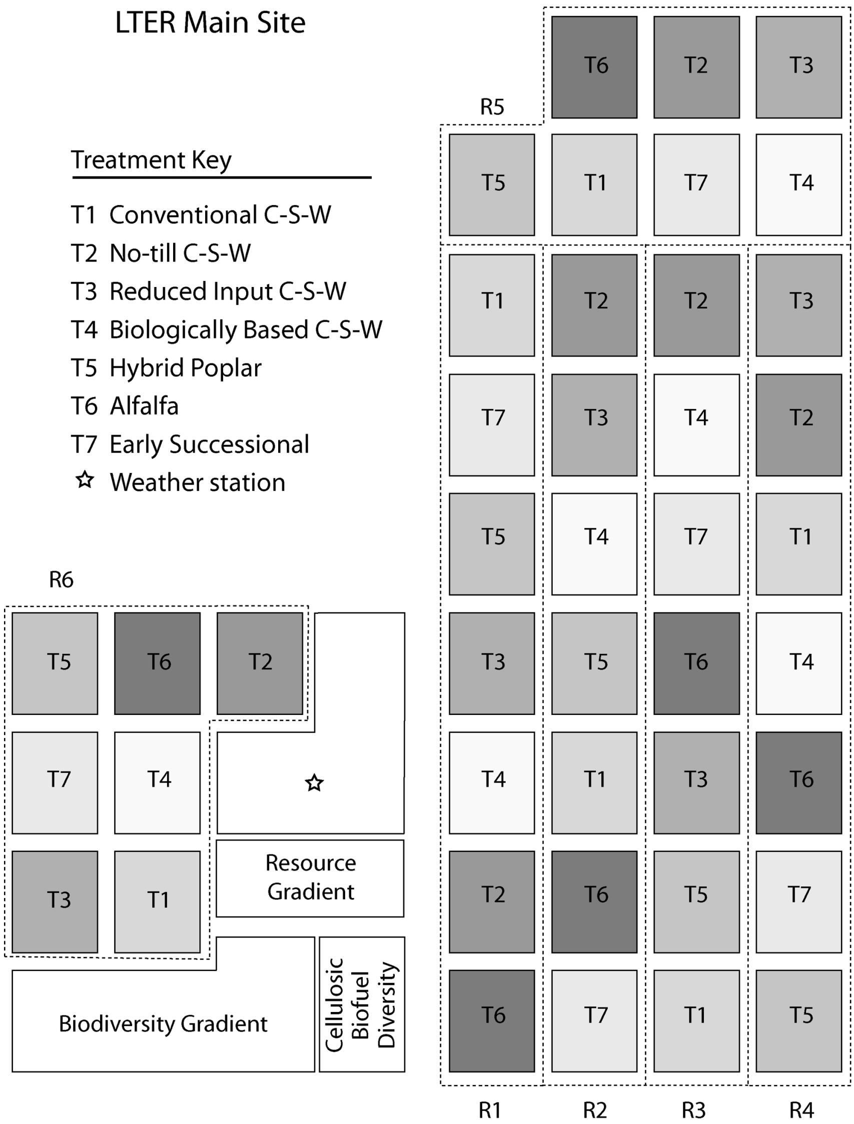

Figure 1.2. Experimental layout for seven systems of the KBS LTER Main Cropping System Experiment (MCSE) at the KBS LTER main site: four annual cropping systems (T1–T4), Alfalfa (T6) and hybrid Poplar (T5) perennial systems, and the Early Successional community (T7). All are replicated as 1-ha plots in six replicated blocks (R1–R6). C-S-W = corn-soybean-winter wheat rotation. Other MCSE systems are located as noted in Figure 1.3. See Table 1.1 and text for management details. Also shown are locations of several ancillary experiments.

recently switchgrass (*Panicum virgatum* L.), miscanthus (*Miscanthus* × *giganteus*), and mixed-species grassland communities. Our diverse agricultural ecosystems are compared to native forest and unmanaged successional communities close by.

Our original global hypothesis, still relevant today, 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—can be concomitantly enhanced.

Many of our specific hypotheses have been addressed using the KBS LTER Main Cropping System Experiment (MCSE) established in 1988 to reflect the range of ecosystem types typical of field–crop landscapes in the upper Midwest. Model ecosystems replicated as 1-ha plots along a management intensity gradient include four annual cropping systems, three perennial crops, and unmanaged ecosystems ranging in successional stage from early to late (Figs. 1.2 and 1.3). The annual cropping systems are corn–soybean–winter wheat rotations ranging in management intensity from conventional to biologically based (the latter is a USDA-certified organic system without added compost or manure). Perennial crops include alfalfa, hybrid poplar trees, and conifers. Successional reference communities range in age from early succession (recently abandoned farmland) to late successional deciduous

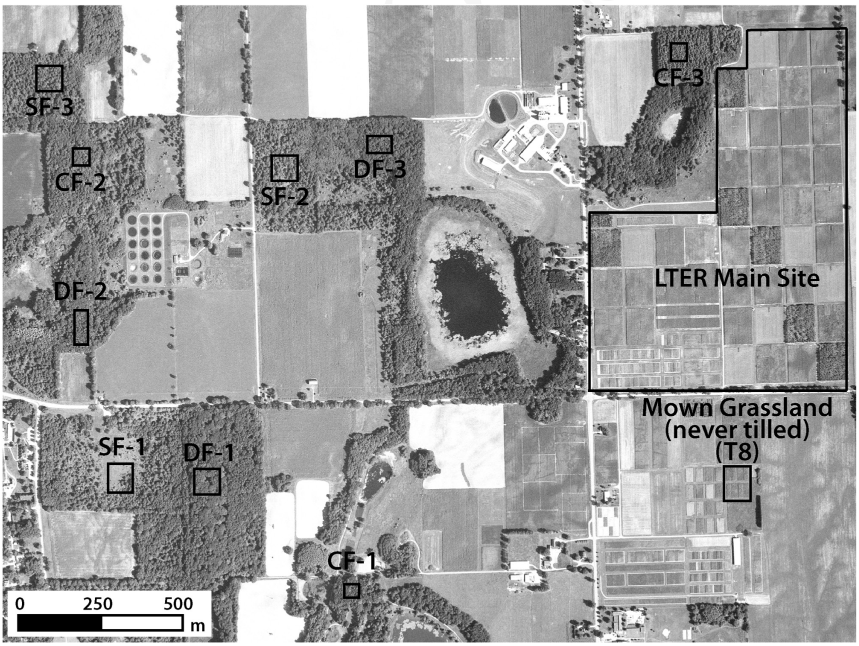

Figure 1.3. Location of mid-successional and forested sites of the KBS LTER Main Cropping System Experiment (MCSE). Included are the Mown Grassland (never tilled) site (T8), and three Coniferous Forest (CF), Mid-successional (SF), and late-successional Deciduous Forest (DF) sites. See Figure 1.2 for LTER main site details and Table 1.1 for further description. Aerial photo background is from August 2011.

forest. Additional experiments have been added since 1988 to address additional long-term hypotheses as described later.

The Conceptual Basis for KBS LTER Research

Research at KBS LTER has steadily grown in scope and complexity since its initiation in 1988. It is now guided by a conceptual model (Fig. 1.4) that integrates both ecological and social perspectives and explicitly addresses questions about the ecosystem services delivered by agriculture. The model is derived from the press-pulse disturbance framework for social-ecological research developed by the national LTER community (Collins et al. 2011) and represents coupled natural and human systems, highlighting relationships between human socioeconomic systems and cropping systems and the landscapes in which they reside. This approach reflects the need to understand both human and natural elements and their interacting linkages. This need is especially acute in agricultural landscapes, where human decisions affect almost every aspect of ecosystem functioning and where the resulting ecological outcomes, in turn, strongly affect human 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 supplied by

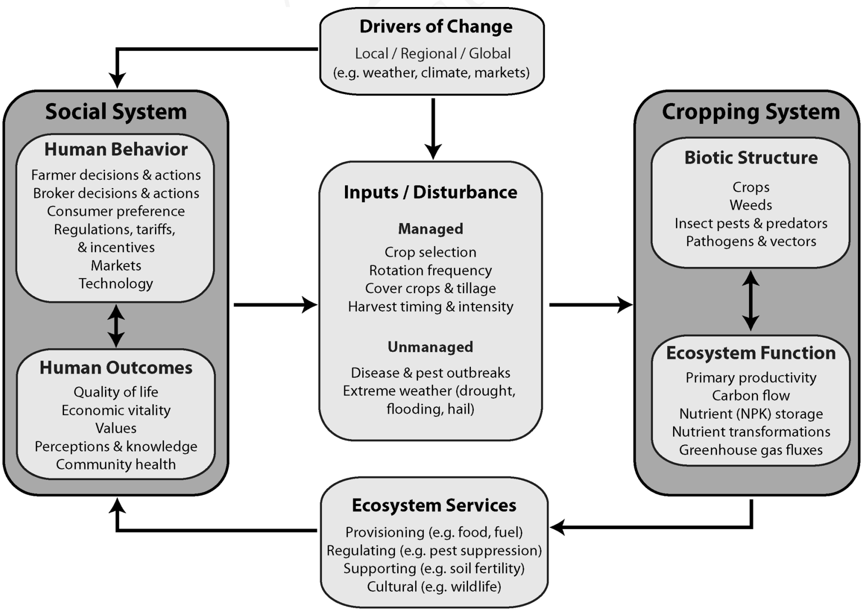

Figure 1.4. Conceptual model currently guiding KBS LTER research. Adapted from Collins et al. (2011).

agriculture, and increasingly, society is recognizing the potential for other services such as improved water quality, the protection and enhancement of biodiversity, climate stabilization via carbon sequestration and greenhouse gas abatement, and social amenities such as verdant landscapes and agrotourism (Robertson and Swinton 2005, Power 2010, Swinton et al. 2015a, Chapter 3 in this volume). 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 and Robertson 2015, Chapter 12 in this volume). Mitigation services provided by alternative practices or other parts of the agricultural landscape can also be considered services provided by agriculture (Swinton et al. 2007). We refer in general to the implementation of agricultural practices that improve the delivery of ecosystem services as "farming for services" (Robertson et al. 2014).

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 subject 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 view these drivers as disturbances to the biophysical or social systems (Fig. 1.4). They can be broadly classified into either "pulse" or "press" disturbances, depending on whether they occur as discrete events or as gradual changes over a more protracted period, respectively (Collins et al. 2011). They can be further grouped into those that are intentional management decisions vs. those that are unintentional and often unanticipated.

Intentional pulsed disturbances that affect field crops include tillage, planting, harvest, and fertilizer and pesticide applications; intentional presses include the gradual adoption of newly developed crop varieties and management technologies. Unintentional pulses include episodic weather events such as short-term droughts and late frosts as well as pest and disease outbreaks, whereas unintentional presses include climate change, increasing atmospheric carbon dioxide (CO_2) concentrations, and declining soil carbon stores. Pulses and presses may act alone or synergistically to affect how we farm, where we farm, and the profitability and sustainability of farming (Gage et al. 2015, Chapter 4 in this volume) as well as the short- and long-term impacts of agricultural activities on the environment at scales from local to global.

Most KBS LTER research to date has emphasized developing an ecosystem-level understanding of ecological structure and function—the right-hand portion of the model (Fig. 1.4). 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—for example, 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 delivery of ecosystem services.

Also important to consider is how factors beyond the field level affect the ability of row-crop ecosystems to deliver these services. Watershed position and landscape complexity can affect many aspects of ecological structure and function; examples include the movement of organisms, nutrients, and water between and among ecosystems, and the spatial patterns of soils and microclimates.

Organisms and Their Interactions

The main groups of organisms providing biological structure in cropping systems include (1) plants as they consume resources both above and below ground (Gross et al. 2015, Chapter 7 in this volume) and regulate the hydrologic cycle (Hamilton 2015, Chapter 11 in this volume); (2) microbes as they control organic matter turnover (Paul et al. 2015, Chapter 5 in this volume), nutrient availability (Millar and Robertson 2015, Chapter 9 in this volume; Snapp et al. 2015, Chapter 15 in this volume), and greenhouse gas fluxes (Schmidt and Waldron 2015, Chapter 6 in this volume; Gelfand and Robertson 2015, Chapter 12 in this volume); (3) insects and pathogens as they respond to changes in the plant community and affect plant productivity (Landis and Gage 2015, Chapter 8 in this volume); and (4) humans as they intentionally and unintentionally create biophysical and chemical disturbance (Swinton et al. 2015a, Chapter 3 in this volume). Each of these groups is a focal area of KBS LTER research and—together with research on watershed biogeochemistry (Hamilton 2015, Chapter 11 in this volume) and regionalization (Gage et al. 2015, Chapter 4 in this volume)—constitutes 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 LTER Experimental Setting

Factorial field experiments, wherein different experimental treatments are established in plots at a single geographic location, offer a powerful means for revealing the influence of individual factors or groups of factors on ecological interactions and agronomic performance. When treatments include a variety of cropping systems, the additional opportunity exists for identifying important interactions that can then be further untangled with nested, single-factor experiments. Furthermore, comparisons of cropping systems to unmanaged, reference plant communities at different stages of secondary succession allow us (1) to gauge the extent to which agriculture has produced long-term changes that may or may not be readily reversed and (2) to understand how noncrop habitats may provide resources for beneficial organisms and modify processes in a manner that might inform sustainable cropping system management.

Plot-scale experimentation provides the basis for sound statistical inference and its value cannot be overstated. But for many questions, the plots of such experiments can be too small to capture important interactions or processes, or the phenomena studied are significantly influenced by adjacent landscape elements. These include biodiversity questions when taxa are mobile or are influenced by other habitats in the landscape. For example, herbivorous insects and their predators as well as birds and other vertebrates typically respond to landscape structure at scales larger than can be accommodated in replicated field plots (Landis 1994, Landis and Marino 1999, Landis and Gage 2015, Chapter 8 in this volume). In some cases, noncrop habitats in the landscape can serve as metapopulation sources and sinks. Likewise, many biogeochemical questions depend on interactions that include landscape position and the presence and location of disproportionalities (Nowak et al. 2006), that is, hotspots of biogeochemical transformations such as high-phosphorus soils, or shallow streams and wetlands through which water flows on its way to larger rivers or lakes (Hamilton 2015, Chapter 11 in this volume).

Addressing these sorts of questions requires a landscape approach, rarely amenable to exact replication and instead more often dependent on regression and other inferential approaches (Robertson et al. 2007). Landscapes are often delineated hydrologically as watersheds or drainage basins, which are hierarchical by nature and can be grouped as needed to ask questions at larger scales. They can also be defined on the basis of other properties or processes—airsheds for questions related to nitrogen deposition or ozone impacts (e.g., Scheffe and Morris 1993), or foodsheds for questions related to the movement of nutrients and other materials related to food products (e.g., Peters et al. 2009).

An understanding of the roles of the social system (Fig. 1.4) requires expanding study boundaries to include pertinent drivers of change and human behaviors that respond to these drivers. In some cases, this might require regional surveys of farmers to understand the factors they weigh when making tillage or crop choices (e.g., Swinton et al. 2015b, Chapter 13 in this volume); in other cases this might require knowledge of the regional economy to understand land-use patterns and decisions (e.g., Feng and Babcock 2010). Where findings can be related back to the systems deployed in our field experiments, they will have the greatest power to contribute to our understanding of the interconnections between socioecological and biophysical realms in our conceptual model (Fig. 1.4).

The KBS LTER Main Cropping System Experiment

The KBS LTER Main Cropping System Experiment (MCSE) is an intensively studied factorial experiment that is the focus of much of the biophysical research at KBS LTER (Figs. 1.2 and 1.3). As mentioned earlier, it includes four annual and three perennial cropping systems plus four replicated reference communities in different stages of ecological succession, including an unmanaged late successional forest (Table 1.1). Seven systems were established and first sampled in 1989; the other four were already established and first sampled as noted below.

Each cropping system is intended to represent a model ecosystem relevant to agricultural landscapes of the region (Gage et al. 2015, Chapter 4 in this volume). They are not intended to represent all major crop × management combinations—to do this would require scores of additional experimental systems. Model systems are arranged along a gradient of decreasing chemical and management inputs. And differences that occur along this management intensity gradient can be understood,

Table 1.1. Description of the KBS LTER Main Cropping System Experiment (MCSE)[a]

Cropping System/ Community	Dominant Growth Form	Management
Annual Cropping Systems		
Conventional (T1)	Herbaceous annual	Prevailing norm for tilled corn–soybean–winter wheat (c–s–w) rotation; standard chemical inputs, chisel-plowed, no cover crops, no manure or compost
No-till (T2)	Herbaceous annual	Prevailing norm for no-till c–s–w rotation; standard chemical inputs, permanent no-till, no cover crops, no manure or compost
Reduced Input (T3)	Herbaceous annual	Biologically based c–s–w rotation managed to reduce synthetic chemical inputs; chisel-plowed, winter cover crop of red clover or annual rye, no manure or compost
Biologically Based (T4)	Herbaceous annual	Biologically based c–s–w rotation managed without synthetic chemical inputs; chisel-plowed, mechanical weed control, winter cover crop of red clover or annual rye, no manure or compost; USDA-certified organic
Perennial Cropping Systems		
Alfalfa (T6)	Herbaceous perennial	5- to 6-year rotation with winter wheat as a 1-year break crop
Poplar (T5)	Woody perennial	Hybrid poplar trees on a ca. 10-year harvest cycle, either replanted or coppiced after harvest
Coniferous Forest (CF)	Woody perennial	Planted conifers periodically thinned
Successional and Reference Communities		
Early Successional (T7)	Herbaceous perennial	Historically tilled cropland abandoned in 1988; unmanaged but for annual spring burn to control woody species
Mown Grassland (never tilled) (T8)	Herbaceous perennial	Cleared woodlot (late 1950s) never tilled, unmanaged but for annual fall mowing to control woody species
Mid-successional (SF)	Herbaceous annual + woody perennial	Historically tilled cropland abandoned ca. 1955; unmanaged, with regrowth in transition to forest
Deciduous Forest (DF)	Woody perennial	Late successional native forest never cleared (two sites) or logged once ca. 1900 (one site); unmanaged

[a]Codes that have been used throughout the project's history are given in parentheses.

predicted, simulated (Basso and Ritchie 2015, Chapter 10 in this volume), and extended to row-crop ecosystems in general.

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

- The Conventional system (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 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 cropping systems. Wheat varieties are in the soft red winter wheat class common in Michigan. 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. 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 system (T2) is managed identically to the Conventional system except for tillage and herbicides. A no-till planter is used to drill seed directly into untilled soil through existing crop residue 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 system has been managed without tillage since its establishment in 1989.
- The Reduced Input system (T3) differs from the Conventional system in the amounts of nitrogen fertilizer and pesticides applied, postplanting soil cultivation (prior to 2008), and winter plant cover. Crop varieties are identical to those in the Conventional system. 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 system: 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 system 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.) follows wheat to precede corn, and soybean precedes wheat. A nonleguminous winter cover crop of fall-planted annual rye grass (*Lolium multiflorum* L.) follows corn to precede soybean.

  The Reduced Input system thus has five species in the rotation—corn/ryegrass/soybean/winter wheat/red clover—so a crop is present at all times of the year during the entire 3-year rotation cycle. Crop varieties are the same as those used in the Conventional system, including genetically modified varieties since 2009.

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

- The Biologically Based system (T4) is similar to the Reduced Input system 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 systems in rainfall (Hamilton 2015, Chapter 11 in this volume). Cover crops are as described for the Reduced Input system. Weed control is provided by tillage and by rotary hoeing and cultivation after planting. This system is certified organic by the USDA, but differs from conventional organic systems because it receives no manure or compost. This creates a system that is as 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 (T6) represents a perennial herbaceous biomass system. Alfalfa is grown in a 6- to 8-year 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 reestablishment 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.
- Poplar (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 (123 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 years then harvested in February 1999 when they were dormant and frozen soil prevented undue soil disturbance. For the second rotation, trees were allowed to coppice (regrow from cut stems) and were harvested in the winter of 2008. After a

fallow break year during which new 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 × 8 ft) row spacing. For this third rotation, the variety *Populus nigra* × *P. maximowiczii* "NM6" was planted with no cover crop; weeds were controlled with herbicides applied in the first 2 years of establishment and fertilizer was 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 and sampled as part of the MCSE beginning in 1993. One of the three sites is dominated (>10% of total biomass) 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 valuable reference communities 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, the dominant plant species (>10% biomass) 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 ca. 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, presettlement soil profile. KBS LTER sampling began in 1989. Plant community dominants (>10% biomass) include smooth brome grass (*Bromus inermis* Leyss.), tall oatgrass (*Arrhenatherum elatius* L.), and blackberry (*Rubus allegheniensis* Porter). Sampling occurs within four replicated 15 × 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 and 1960s (Burbank et al. 1992). Since that time they have been allowed to undergo succession, which is occurring at different rates across the replicates, possibly reflecting differences in soil fertility. One site (SF-1, abandoned in 1951) has limited overstory growth and is dominated (>10% biomass) by tall oatgrass, Canada goldenrod, quackgrass (*Elymus repens* L.), timothy grass, and Kentucky bluegrass.

Transition to forest is well under way in the remaining two sites, abandoned from agriculture in 1963 and 1964; overstory dominants reflect nearby late successional deciduous forests and understory dominants include the invasive shrubs oriental bittersweet (*Celastrus orbiculatus* Thunb.) and glossy buckthorn (*Rhamnus frangula* L.). KBS LTER sampling began in 1993.

- Late successional Deciduous Forest (DF) stands comprise the endpoint of the management intensity gradient. Soils of these three hardwood forest reference sites have never been plowed. Overstory dominants (>10% biomass) 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* Marshall). 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. KBS LTER sampling started in 1993.

All MCSE systems and communities are replicated and most are within the same 60-ha experimental area, known as the LTER main site (Fig. 1.2); others, which for historical or size reasons could not be included in the main site layout, are on the same soil series within 1.5 km of the other plots (Fig. 1.3). Within the LTER main site are the four annual cropping systems, the Alfalfa and hybrid Poplar perennial cropping systems, and the Early Successional community. All are replicated as 1-ha plots in six blocks of a randomized complete block design (Fig. 1.2), for a total of 42 plots 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 LTER main site (Fig. 1.3); 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 late successional Deciduous Forests are each replicated three times in the landscape around the main site (Fig. 1.3). Within each replicated system, the sampling area is embedded within a larger area of similar vegetation and land-use history.

Plot sizes for MCSE systems in the main site (Fig. 1.3) 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 (1) 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 farmers; (2) help to ensure the integrity of long-term sampling by avoiding the danger of sampling the same locations multiple times years apart; and (3) avoid some of the scale effects associated with biodiversity questions for different taxa—for example, seed banks and noncrop plant diversity would not be well represented in 0.01-ha or smaller plots commonly studied in agricultural research, although even 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, replicate 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 × N fertilized microplots within the Early Successional community (Gross et al. 2015, Chapter 7 in this volume); many have been shorter term.

Regular measurements for all 11 systems and communities in the MCSE include (1) plant species composition, above-ground net primary productivity, litter fall, and crop yield; (2) predaceous insects, in particular, coccinellids (ladybird beetles); (3) microbial biomass and abundance; (4) soil moisture, pH, bulk density, carbon, inorganic nitrogen, and nitrogen mineralization; (5) NO_3^- concentrations in low-tension lysimeters installed at a 1.2-m depth (Bt2/C horizon) in replicate plots of all systems; and (6) a number of weather variables measured at a weather station on the MCSE. Precipitation chemistry is monitored as part of the National Atmospheric Deposition Program/National Trends Network at another 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 systems. The soil seed bank is sampled on a 6-year cycle.

Ancillary Experiments

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

The MCSE Scale-Up Experiment

The need to understand how findings from our 1-ha MCSE cropping systems scale up to commercially sized fields motivated the establishment of the MCSE Scale-Up Experiment (Fig. 1.5). 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

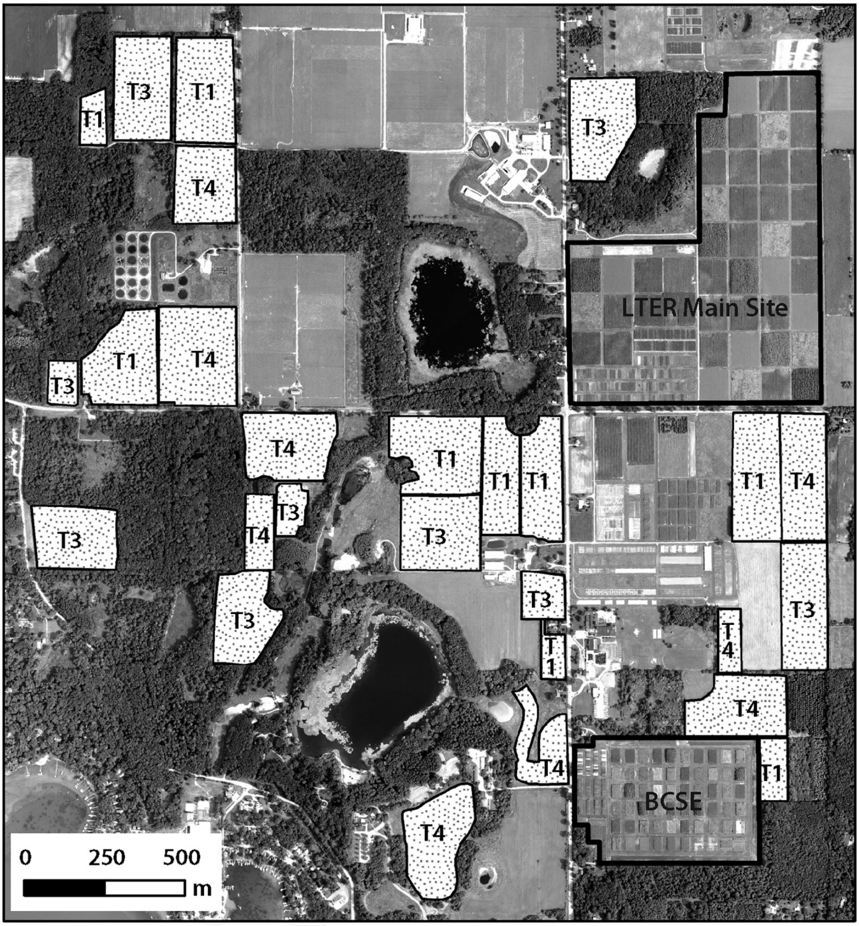

Figure 1.5. Main Cropping System Experiment (MCSE) Scale-up fields (n = 27) managed to address questions related to the scalability of results from the MCSE depicted in Figure 1.2. Management corresponds to the MCSE Conventional (T1), Reduced Input (T3), and Biologically Based systems (T4; see Table 1.1). Also shown is the location of the Bioenergy Cropping System Experiment (BCSE). Aerial photo background is from August 2011.

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 2015, Chapter 8 in this volume).

From the fall of 2006 through the fall of 2013, 27 fields managed by the Kellogg Farm were assigned to one of three MCSE annual cropping systems: 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 system × entry point combination (3 systems × 3 entry points × 3 replicates). Fields range in size from 1 to 7.5 ha, adjoin a number of different habitat types, and have a variety of perimeter complexities. Regular sampling activities include agronomic yields.

Biodiversity Gradient Experiment

The Biodiversity Gradient Experiment was established on the LTER main site (Fig. 1.2) 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 MCSE Biologically Based system (i.e., no synthetic chemical inputs). This experiment reveals how crop species and rotational complexity affect yield, weed competition, soil biogeochemical processes, microbial diversity, and other variables (Gross et al. 2015, Chapter 7 in this volume).

Resource Gradient Experiment

The Resource Gradient Experiment was established on the LTER main site (Fig. 1.2) in 2003 to investigate nitrogen and water constraints on crop yield. MCSE annual crops (either corn, soybean, or wheat) are nitrogen-fertilized at nine different rates and are either irrigated or rain-fed. Fertilizer rates differ by crop; for corn the range has been 0 to 292 kg N ha^{-1} and for wheat 0 to 180 kg N ha^{-1}. Soybeans are normally not fertilized (but were in 2012). Irrigation is sufficient to meet plant water needs as predicted by weather and SALUS, a crop growth model that calculates instantaneous water balance (Basso and Ritchie 2015, Chapter 10 in this volume). A linear move irrigation system applies water 0–3 times per week during the growing season depending on recent rainfall and crop water need. Crops are otherwise managed as for the MCSE No-till system. In addition to crop yield, greenhouse gas exchanges between soils and the atmosphere are measured in various treatments (Millar and Robertson 2015, Chapter 9 in this volume).

Living Field Lab Experiment

The Living Field Laboratory (LFL) was established on land just north of the MCSE 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. “Integrated” 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 has been 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 to 2003 (Snapp et al. 2010); since 2006 the LFL has initiated new studies including a perennial wheat project (Snapp et al. 2015, Chapter 15 in this volume). The LFL was decommissioned in Fall 2014.

Bioenergy Cropping System Experiment

The Great Lakes Bioenergy Research Center's (GLBRC) Bioenergy Cropping System Experiment (BCSE) was established in 2008 south of the LTER main site (Fig. 1.5) 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 (five 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 native prairie. In 2012 the corn–soybean–canola system was terminated and two additional systems added: one a continuous corn + cover crop system and the other a corn–soybean + cover crop system. Regular measurements in the BCSE are similar to those made in the MCSE, but also include time domain reflectometry (TDR) soil water profiles and automated chamber measurements of soil-atmosphere greenhouse gas exchanges. An identical GLBRC-sponsored experiment on Mollisol soils is located in Arlington, Wisconsin.

In addition, larger biofuel scale-up fields of continuous corn, switchgrass, and restored prairie were established in 2009 on both existing cropland and on land that had been in the USDA Conservation Reserve Program (CRP) for 22 years. These KBS sites are about 10 km from the main biofuels experiment. The BCSE 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 Biofuel Diversity Experiment

The Cellulosic Biofuel Diversity Experiment is designed to test the long-term impact of plant diversity on the delivery of ecosystem services from cellulosic biofuel production systems. The experiment is located within the LTER main site (Fig. 1.2). Twelve different cropping systems vary in species composition and nitrogen input. Systems include continuous corn, corn–soybean, two varieties of switchgrass fertilized differently, a C_3 and C_4 grass plus legume mix, and four different prairie restorations with 6, 10, 18, or 30 different species at establishment. Replicate plots are 9 × 30 m replicated in four randomized blocks, established in 2008.

The Regional Setting

Climate, Soils, and Presettlement Vegetation

Climate at KBS is humid, continental, and temperate (Fig. 1.6). Annual precipitation averages 1005 mm yr^{-1}, with an average snowfall of ~1.3 m (1981–2010; NCDC 2013). Precipitation is lowest in winter (17% of total) and is otherwise evenly distributed among the other three seasons (25–30%). Potential evapotranspiration exceeds precipitation for about 4 months of the year (Crum et al. 1990; see

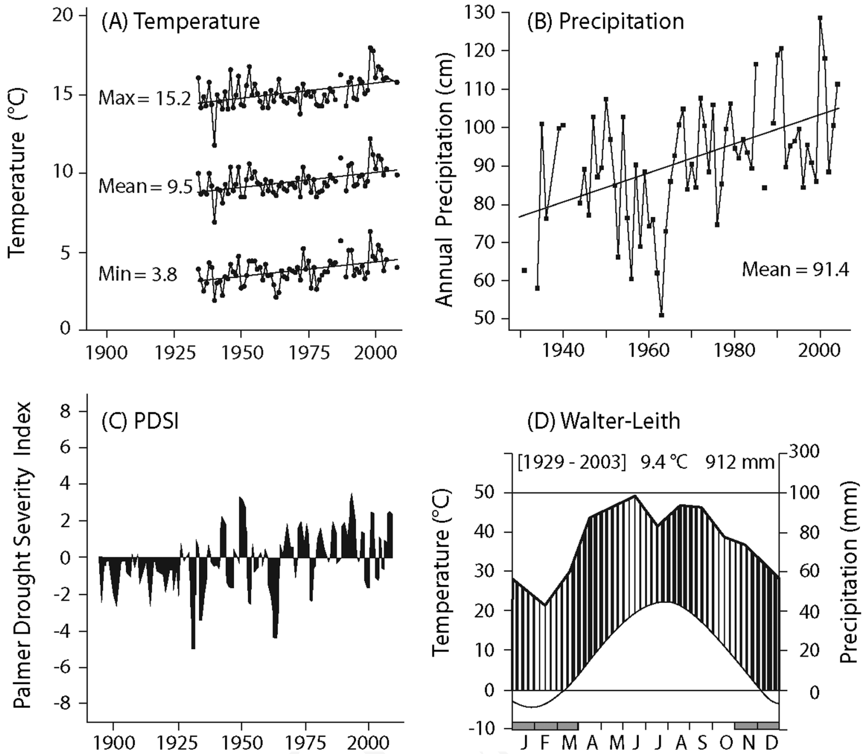

Figure 1.6. Long-term (1929–2008) trends for temperature and precipitation at KBS: (A) annual means of daily air temperatures showing maximum (upper line), minimum (bottom), and daily (24-hour) values (middle) in °C (means for the 80-year period are given to the left of each data series); (B) total annual precipitation (cm); (C) mean annual Palmer Drought Severity Index (PDSI); and (D) monthly mean air temperature and precipitation depicted as a Walter-Leith climate diagram. Negative PDSI indicates water deficit conditions for the region. Redrawn from Peters et al. (2013).

Hamilton 2015, Chapter 11 in this volume, Fig. 11.3). The mean annual temperature is 10.1°C, ranging from a monthly mean of –3.8°C in January to 22.9°C in July (1981–2010; NCDC 2013). Climate change models predict significant alterations in the amount of precipitation and its variability for the Midwest, in particular, the frequency and intensity of precipitation events (Easterling et al. 2000, Weltzin et al. 2003). At KBS, air temperature and precipitation have both shown increasing trends over the past several decades (Fig. 1.6), as has the incidence of large rain events. A warming trend is also apparent from the ice records of area lakes (Fig. 1.7).

The physiography of southwest Michigan is characteristic of a mature glacial outwash plain and moraine complex. The retreat of the Wisconsin glaciation, ~18,000 years ago in southwest Michigan, left a diverse depressional pattern of many kettle lakes and wetlands interspersed among undulating hills and outwash

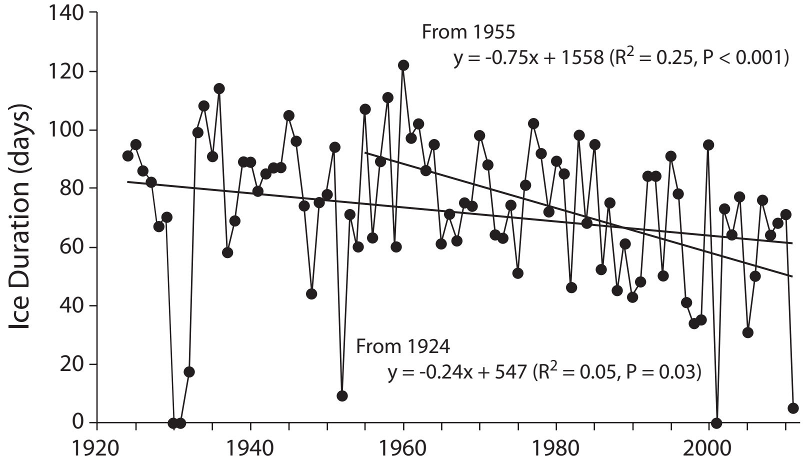

Figure 1.7. Long-term trends in ice duration on Gull Lake at KBS for the periods 1924–2011 and 1955–2011. Ice seasons potentially span two calendar years and therefore the x-axis depicts the year each winter began. From S.Hamilton (unpublished data).

channels. There are 200 lakes within 50 km of KBS, most of which originated as ice-block depressions in the outwash plains formed as the glacial ice melted. KBS is located within the Gull Creek/Gull Lake watershed (97 km^2) and the Augusta Creek watershed (98 km^2), both within the Kalamazoo River basin (5232 km^2). At the watershed scale, most water movement occurs through groundwater aquifers, and water sources to all streams and most lakes and wetlands are dominated by groundwater inputs (Hamilton 2015, Chapter 11 in this volume).

Soils in the area thus developed on glacial till and outwash following the last glacial retreat. The predominant soils at and around KBS are Alfisols, developed under upland forest vegetation. MCSE soils are well-drained Alfisol loams of the Kalamazoo series (fine-loamy, mixed, mesic Typic Hapludalfs) co-mingled with well-drained loams of the Oshtemo series (coarse-loamy, mixed, mesic Typic Hapludalfs) (Mokma and Doolittle 1993, Crum and Collins 1995). Surface soil sand and clay contents average 43 and 17%, respectively (Robertson et al. 1997), and dominant silicate minerals include plagioclase, K-feldspar, quartz, and amphibole (Hamilton et al. 2007). Carbonate minerals (dolomite and calcite) are common in glacial drift and occur at depths below 1 m; they have been leached out of the upper soil profile at KBS (Kurzman 2006, Hamilton 2015, Chapter 11 in this volume), as is typical of glacial soils elsewhere in the Great Lakes region (Drees et al. 2001).

Pre-European settlement vegetation of the area consisted of a mixture of forests, oak savannas, and prairie grasslands (Gross and Emery 2007, Chapman and Brewer 2008). Southwest Michigan was part of the "prairie peninsula" (Transeau 1935) that appears to have developed during a prolonged dry period 4000–8000 years ago along the south and southeastern edge of Lake Michigan. Fires were likely frequent during this period and, beginning ca. 700 C.E., were actively promoted by local

Native Americans of the Mascouten and Potawatomi tribes in order to maintain game habitat (Legge et al. 1995).

Human Settlement and Agricultural Transitions

The current human landscape of SW Michigan (Fig. 1.8) is largely a product of its agricultural history, formed by demographic, social, and economic forces interacting within an ecological context of climate, soils, and natural vegetation. Rudy et al. (2008) provide a comprehensive and insightful account of the major periods of agricultural transitions within the region.

Southwest Michigan was inhabited beginning with glacial retreat ~16,000 B.C.E. By 8000 B.C.E. Paleo-Indians foraged for fish and game in the area, and evidence exists of at least one indigenous cultigen (a sunflower) by the start of the Early Woodland Period in 1000 B.C.E. By the Late Woodland Period (1200 C.E.), there was widespread incorporation of corn, bean, and squash cultivation around semi-permanent villages. By 1670 C.E., when Michigan's Lower Peninsula was depopulated by the Iroquois, the Potawatomi Indians had established large permanent villages with intercropped gardens of corn, pumpkin, squash, and beans in fields cleared of trees by girdling and fire. Following repopulation of the area in the early 1700s, the Potawatomi in the region's south and the Ottawa in the north cultivated corn and other vegetables as well as fruit trees, which supplemented the diets of as many as 10,000 Native Americans.

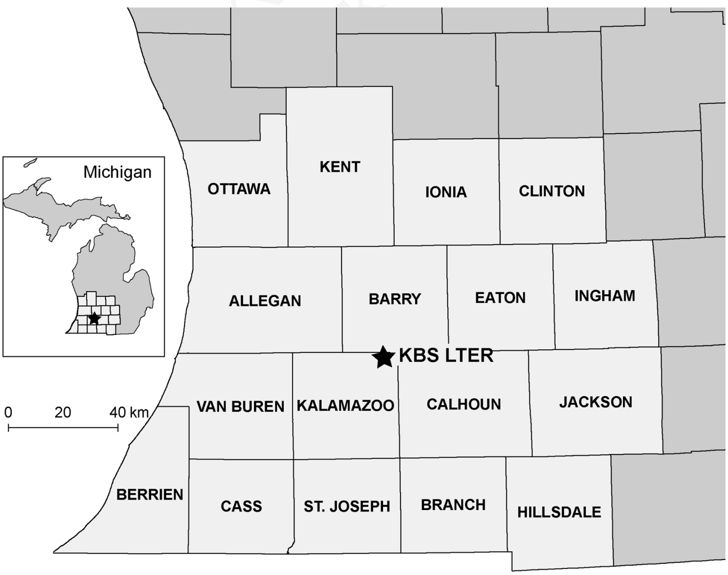

Figure 1.8. Southwest Michigan counties that comprise the regional setting for KBS LTER (Rudy et al. 2008).

By 1830, ~10,000 settlers of European descent had migrated to the area, driven by high land and low grain prices in the East, the opening of the Erie Canal in 1825, and the introduction of fruit trees. Most settlers were New Englanders (Gray 1996) and they first occupied the prairie and oak openings that had been farmed by the Potawatomi they displaced.

Rudy et al. (2008) describe six agricultural periods in southwest Michigan that define present-day agriculture. The first is the largely extensive development period that occurred prior to 1898 when land was cleared, drained, and farmed, mainly for the production of wheat for human consumption and hay for draft animals. The second is the 1899–1919 Golden Age of Agriculture marked by expanding international markets with their high grain prices and the introduction of new techniques for crop cultivation and animal breeding brought to farmers by the university-based Cooperative Extension Service.

The Agricultural Depression began ca. 1920 as a result of national overproduction following the return of European agriculture after World War I, and persisted throughout the Great Depression. It was exacerbated by mechanization and tractor-driven increases in productivity that at the same time opened to row-crop production pasturage that had been formerly used to feed draft animals. Agricultural Fordism (1941–1973) followed the Agricultural Depression and was marked by agriculture's increased need for capital goods such as tractors, hybrid seeds, and pesticides as well as by farm families' shift to a consumer orientation. Together, these trends encouraged agricultural intensification and, in particular, simple monoculture rotations and a near-singular focus on increasing productivity. The average farm size in this period grew from ~35 to ~60 ha (~90 to ~150 acres).

The period 1974–1989 found southwest Michigan farm operators squeezed between a continued downward trend in real prices for agricultural commodities and increasing production costs. The difference was relieved to some extent by government payments, which by the 1990s constituted >50% of net farm income. Southwest Michigan farmers also responded with strategies that included greater off-farm income and market opportunities for more diverse foods including organic and specialty crops. Even so, crop agriculture in the region was and remains grain dominated: in 2007 ~81% of cropland in the 17-county area was used to grown corn (47%), soybean (29%), and wheat (5%) (USDA 2009). Forage (11%; commonly alfalfa) and vegetables and orchards made up most of the remainder.

Globalization since 1990 marks Rudy et al.'s (2008) sixth major period, one in which rural agricultural dynamics are shifting rapidly. By the late 1900s, agrifood systems had an increasingly global scope with important local consequences. In southwest Michigan, as elsewhere, this has exacerbated tensions between agricultural production and environmental conservation as well as struggles over the social and environmental consequences of, in particular, exurban sprawl, agrichemical use, and industrial animal production. The local landscape now is a mixture of cultivated and successional fields, woodlots dominated by northern hardwood trees, private residences, and lakes and wetlands.

KBS LTER (MCSE) vs. Regional Crop Yields

KBS LTER crop yields are typical of rain-fed yields elsewhere in the North Central Region. For the 21-year period from 1989 to 2009, MCSE no-till soybean yields (2.6 ± 0.2 SD Mg ha^{-1} at standard 13% moisture; or 39 bu acre^{-1}) were similar to average Kalamazoo County yields (2.5 ± 0.1 Mg h^{-1}; 37 bu acre^{-1}), which were similar to soybean yields for the entire United States (2.8 ± 0.1 Mg ha^{-1}; 42 bu acre^{-1}) (NASS 2012a). No-till wheat yields at KBS LTER (3.7 ± 0.3 Mg ha^{-1} at standard 13% moisture; 55 bu acre^{-1}) were slightly higher than average Kalamazoo County yields (3.4 ± 0.3 Mg ha^{-1}; 51 bu acre^{-1}) and national yields (3.5 ± 0.1 Mg ha^{-1}; 52 bu acre^{-1}) for soft red wheat, which makes up ~25% of total U.S. wheat production and is the dominant class grown around KBS.

Corn yields are more variable, reflecting the greater sensitivity of corn yields to low rainfall periods and growing season heat waves, especially during pollination

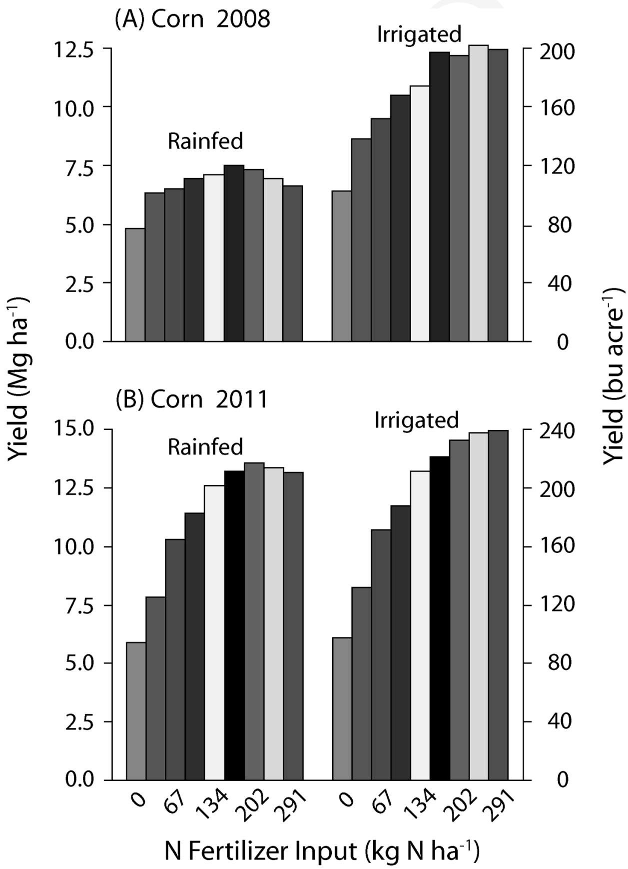

Figure 1.9. Corn yields in (A) 2008 and (B) 2011 in the KBS LTER Resource Gradient Experiment. For comparison, average U.S. corn yields in 2008 and 2011 (ERS 2013) were 9.7 and 9.2 Mg ha^{-1}, respectively (154 and 147 bu acre^{-1}).

(Hatfield et al. 2011). When rainfall is adequate, KBS LTER corn yields are ~12.5 Mg ha^{-1} at standard 15% moisture (199 bu acre^{-1}). In most years, however, yields are constrained by rainfall, as they were during a 2008 local drought when rain-fed corn yields in the Resource Gradient Experiment (Fig. 1.9) were only 7.5 Mg ha^{-1} (120 bu acre^{-1}), as compared to irrigated yields of 12.5 Mg ha^{-1} (199 bu acre^{-1}) and national average corn yields of 9.7 Mg ha^{-1} (155 bu acre^{-1}). In contrast, 2011 saw favorable precipitation; rain-fed corn yields were 13.4 Mg ha^{-1} (215 bu acre^{-1}) against a national average of 9.1 Mg ha^{-1} (147 bu acre^{-1}) and with less response to irrigation (Fig. 1.9).

Over all years during the 1989–2009 period, MCSE corn yields averaged 6.4 ± 0.7 Mg ha^{-1} (102 bu acre^{-1}). This is lower than county (7.4 ± 0.2 Mg ha^{-1}; 118 bu acre^{-1}) and national (8.4 ± 0.2 Mg ha^{-1}; 134 bu acre^{-1}) averages for the same period. For 4 of the 9 MCSE corn years in this period, yields were at or above county and national yields; for 3 years, corn yields were not significantly different from (but lower than) county and national yields; and for 2 years, corn yields were significantly lower than county and national averages. However, both county and national yields include those from irrigated acreage, which inflate yield comparisons relative to rain-fed MCSE yields. In Kalamazoo County about 38% of corn acreage is irrigated and, nationally, about 15% (NASS 2012b). Overall KBS LTER corn yields and variability are thus fairly typical of those experienced by rain-fed Kalamazoo County growers, and reflect how rain-fed corn will vary with the year-to-year variability in growing season rainfall that is typical for farms within the region.

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 and aesthetic services that emerge from a landscape of varied vegetation and topography (Bolund and Hunhammar 1999, Swinton et al. 2015a, Chapter 3 in this volume). 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 to address (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 2015, Chapter 8 in this volume). And 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 scale that is the focus for KBS LTER landscape-level research. Rather, our landscape research setting expands outward from MCSE sites to local fields (e.g., Gelfand et al. 2011); local watersheds (e.g., Hamilton 2015, Chapter 11 in this volume); southwest Michigan (e.g., Rudy et al. 2008); the state of Michigan (e.g., Ma et al. 2012); the Great Lakes states (e.g., Landis et al. 2008); and the U.S. Midwest (e.g., Grace et al. 2011, Gelfand et al. 2013), as dictated by the questions under investigation.

How large a landscape might KBS LTER research represent? Michigan is among the 12 states that produce most of the nation's corn, and is thus included in the USDA's designated North Central Region, part of which is known as the U.S. Corn Belt. Corn Belt states include 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 (Fig. 1.10; 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. 2015, Chapter 4 in this volume). Another, more robust approach to extend KBS LTER research findings would be to establish cooperative agricultural sites within the region at which coordinated experiments and observations might be conducted (Robertson et al. 2008a), similar in power to the many cross-site LTER syntheses now in the literature (Johnson et al. 2010). The nascent Long-Term Agricultural

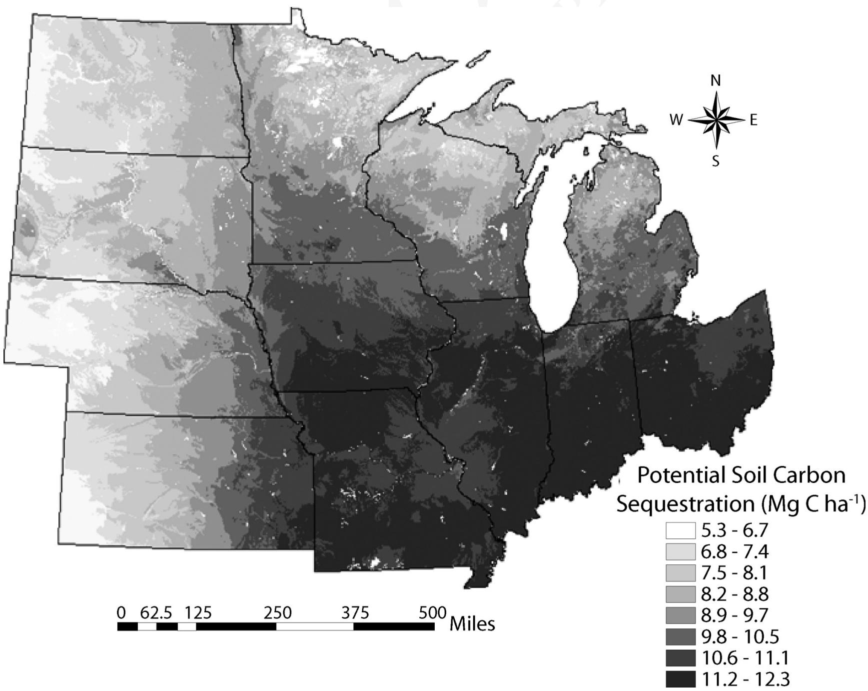

Figure 1.10. Potential soil carbon sequestration expected on adoption of no-till management in the USDA's North Central Region. Predicted values are modeled by the SOCRATES soil organic carbon model (Grace et al. 2006).

Research Network (Robertson et al. 2008a, Walbridge et al. 2011) may provide such opportunities in the future.

Summary

An ecological understanding of the row-crop ecosystem is necessary for designing agricultural systems and landscapes that depend less on exogenous inputs of chemicals and energy and more on internally provided resources for sustaining the production of food, fiber, and fuel, while also optimizing the delivery of other ecosystem services such as pest and disease suppression, nutrient acquisition and conservation, and water-quality protection. This understanding must be based on fundamental knowledge of interactions among major functional groups in agricultural ecosystems and landscapes—plants, microbes, arthropods, and humans—and how interactions change with management and natural disturbance to affect the provision of services.

A conceptual model that incorporates coupled natural and human systems is appropriate for asking many of the most relevant questions in agricultural ecology. The KBS LTER conceptual model (Fig. 1.4) provides a means for asking how the structure and function of row-crop ecosystems interact to deliver ecosystem services. The two linked realms of the model reflect how ecosystem services affect and are perceived by people, who might then directly or indirectly influence market and farmer decisions, public policy, and other actions that feed back to affect row-crop management—thus iteratively changing ecological interactions within the systems and subsequently the delivery of ecosystem services. Additionally, the model provides a framework to analyze the social and ecological consequences of external, unintentional drivers such as climate change.

The KBS LTER experimental approach is to intensively study interactions within model ecosystems, both cropped and unmanaged, and to then extend these findings to the larger landscape through knowledge of human interactions, both social and economic, and targeted observations made at the scale of commercial farms, watersheds, and broader landscapes. Models tested locally can extend insights still further to regional scales.

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