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Snapp, S. S., R. G. Smith, and G. P. Robertson. 2015. Designing cropping systems for ecosystem services. Pages 378-408 in S. K. Hamilton, J. E. Doll, and G. P. Robertson, editors. *The Ecology of Agricultural Landscapes: Long-Term Research on the Path to Sustainability*. Oxford University Press, New York, New York, USA.

Designing Cropping Systems for Ecosystem Services

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Almost all intensive row-crop ecosystems depend on external chemical inputs such as nitrogen fertilizers and pesticides for their high yields. This dependency has had important consequences for the environment and for ecosystem services (MEA 2005; Swinton et al. 2015a, Chapter 3 in this volume) that underpin these systems' long-term sustainability (Robertson and Swinton 2005). Well-known consequences of chemical inputs include biodiversity loss, reductions in water quality, increased greenhouse gas emissions, and degradation of soil resources (Matson et al. 1997, Tilman et al. 2002, Robertson et al. 2004). Agriculture is also facing mounting challenges in the form of climate change and increasing fossil fuel costs—all in the context of an increasing global demand for food over the coming decades. These challenges call for a reevaluation of modern agricultural practices and the supporting and provisioning services that agroecosystems provide.

Several key questions must be answered before we can hope to ensure the long-term sustainability of row-crop production systems and their associated ecosystem services. First, to what degree can agricultural systems be designed to be regenerative (Pearson 2007), enhancing supporting and regulating services so that nutrients and other resources are conserved within the system and any external inputs are used most efficiently? Second, what factors determine agricultural resilience and the capacity for agriculture to maintain productivity in the face of external stressors (Snapp 2008)?

The future of agriculture depends on our ability to understand both the efficient use of natural resources and the ecological principles that promote agroecosystem resilience and stability. While the production of food, fiber, and fuel will remain core goals of farming systems, the provision of other ecosystem services will become increasingly important. Measures to enhance agricultural yield will be evaluated with greater attention to potential trade-offs among other ecosystem services (Syswerda and Robertson 2014).

Experimental investigations at the Kellogg Biological Station Long-Term Ecological Research site (KBS LTER) provide insights into the productivity of different row-crop production systems vis-à-vis ecosystem services such as carbon (C) sequestration, nutrient cycling, pest protection, and energy efficiency, and consequent impacts on soil and water resources. Such insights could be valuable for guiding agriculture through the coming challenges of feeding, clothing, and powering a growing global population with finite natural resources and uncertain trajectories of environmental change.

In this chapter, we report on key agroecosystem performance and ecosystem service indicators measured in KBS cropping system experiments. We include results from both the Main Cropping System Experiment (MCSE) as well as the Living Field Laboratory Experiment (LFL) (Robertson and Hamilton 2015, Chapter 1 in this volume). Alternative cropping systems in these experiments include reduced soil disturbance and complex mixtures of grain crops and winter cover crops such as red clover (*Trifolium pretense* L.) and annual rye (*Secale cereal* L.) that are grown in between grain crops to conserve resources and increase soil fertility. Cover crops are included in many of the KBS LTER agricultural systems because cover crops promote a host of supporting ecosystem services related to soil organic matter, nutrient cycling, water quality, and soil conservation (Snapp et al. 2005, MEA 2005).

Quantifying the benefits and potential trade-offs associated with cover crops and other agricultural practices that maintain or enhance ecosystem services will provide insights for policy makers, land managers, and agricultural advisors. Over two decades of experimentation at KBS provide a unique opportunity to test how a variety of practices—reducing external inputs, no-tillage production, and enhancing plant and residue diversity—affect grain production and ecosystem services, including supporting and regulating ecosystem services.

Agriculture in Michigan

Historical trends in southern Michigan, the location of the KBS LTER, show that agrarian systems have changed dramatically over the last two centuries (Gage et al. 2015, Chapter 4 in this volume). The anthropological record across the upper U.S. Midwest suggests a mosaic of land uses prior to European settlement. Highly diverse horticultural systems were practiced in specific locales, intermixed with low-intensity forest and grassland management (Rudy et al. 2008). In the early to mid-1800s, Americans of European descent moved westward from New England and began to clear forests and drain wetlands for corn (*Zea mays* L.) and small grains including oats (*Avena sativa* L.) and wheat (*Triticum aestivum* L.) (Gray 1996). In the early 1900s, market opportunities expanded for a wide range of horticultural crops and livestock products. New crops such as alfalfa (*Medicago sativa* L.) and soybean (*Glycine max* L.) were promoted by the emerging university extension service, and a diverse suite of crops was grown throughout Michigan (Rudy et al. 2008). A century later, low-diversity row-crop systems supported by agrochemical use now dominate the landscape, and mixed cropping systems—in which livestock are supported mainly or solely by crops grown on-farm—are rare.

Current policies support the production of inexpensive food and affect the livelihoods of many rural communities. To remain economically viable, farmers necessarily focus on maximizing cash crop production (Swinton et al. 2015b, Chapter 13 in this volume). Corn, soybean, and wheat are grown over wide areas due to superior biological traits—including rapid growth, effective resource acquisition, and an ability to translate inputs into grain yield. Changing the portfolio of crops grown and better integrating crops and livestock to improve the delivery of ecosystem services face considerable challenges, in part because the contemporary socioeconomic context and infrastructure reinforce current farming systems.

Further, in recent decades U.S. subsidy policies have favored corn, soybean, and wheat among the few crops that are targeted for direct price support payments. In this environment, it is not surprising that an increasingly narrow range of crops are grown, with less production of forage and hay crops, small grains, minor legumes, or specialty oil and grain crops. At the same time, awareness is growing that reliance on these few crops has environmental costs and increases the vulnerability of significant portions of the food production system.

Long-Term Agricultural Ecosystem Experiments at KBS LTER

The ecological principles that underpin the functioning of natural ecosystems apply to agroecosystems as well, and KBS LTER cropping system experiments are designed to elucidate key processes, population and community-level dynamics, and interactions. The overarching research goal of the KBS LTER is to test the hypothesis that biological processes can substitute for chemical inputs without sacrificing high yields (Robertson and Hamilton 2015, Chapter 1 in this volume). The Main Cropping System Experiment (MCSE) was established in 1989 to provide a practical range of model systems across which these key ecological attributes could be intensively examined over long time periods. The LFL (Sánchez et al. 2004) was established in 1993 to extend MCSE findings to a broader range of farm-relevant cropping systems and, in particular, to separate crop diversity as a distinct factor from crop management. The LFL includes systems with a wider range of crop diversity and nitrogen (N) sources than does the MCSE. Properties that differ among various MCSE and LFL systems include perenniality (the duration of living cover), plant diversity (the number of species in a rotation), types and quantities of fossil fuel vs. biologically derived inputs (including energy), and management-related disturbances (tillage regime).

Resource gradients and disturbances from fire, flooding, tillage, and pests are common regulators of productivity and resource flux in agricultural ecosystems across the world. Processes such as biological N fixation and organic matter accumulation are at the foundation of traditional agriculture (Greenland and Nye 1959), including the bush-fallow or swidden agriculture that was historically practiced across North America prior to European contact (Sylvester and Gutmann 2008). For thousands of years, farmers have used soil disturbance and burning as primary means to enhance nutrient availability in synchrony with crop demand and to suppress weeds. Native vegetation was used as part of long "bush-fallow" crop rotations to allow successional processes to rebuild soil fertility.

Successional processes can be used in a sustainable manner to produce food and other agricultural products in contemporary agricultural systems, given sufficient time and access to land. However, these resources are often in short supply due to economic and population pressures, and modern agricultural systems rely instead on intensive energy and chemical inputs (Tilman et al. 2002). As a consequence, there has been limited attention paid to the underlying ecological processes that mediate agricultural production and control the pools and fluxes of C and nutrients in agricultural soils.

The KBS Main Cropping System Experiment

The Main Cropping System Experiment (MCSE) evaluates agricultural row-crop systems that vary in management intensity (Table 15.1); see Robertson and Hamilton (2015, Chapter 1 in this volume) for a full description. In brief, we compare four management strategies for a corn–soybean–winter wheat rotation: (1) the Conventional system uses fertilizer and herbicide inputs, and conventional tillage as recommended by Michigan State University Extension; (2) the No-till system uses conventional management but for permanent no-till soil management; (3) the Reduced Input system uses biologically based management, including winter cover crops, to reduce synthetic chemical inputs to ~one-third of those used in the Conventional system; and (4) the Biologically Based system uses biologically based management to eliminate synthetic chemical inputs altogether. No systems receive manure or compost. The Reduced Input and Biologically Based systems include cover crops of red clover interseeded in wheat in the spring, and annual rye planted after corn harvest in the fall. Wide row spacing and mechanical cultivation are used to control weeds in these two systems. A fifth system, Alfalfa, is managed conventionally as a continuous forage crop, replanted on a ~6-year schedule following a break year in a grain crop.

The Reduced Input and Biologically Based systems model alternative agriculture practices that make up a small but active sector of U.S. agriculture (Swinton et al. 2015b, Chapter 13 in this volume). For example, the Biologically Based system simulates organic management practices and is USDA-certified organic, although it is unconventionally organic in that neither manure nor compost are used as inputs. The total acreage of certified organic cropland in the U.S. has increased more than 6-fold from 1992 to 2008 and made up 0.7% (1.1 million ha) of total U.S. cropland in 2008 (ERS 2011). The Reduced Input system includes integrated nutrient and pest management practices such as closely monitoring nutrient availability and pest and beneficial insect populations, which allows external inputs to be reduced by about two-thirds in this system. Herbicide application was banded within the crop row until the shift was made in 2011 to broadcast application, and N fertilizer is applied at lower rates. This reduction in N fertilizer use is significant in light of the fact that in many cropping systems fertilizer is frequently applied in excess of crop demand (Robertson 1997, Gardner and Drinkwater 2009). The effects of

Table 15.1. Description of row cropping systems of the KBS LTER Main Cropping System Experiment (MCSE) and Living Field Lab Experiment (LFL).[a]

Experiment/System	Crop Rotation	Management
Main Cropping System Experiment (MCSE)		
Conventional (T1)	Corn–soybean–winter wheat	Prevailing norm for tilled corn–soybean–winter wheat rotation (c–s–w); standard chemical inputs, chisel-plowed, no cover crop, no manure or compost
No-till (T2)	Corn–soybean–winter wheat	Prevailing norm for no-till c–s–w; standard chemical inputs, permanent no-till, no cover crop, no manure or compost
Reduced Input (T3)	Corn–soybean–winter wheat	Biologically based c–s–w managed to reduce synthetic chemical inputs; chisel-plowed, winter cover crop of red clover or annual rye, no manure or compost
Biologically Based (T4)	Corn–soybean–winter wheat	Biologically based c–s–w managed without synthetic chemical inputs; chisel-plowed, mechanical weed control, winter cover crop of red clover or annual rye, no manure or compost; certified organic
Alfalfa (T6)	Alfalfa	5- to 6-year rotation with wheat as a 1-year break crop
Living Field Lab Experiment (LFL)		
Organic	One species—corn Two species—corn with cover crop Three species—corn, corn, soybean, winter wheat Six species—three species rotation with three cover crop species	Biologically based without synthetic chemical inputs; five entry points in annual rotation: continuous corn and each of corn, corn, soybean, wheat (c–c–s–w); winter cover crop(s) of crimson clover in two species rotation and of crimson clover, annual rye, and red clover in six species rotation; chisel-plowed; certified organic practices; dairy compost; mechanical weed control
Integrated Conventional	Same as organic above	Biologically based with reduced synthetic chemical inputs; same crop rotations as organic above; chisel-plowed; targeted application of herbicides and N fertilizer; mechanical weed control

[a] Site codes that have been used throughout the project's history are given in parentheses. For further details, see Robertson and Hamilton (2015, Chapter 1 in this volume).

excess fertilizer N include enhanced production of the greenhouse gas nitrous oxide (McSwiney and Robertson 2005, Hoben et al. 2011), promotion of invasive species (Davis et al. 2000), accelerated changes in some soil organic matter pools (Grandy et al. 2008), and contamination of ground and surface waters with attendant eutrophication (Hamilton 2015, Chapter 11 in this volume; Millar and Robertson 2015, Chapter 9 in this volume).

Prior to the 1980s, row-crop agriculture was heavily reliant on tillage to prepare the soil for planting and to manage weeds. Now a significant proportion of row-crop land is under no-till production (Horowitz et al. 2010), due in part to the use of herbicide-resistant crop varieties. No-till production practices allow farmers to reduce the number of soil-disturbing equipment passes and attendant potential for surface erosion. Benefits of no-till include a decreased requirement for fossil fuel, reduced loss of soil, nutrients, and pesticides in runoff water, better soil water infiltration and water-holding capacity, and a more stable environment for soil organisms. In the MCSE No-till system, the number of equipment passes has been reduced by 26%—from 8.4 to 6.2 per year—as compared to the Conventional system (Gelfand et al. 2010). Reduced soil disturbance has led to greater soil C accumulation in the top 5 cm of soil in the No-till system (3.6 kg C m^{-2}) compared to the Conventional system (3.2 kg C m^{-2}) (Syswerda et al. 2011). The Biologically Based system also led to a greater soil C accumulation (3.8 kg C m^{-2}), similar to the No-till system, but as discussed in more detail below, this occurred despite frequent soil disturbance from plowing and rotary hoeing for mechanical weed control.

One of the sustainability principles evaluated in the MCSE is the role of plant diversity in agroecosystem performance, including net primary productivity (NPP), nutrient retention, and ecosystem stability. Generally, positive relationships have been shown among diversity, NPP, and other ecosystem services in grasslands and other low nutrient, semi-managed, and natural systems (e.g., Hector et al. 1999; Tilman et al. 2001; Hooper et al. 2005, 2012). In row-crop systems, biodiversity is generally a function of crop rotation, intercropping, and inclusion of accessory crops such as winter cover crops. In both long-term (Syswerda et al. 2011, 2012) and shorter-term comparisons (Drinkwater et al. 1998, Maeder et al. 2002), more diverse organic systems have accumulated more soil organic matter and leached less nitrate than paired systems under conventional management.

However, such comparisons cannot distinguish between the effects of plant diversity per se and other management practices that differ among the experimental systems. As a consequence, diversity has rarely been studied as a discrete factor (Gross et al. 2015, Chapter 7 in this volume). The LFL and Biodiversity experiments (Smith et al. 2008; Robertson and Hamilton 2015, Chapter 1 in this volume; Gross et al. 2015, Chapter 7 in this volume) were established at KBS to more explicitly investigate the effects of plant diversity and rotational complexity in biologically based cropped ecosystems (Sánchez et al. 2004, Snapp et al. 2010a).

The KBS Living Field Lab Experiment

The LFL was designed with input from a farmer advisory group and has played an important role, especially in outreach at KBS. The aim of the LFL is to test farm-relevant combinations of intensively managed systems where crop diversity can be examined as a separate factor from other management factors (Sánchez et al. 2004). This allows comparison of common crop sequences such as continuous corn vs. more diverse corn rotations. Management factors include nutrient sources (combinations of conventional fertilizer and composted manure) and weed control (conventional herbicide inputs vs. mechanical cultivation).

The factorial, split-plot design of the LFL includes management regime (Organic vs. Integrated Conventional) as a main plot system and plant biodiversity (comparing one, two, three, and six plant species) as subplot treatments. The Organic system relies on certified organic practices including the application of dairy compost for fertility and tillage for weed management, while the Integrated Conventional system uses herbicides at rates one-third of conventional rates and composted manure and synthetic N fertilizers at rates two-thirds of conventional (Sánchez et al. 2002, 2004). Five entry points for cropping system diversity are included within each management system, where one plot is continuous corn and the other four plots represent each phase of a 4-year rotation of corn–corn–soybean–wheat. Cover crops are grown on half of each plot (red clover, crimson clover [*Trifolium incarnatum* L.] and annual ryegrass); the other half is winter fallowed, with some limited plant cover provided by the presence of winter annual weeds (Smith and Gross 2006a).

It is experimentally challenging to manipulate crop diversity in isolation from management, as management practices are typically "bundled" and therefore multifunctional (Snapp et al. 2010a). In conventional management, for example, reliance on chemical inputs for pest control and nutrient supply allows simplification of the system to a few highly productive species. In contrast, biologically based management, including organic management, commonly relies on a mixture of species that promote internal processes such as N fixation, mineralization, and pest suppression (Lowrance et al. 1984, Drinkwater and Snapp 2007).

Agronomic Lessons from the KBS MCSE

Productivity

Agronomic productivity in the MCSE annual crops over 17 years (1989–2007) has shown consistent responses to management. The No-till system has the overall highest average annual grain yield across all three crops at 4.2 Mg ha^{-1} and the Biologically Based system the lowest at 2.9 Mg ha^{-1} (Table 15.2; Gelfand et al. 2010). Grain yield in the cereal crops—corn and wheat—has been substantially reduced under biologically based management, compared to no-till. In contrast, soybean yields have not been reduced under biologically based management compared to conventional. Although soil moisture and weed pressure likely contribute to low yields in some years, insufficient N supply appears to be the key factor influencing biologically based corn and wheat production. This is supported by the success of soybeans, which provide their own N via biological N fixation, and by low levels of soil inorganic N (nitrate [NO_3^-] and ammonium [NH_4^+]) in soils of the Biologically Based system during other parts of the rotation. For example, at midseason in the corn phase of the Biologically Based system, soils contain 17 mg N kg^{-1}, on average, as compared to 29 mg N kg^{-1} at midseason in soils of the Conventional system (Millar and Robertson, 2015, Chapter 9 in this volume). Nitrogen deficiency in organic systems has been observed in other agroecosystem experiments (Cavigelli et al. 2008), and it is typical of agriculturally converted grassland areas where minimal agricultural inputs are applied (Smith et al. 2008). Biological management for the MCSE relies on N fixation from legumes in the rotation, with no supplementation from manure or compost.

Table 15.2. Annual average crop grain yield and energy balances for KBS LTER MCSE annual cropping systems over the period 1989–2007.

System	Crop Yield				Crop Rotation Energy Balance[a]			Energy Efficiency Output:Input Ratio
	Corn	Wheat	Soybean	System	Farming Energy Inputs	Food Energy Output	Net Energy Gain	
	(Mg ha^{-1} yr^{-1})				(GJ ha^{-1} yr^{-1})			
Conventional	5.90	3.54	2.33	3.92	7.1	72.7	65.6	10
No-till	6.25	3.74	2.65	4.21	4.9	78.5	73.6	16
Reduced Input	5.23	3.09	2.57	3.63	5.2	66.9	61.7	13
Biologically Based	4.08	2.05	2.48	2.87	4.8	53.1	48.3	11
Alfalfa				6.85	5.5	26.1	20.6	5

[a] Energy balance of systems is based on actual farm management operations and inputs (from Gelfand et al. 2010). Food energy output is for direct human consumption except in the case of alfalfa, which is fed to livestock.

Year-to-year yield variability has been high in all MCSE systems (Smith et al. 2007). This is not surprising, given that annual precipitation has ranged from 60 to 110 cm per year over this period. Precipitation is historically evenly distributed throughout the growing season at KBS, but over the last two decades dry spells have commonly occurred during critical crop development stages, and well-drained KBS loam soils have a limited ability to buffer midseason drought because of their relatively low moisture holding capacity (150 mm to 1 m; Crum and Collins 1995). Climatic predictions for Michigan as for the Midwest call for a lower frequency but increasing severity of precipitation events (Schoof et al. 2010; Gage et al. 2015, Chapter 4 in this volume).

The MCSE experimental design for annual crops—with one crop rotation phase present per year—allows management effects on interannual yield variability to be tested for each crop for a different set of years. Smith et al. (2007) analyzed temporal variability by calculating the coefficient of variation for interannual grain yield to show that corn yield variability was not influenced by management system. In wheat, however, variability followed the ranking No-till (coefficient of variation, CV = 0.22) < Conventional (0.35) < Reduced Input (0.40) < Biologically Based (0.50). Soybean yield variability overall was lower, and the response to management was similar to that of wheat: No-till (CV = 0.18) = Conventional (0.18) < Reduced Input (0.25) < Biologically Based (0.34). The lower temporal variability in No-till and Conventional systems suggests that intensive use of agricultural chemicals can mitigate the impacts of weather variability—whether due to weeds, nutrient supply, timely access to fields, or some other less obvious factor. This finding stands in contrast to a long-term field experiment in Pennsylvania showing that organic production systems maintained yields in low rainfall years (Lotter et al. 2003). Improvements in soil organic matter and water storage have been proposed as key processes supporting gains in yield stability under organic management (El-Hage Scialabba and Müller-Lindenlauf 2010). However, MCSE data provide no evidence that Reduced Input and Biologically Based systems resulted in greater cropping system resistance to changing weather patterns.

Soil Carbon

Over the first 10 years of the MCSE, the No-till system rapidly accumulated soil C relative to the Conventional system; by 2001 soil C was 8.5 kg m^{-2} to a 1-m depth. This was 23% higher than in the Conventional system, which held 6.9 kg C m^{-2} (Fig. 15.1A). Surprisingly, over the same time period, a 20% increase of soil C in the Biologically Based system also occurred, even though this system relies on frequent soil disturbance to manage weeds (Fig. 15.1B). This suggests that the soil C that accumulates under biological management is physically stable and persistent. In contrast, soil C accumulation under no-till management is evidently vulnerable

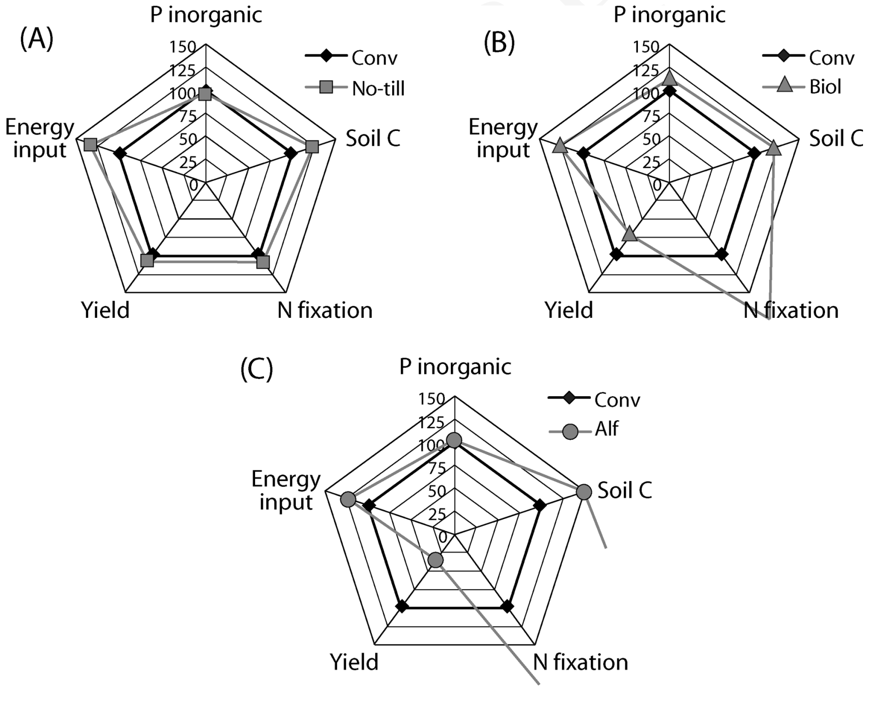

Figure 15.1. Ecosystem services from the KBS LTER Main Cropping System Experiment (MCSE). Results are presented as percent change relative to the Conventional (Conv) system in radial graphs for (A) No-till, (B) Biologically Based (Biol), and (C) Alfalfa (Alf). Values for the Conventional system used as 100%: soil inorganic phosphorus 30 mg P kg^{-1}; soil C 3.2 kg m^{-1}; biological N fixation 27 kg N ha^{-1} yr^{-1}; grain yield 3.92 Mg ha^{-1}, with alfalfa forage biomass valued at 1/5th grain; and energy inputs 7.1 GJ ha^{-1} yr^{-1}. Note that biological N fixation for alfalfa extends beyond the range of the figure.

to loss with physical disturbance; Grandy and Robertson (2006) found rapid C loss following a single initial tillage of plots in the MCSE Mown Grassland (never tilled) community. That C gains under biologically based management occurred despite tillage implicates that other factors, such as crop diversity, residue quality, or a longer annual crop duration, may lead to more persistent soil C accumulation than under no-till. Combining these factors with no-till is an intriguing possibility for building soil C even faster than no-till or biologically based management alone.

Research on soil C sequestration in other long-term agroecosystem experiments has been consistent with KBS MCSE findings. Biodiverse cropping systems have been shown to be generally associated with soil C gains if N fertilizer inputs are nil or minimal (Drinkwater et al. 1998, Russell et al. 2009). More important than diversity may be the duration of living cover. The perennial crop systems in the MCSE have accumulated more C than have the annual crop systems. Carbon gains in the Alfalfa system, for example, had increased by 50% 12 years after establishment (Grandy and Robertson 2007). This may be attributed, in part, to the long growing season for C fixation in alfalfa, which has ~70 more growing days than the 115-day corn growing season and ~30 more days than corn interseeded with a winter cover crop. No tillage is conducted in the Alfalfa system, and the combination of C inputs from roots, continuous cover, and lack of disturbance has led to substantial gains in soil C (Fig. 15.1).

Energy Efficiency

Evaluating the performance of different management systems is a challenge when inputs and outputs vary considerably. Substantial amounts of fossil energy are consumed in common management inputs and practices, including fertilizer, pesticides, and field operations conducted by labor-saving machinery. Organic farming is often assumed to require less energy because of the absence of synthetic chemicals and fertilizers (Pimentel et al. 2005), even though field operations can also be energy-intensive. Forage production and conservation tillage systems are moderately intensive types of agriculture. High economic yields tend to be associated with energy-intensive, conventional agriculture, and questions arise regarding the associated trade-offs. Is a system with low-energy input more efficient if outputs are also low? An assessment of energy balance for the whole cropping system is one way to evaluate these trade-offs (Hülsbergen et al. 2001, Gelfand et al. 2010).

In the MCSE, annual farming energy inputs varied from 4.8 GJ ha^{-1} in the Biologically Based system to 7.1 GJ ha^{-1} in the Conventional system (Table 15.2; Gelfand et al. 2010). Energy inputs were generally lower than previously reported for conventional management in long-term row crop trials in Pennsylvania (Pimentel et al. 2005) and in Central Europe (Maeder et al. 2002). This may be a reflection of the recommended management practices for Michigan field crop production, which do not rely on manure amendments or high fertilization rates (Gelfand et al. 2010). Energy outputs were evaluated in terms of food produced for direct human consumption, or indirect consumption in the case of alfalfa, where energy outputs were based on meat produced when harvested biomass is used as ruminant livestock feed (Table 15.2). The No-till system was the most efficient grain production system, with net energy gains of 74 GJ ha^{-1} yr^{-1}. This was due to a combination of high productivity and moderate energy usage. Although the Biologically Based system had similar energy input as the No-till system (4.8 vs. 4.9 GJ ha^{-1} yr^{-1}, respectively), the net energy gain was substantially lower, owing to lower yields of corn and wheat. Consequently, energy efficiency (output:input) among the annual cropping systems followed the order No-till (16) > Reduced Input (13) > Biologically Based (11) > Conventional (10) (Table 15.2; Gelfand et al. 2010).

Greenhouse Gas Mitigation

The MCSE systems have also provided insight into understanding and mitigating impacts of management intensity on greenhouse gas fluxes. Greenhouse gas exchanges between soils and the atmosphere—nitrous oxide (N_2O), carbon dioxide (CO_2), and methane (CH_4)—have been evaluated for all MCSE systems (Robertson et al. 2000; Gelfand and Robertson 2015, Chapter 12 in this volume). Overall, row-crop production in the MCSE increases greenhouse gas emissions from soils through enhanced N_2O emissions and diminished CH_4 consumption, as has been shown in many other systems as well (Robertson and Vitousek 2009; Gelfand and Robertson 2015, Chapter 12 in this volume).

Within a particular cropping system, N fertilization rate is the best single predictor of N_2O emissions (Millar and Robertson 2015, Chapter 9 in this volume) and N_2O emission rates increase exponentially above a certain fertilization threshold, presumably where crop N needs are saturated (McSwiney and Robertson 2005, Ma et al. 2010, Hoben et al. 2011). These observations underscore the importance of applying N fertilizer at a dose that matches crop requirements. This principle can be challenging to implement in a rain-fed environment as crop growth—and thus requirements for N—vary from year to year with precipitation. However, because ~50% of crop N needs are typically met by N mineralization from soil organic matter (Robertson 1997), also itself a precipitation-dependent process (Robertson and Paul 2000), crop response to fertilizer rate tends to be stable from year to year for a given location. At KBS, application of N fertilizer above the crop optimum has been shown to be associated with 2-fold higher emissions of N_2O (McSwiney and Robertson 2005) with little if any yield benefit. This suggests that widespread adoption of more conservative N fertilizer rates could significantly reduce U.S. N_2O emissions (Millar et al. 2010, Grace et al. 2011).

Water Quality

Water quality is an important attribute of cropping system performance—water leaving the system carries sediments and chemicals that can pollute surface and groundwater far from the point of origin. While many components of water quality are measured at KBS LTER (Hamilton 2015, Chapter 11 in this volume), the loss of nitrate by leaching into infiltrating water provides a reasonable sentinel for solute loss in general, and is important in its own right as a contributor to indirect N_2O fluxes downstream (Beaulieu et al. 2011), to human health via groundwater drinking water supplies (Powlson et al. 2008), and to coastal eutrophication (Diaz and Rosenberg 2008).

That nitrate loss differs among MCSE cropping systems provides another metric for gauging differences in their delivery of ecosystem services. To the extent that N conservation can be considered an ecosystem service, then, the system with the lowest nitrate loss (either absolute or relative to yield) can be considered a greater service provider. While the system with the greatest loss could conversely be viewed as the greater disservice provider, comparisons are more straightforward if put in terms of positive services (Swinton et al. 2015a, Chapter 3 in this volume).

By this metric, then, for the annual cropping systems of the MCSE, in absolute terms the Biologically Based system provided the most nitrate conservation, with average leaching losses of 19 kg NO_3^--N ha^{-1} yr^{-1} over an 11-year (1995–2006) period (Syswerda et al. 2012). This compares to the Conventional system's average loss of 62 kg NO_3^--N ha^{-1} yr^{-1}. The No-till and Reduced Input systems were intermediate to these at 42 and 24 kg NO_3^--N ha^{-1} yr^{-1}, respectively. In relative yield-scaled terms, the differences were smaller but the rankings identical: 18, 11, 7.3, and 7.2 kg NO_3^--N Mg^{-1} yield for Conventional, No-till, Reduced Input, and Biologically Based systems, respectively.

Pest Suppression

An important regulating ecosystem service that can be affected by agricultural management practices is suppression of pests. Weeds are a particularly important group of pests because they reduce crop quality by competing for soil nutrients, water, and light, and by interfering with harvest. Agricultural practices such as tillage, crop rotation, fertilizer and herbicide application, and cover crop use can affect weed populations directly by causing seedling mortality, by inhibiting or promoting seed germination, and by changing weed nutrient status (Liebman et al. 2001). Management practices can also affect weeds indirectly by altering weed–crop competitive relationships (Liebman and Davis 2000, Ryan et al. 2010) or through effects on seed predator populations (Menalled et al. 2007). Management additionally influences soil processes, such as feedbacks with soil biota that reduce weed survival and fitness (Li and Kremer 2000, Davis and Renner 2007).

Weed population data have been collected regularly in the MCSE systems (Gross et al. 2015, Chapter 7 in this volume). The most recent syntheses of these data indicate that the four annual row-crop systems differ in terms of capacity for weed suppression (Davis et al. 2005; Gross et al. 2015, Chapter 7 in this volume). In general, the Biologically Based system is the least weed suppressive (i.e., has more weeds), with weed biomass varying across years from 48 to 148 g m^{-2} compared to the other three systems, where biomass has ranged from less than 3 to over 50 g m^{-2} (Davis et al. 2005). The lack of herbicide use and reduced crop productivity in the Biologically Based system have likely contributed to this system's weed pressure.

An additional factor contributing to weed suppression could be weed seed predator populations, which have also differed by system (Menalled et al. 2007). Populations of seed-predating carabid ground beetles (Coleoptera: Carabidae), which are sensitive to soil disturbance, were over three times higher and seed predation rates over two times higher in the No-till system compared to the Biologically Based system. Taken together, these results are consistent with herbicide use and soil disturbance as key determinants of weed suppression services. However, given that both herbicide use and soil disturbance are associated with a host of potential ecosystem disservices, there is a clear need for research into alternative weed management practices that improve pest suppression services without incurring significant trade-offs in the form of soil or water degradation.

Ecosystem Service Trade-offs

Three of the more important ecosystem services associated with different management systems—yield, nitrate loss, and soil C gain—are summarized in Table 15.3.

Table 15.3. Evaluation of yield reductions and environmental gains associated with alternative systems relative to conventional management.[a]

Experiment/ System	Average Crop Yield[b] (kg grain ha^{-1})	Nitrate Leaching Loss[c] (kg NO_3^--N ha^{-1} yr^{-1})	Soil C Gain[d] (kg C ha^{-1} yr^{-1})	Yield Trade-off— Nitrate Mitigation (kg NO_3^--N kg^{-1} grain)[e]	Yield Trade-off— Soil C Accumulation (kg C kg^{-1} grain)[f]
Main Cropping System Experiment (MCSE): Corn–Soybean–Wheat					
Conventional	3511	62	0		
No-till	3853	42	330	–0.06	0.96
Reduced Input	3597	24	200	–0.44	2.33
Biologically Based	2765	19	500	0.06	–0.67
Living Field Lab Experiment (LFL): Continuous Corn					
Integrated Conventional	6420	74	80		
Organic	5050	32	900	0.03	0.59

[a] All values expressed on an annual basis, based on yield reductions or enhancements associated with alternative management relative to conventional management vs. reductions in nitrate (NO_3^-) leached and gains in soil carbon (C).

[b] MCSE grain yield average for corn–soybean–wheat rotations from 1996 to 2007 (Syswerda and Robertson 2014); LFL continuous corn grain yield average from 1994 to 2000 (Snapp et al. 2010a).

[c] MCSE leaching losses monitored from 1995 to 2006 (Syswerda et al. 2012); LFL leaching losses monitored from 1994 to 2000 (Snapp et al. 2010a).

[d] MCSE soil C gain in the A/Ap horizon from 1989 to 2001 (Syswerda et al. 2011); LFL soil C gain in the 0- to 20-cm horizon from 1993 to 2008 (Snapp et al. 2010a).

[e] Trade-off relative to conventional management, where the change in leached nitrate-N is reported as a ratio to change in grain yield. A negative value implies less N leaching per unit of change in yield, indicating a desirable trade-off with respect to that ecosystem disservice.

[f] Trade-off relative to conventional management, where the change in soil C sequestered is reported as a ratio to change in grain yield. A positive value implies more C sequestration per unit of change in yield, indicating a desirable trade-off with respect to that ecosystem service.

In the MCSE, relative to the Conventional system, the Reduced Input system stands out for its ability to reduce nitrate loss and accumulate soil C while maintaining high grain yields. While the Biologically Based system has provided greater nitrate and C conservation benefits, yields have been substantially lower, resulting in a significant yield vs. ecosystem service trade-off. Likewise in the LFL, ecosystem service benefits in the Organic system come at the cost of a significant yield penalty (Table 15.3). The extent to which these trade-offs might be acceptable will depend on many factors, including the goals and economic position of land managers. Public interests as embedded in policy will also need to assess trade-offs among services, weighing the relative and absolute value of different services to society.

Trade-offs also exist between crop yield and greenhouse gas mitigation services, which can be evaluated as reductions in the global warming impact (GWI). The MCSE No-till system combines high yields with a high soil C sequestration potential, and even in the face of higher chemical use, the No-till system had a low net GWI (–14 g CO_2e m^{-2} yr^{-1}) as compared to the Conventional system (101 g CO_2e m^{-2} yr^{-1}; Gelfand and Robertson 2015, Chapter 12 in this volume). In both systems, N fertilizer use contributed similarly to GWI, as did the enhanced liming requirement associated with fertilizer use. Other long-term experiments have shown that N fertilization is associated with decreased exchangeable calcium, magnesium, and potassium levels, and lower cation exchange capacity, leading to increased requirements for liming (Liu et al. 1997). The direct relationship of N fertilization with liming requirements, as well as the role of liming in the overall GWI of agricultural systems, was evaluated at KBS and for agricultural row-crop systems in general by Hamilton et al. (2007).

The Biologically Based system also provides greenhouse gas mitigation services. This system uses no N fertilizer and sequesters considerable soil C over the long term (note that no C gains were observed initially; Robertson et al. 2000). However, the moderate grain yields associated with the Biologically Based system reduce its net energy gain (Table 15.2) and raise its greenhouse gas intensity (g CO_2e per unit yield). Low productivity would also be expected to jeopardize profitability, which is a precondition for economic sustainability. The current profitability of the Biologically Based system depends to a considerable extent on a market premium, such as those typically paid for organic products (Chavas et al. 2009, Jolejole 2009).

Overall, the costs and benefits associated with biodiversity and other alternative practices are complex. The interaction of management practice and cropping system diversity is a primary focus of the LFL, discussed in the next section.

Agronomic Insights from the KBS LFL

Productivity

On a global basis, there is a growing requirement for grain for food and livestock feed. The quantity of grain produced is the most important service provided by field crops, and it is a key determinant of profitability on many farms. The type of grain produced and its market price are important, but the foundation to generating profit is sufficient production, and crop species vary in their ability to deliver this. Corn provides a biological advantage over other major grain crops such as soybean and wheat because of its greater efficiency at transforming sunlight into grain. This is shown by a broad-stroke comparison of LFL grain yields on a whole system basis. Figure 15.2 shows that a continuous corn rotation produced 5.7 Mg ha^{-1} yr^{-1} of grain, on average, over 4 years, whereas over the same period a corn–corn–soybean rotation produced 4.6 Mg ha^{-1} yr^{-1} (means for Organic and Integrated Conventional systems). Cumulative grain production over this period was 20.2 Mg ha^{-1} in the Organic one-species system (continuous corn), 17.1 Mg ha^{-1} in the Organic three-species (rotation crop sequence), 25.7 Mg ha^{-1} in the Integrated Conventional one-species system, and 19.7 Mg ha^{-1} in the Integrated Conventional three-species system.

On a whole system basis, the low-diversity continuous corn system produced the most grain. However, a higher market price for soybean and wheat will in many cases compensate for the moderate yield potential of rotated crops compared to corn. This will be especially true in locales without high corn subsides.

Nevertheless, LFL crop diversity enhanced corn grain yield: corn in rotation was almost always associated with higher yields compared to continuous corn (Fig. 15.2). Although diversity imparted via cover crops was not associated with higher corn grain yield in the Integrated Conventional system, a positive trend was observed in the rotated Organic system. No biodiversity effect of cover crops was

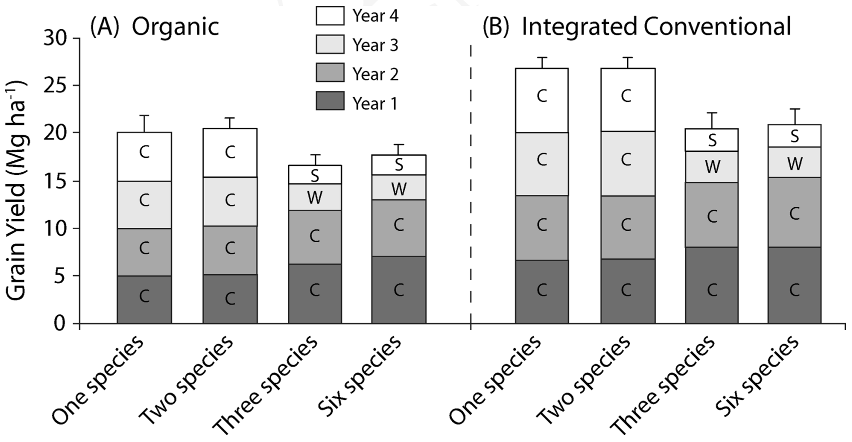

Figure 15.2. Grain yields in the various diversity treatments of the Living Field Lab (means and standard deviations for four replicate plots). A) Annual grain yield average in a four-year rotation sequence under Organic management at the Living Field Lab, where C=corn, W=wheat and S=soybean. The cropping systems include one species (continuous C), two-species (continuous C with a winter annual cover crop), three species (rotated C-C-S-W), and six species (C-C-S-W with winter cover crops red clover, annual ryegrass and crimson clover). B) Annual grain yield average under Integrated Conventional management; cropping systems as described for Organic.

observed in soybean or wheat. The modest effect of biodiversity on corn productivity may have been influenced by N fertilization: species diversity is known to enhance overall productivity in infertile plant communities (Tilman et al., 2001), but would have a minimal effect in a nutrient-enriched environment such as fertilized corn. Also surprisingly, as for corn in the MCSE, diversity had no effect on the variability of grain yield over time: the coefficient of variation over 12 years was 37% in both continuous corn and in the diversified systems for both the Organic and Integrated Conventional systems (Snapp et al. 2010a).

Management other than rotational diversity also influences grain yield. The average grain yield in monoculture corn in the Organic system was 5.0 Mg ha^{-1} yr^{-1}, 22% lower than monoculture corn in the Integrated Conventional system (Snapp et al. 2010a). Similarly, a 22-year European trial showed that organic management was associated with yields ~20% lower than conventional across a range of crop species (Maeder et al. 2002). In the Mid-Atlantic region of the U. S., Cavigelli et al. (2008) documented >30% yield reductions in organic vs. conventionally managed crops. This yield reduction is not surprising, as management intensity and reliance on external inputs are generally associated with high crop yields. In the adjacent MCSE systems, corn grain yields in the Conventional and No-till systems were higher than in the Reduced Input and Biologically Based systems over the period 1989–2007 (Table 15.2), although overall grain yield of the corn–soybean–wheat rotation in the Reduced Input system equaled that of the Conventional system when averaged over 1996–2007 (Table 15.3).

Moderate yield reductions under organic management are typically compensated for by market premiums. A profitability analysis of a long-term trial in Wisconsin showed an 85 to 110% increase in profit for organically managed grain crop systems when organic price premiums were included (Chavas et al. 2009). Jolejole (2009) found a similar result in an analysis of the MCSE systems: the Biologically Based system was more profitable than the Conventional system when assigned premium prices; otherwise, lower yields and higher labor and cover crop costs offset savings in chemical use.

Grain yield in LFL systems varied markedly with year (Snapp et al. 2010a). Under organic management, where N supply is often limiting, the highest corn yield was obtained >58% of the time in the six-species system (with the legumes red clover and crimson clover). Dry summer conditions in lower-yielding years and the well-drained nature of the site may explain why diversity did not support high corn yields in water-deficient years (Snapp et al. 2010a). Weed competition has also been markedly variable over time and may have contributed to a low corn yield response in some years, despite management designed to control weeds (see below; Smith and Gross 2006a).

Soil Carbon and Phosphorus

Soil organic matter and fertility are key supporting services in agriculture. Management and diversity both affected LFL soil resources. Organic management maintained inorganic phosphorus and enhanced soil organic C by 52%, compared to initial values at the onset of the experiment (Table 15.4). Integrated conventional

Table 15.4. Soil characteristics and significant differences by treatment in the Living Field Lab systems.[a]

Management/ Diversity	Soil C Content ($kg\ m^{-2}$)	Total N ($mg\ N\ kg^{-1}$)	C/N Ratio	Phosphorus[a] ($mg\ P\ kg^{-1}$)	Potassium[a] ($mg\ K\ kg^{-1}$)	Calcium[a] ($mg\ Ca\ kg^{-1}$)
Integrated Conventional						
One species	2.7	0.85	9.43	29.8	94.4	1288
Two species	2.8	0.88	9.22	21.9	79.9	972
Three species	2.8	0.90	9.27	25.4	64.5	1074
Six species	3.3	0.94	10.22	28.0	68.1	1126
Organic						
One species	3.9	1.15	11.09	50.9	94.1	1299
Two species	3.9	1.17	9.91	53.4	125.5	1491
Three species	4.1	1.20	10.96	44.1	101.5	1395
Six species	3.7	1.10	11.07	40.7	117.2	1443
Analysis of Variance (ANOVA)	*P*-value					
Management (M)	<0.0001	<0.0001	<0.003	<0.0001	<0.001	0.014
Diversity (D)	NS	NS	NS	0.04	NS	NS
M × D	NS	NS	NS	NS	NS	NS

[a] Soils sampled 0- to 20-cm depth in April 2008. Phosphorus, potassium, and calcium extracted using the Mehlich III method. NS = Not significant ($\alpha = 0.05$).
Source: Adapted from Snapp et al. (2010b).

production, on the other hand, did not maintain soil phosphorus and had almost no discernable effect on soil organic C. Cropping system diversity was not associated with enhanced soil C in the LFL. Processes influencing C sequestration are complex; organic corn rotations have been associated with both declines (Studdert and Echeverria 2000) and accumulations (Russell et al. 2009) of soil C.

Water Quality

Nitrate leaching, an indicator of water quality, was measured in the LFL by installing gravimetric water samplers in cover crop plots. Nitrate loss was pronounced under corn production, primarily in the spring months prior to planting corn (Sánchez et al., 2004; Snapp et al. 2010a). Farmers manage for high soil N availability at the onset of growth, particularly for N-demanding crops such as corn. Soil amended with compost or other N sources that are high in C content (such as cover crop residues) may be an important means for managing N, using temporary immobilization to reduce the spring inorganic N pool (McSwiney et al. 2010). Systems receiving fertilizer N—whether synthetic or organic—require especially careful management during the spring when intense rainfall events and limited plant growth lead to high leaching potential.

The Organic system leached 32 kg NO_3^--N $ha^{-1}\ yr^{-1}$, which was about half as much as the Integrated Conventional system (74 kg NO_3^--N $ha^{-1}\ yr^{-1}$), as shown by gravimetric lysimeters monitored from 1994 to 2000 (Snapp et al. 2010a;

Table 15.3). Organic management relied on compost and cover crops for N supply. These C-rich nutrient sources may have temporarily immobilized inorganic N and reduced N loss. However, immobilization of N can also reduce crop yields, depending on the competitiveness of plant roots for N, and how fast N is turned over during microbial assimilation (Drinkwater and Snapp 2007).

Pest Suppression

The effects of crop rotation and management system (Integrated Conventional vs. Organic) on weed suppression services in the LFL experiment were investigated from 2001 to 2004 (Smith and Gross 2006a). Over that time, and similar to what has been observed in the MCSE (Davis et al. 2005; Gross et al. 2015, Chapter 7 in this volume), weed biomass was more than 10 times higher in the Organic compared to the Integrated Conventional system. In addition to total weed biomass, the composition of the weed community also differed between the two management systems, with smooth crabgrass (*Digitaria ischaemum* [Schreb.] Schreb. ex Muhl.) and Carolina horsenettle (*Solanum carolinense* L.) dominating the Integrated Conventional system, and common ragweed (*Ambrosia artemisiifolia* L.) and common lambsquarters (*Chenopodium album* L.) dominating the Organic system.

In contrast to the overriding influence of management system, crop rotation per se did not affect weed biomass. Crop rotation did, however, interact with management system to affect the interannual variability of the composition and structure of the weed community. Compared to conventionally managed crops and the Organic continuous corn system, weed community composition in the organic rotation was significantly more variable from one year to the next (Smith and Gross 2006a). This result is likely due, in part, to greater annual changes in the composition of weed species added to the seed bank (Smith and Gross 2006b), and suggests that an important regulating ecosystem service that crop rotation and diversification provide is to reduce the likelihood of developing a consistent weed community that is resistant to other weed management practices applied to the cropping system.

Ecosystem Service Trade-offs

As compared to the Integrated Conventional system, reduced inputs in the Organic system resulted in both yield reduction and enhanced ecosystem services in the form of soil C accretion and lower nitrate leaching losses (Table 15.3). To explicitly explore this trade-off, yield reductions in the Organic two-species and six-species systems were calculated relative to yield in the Integrated Conventional two-species system—chosen as a baseline system that followed all recommended integrated practices. We simultaneously evaluated soil C gains and the extent of nitrate leached in the Organic vs. Integrated Conventional systems over a 6-year period. Finally, the yield reduction was expressed in relation to soil C gained and nitrate leaching reduced (Table 15.3).

The Organic system produced 1370 kg ha^{-1} yr^{-1} less grain than the Integrated Conventional system, but resulted in substantial gains in soil C (820 kg ha^{-1} yr^{-1}) and reduced nitrate leaching losses by 42 kg N ha^{-1} yr^{-1} (Table 15.3). Increasing crop diversity in the LFL Organic system did not further improve these biogeochemical benefits (Snapp et al. 2010b).

In the MCSE, the gains in soil C with Biologically Based (Organic) management were higher than those obtained under No-till management (Table 15.3), but less than those associated with set asides or planting a perennial crop (Grandy and Robertson 2007, Piñeiro et al. 2009). The 50% reduction of nitrate leaching in the Organic system at the LFL was a significant achievement.

Designing Sustainable Agricultural Systems

KBS research highlights some of the trade-offs involved in developing row-crop systems that are more sustainable—more profitable, more environmentally benign, and more socially acceptable: in short, those that deliver a more desirable mix of ecosystem services (Robertson and Harwood 2013, Syswerda and Robertson 2014). Evidence from KBS and elsewhere (Robertson et al. 2007; Snapp et al. 2010a, b) shows that all services cannot be maximized simultaneously in agricultural systems; consequently, it is necessary to set priorities. Presently, priorities are set largely by markets and government policies that incentivize production and allow environmental costs to be externalized to society as a whole. Understanding trade-offs, especially with respect to yields, is an essential first step for incentivizing additional services. To the extent that most farmers' first priority is staying in business (Swinton et al. 2015b, Chapter 13 in this volume), the cost of providing any service that reduces farm profitability must be borne by society. This is particularly true for those services perceived primarily as a public good—greenhouse gas mitigation and water quality, for example. For services perceived to have local value—soil C storage as it affects soil fertility and crop diversity as it affects pest suppression, for example—costs are more willingly borne by the farmers (Swinton et al. 2015b, Chapter 13 in this volume). For example, biologically based row-crop management is shown at KBS LTER to improve soil C storage and water quality, but at the expense of reduced yields in cereals. Making up the yield difference represents the cost of providing these services.

The relationships between yield and other ecosystem services are complex. Management practices are commonly bundled within systems, so it can be difficult to prescribe one practice alone. In the MCSE No-till system, for example, the benefits of low soil disturbance come with a need for greater herbicide use. Within the Reduced Input and Biologically Based systems, the duration of living plant cover is high, providing water quality and soil C benefits, but soil disturbance is also high. These systems also have enhanced rotational diversity that promotes biological N fixation, reducing the requirement for N fertilizer inputs, but more fossil fuel is required to plow under the cover crop, kill weeds, and enhance residue contact with soil to promote the mineralization and release of nutrients in concert with crop demand.

Conservation Agriculture

Conservation agriculture is a broad term that considers many of the system design principles evaluated here (Govaerts et al. 2009). This management approach shifts the emphasis from conservation tillage practices to principles-based management that emphasizes: (1) reduction in tillage to ensure disturbance remains below a set percentage, (2) sufficient retention of residues to provide cover and protect soil from erosive forces, and (3) diversified crop rotations that mitigate against pest problems and ensure a mixture of residue qualities and heterogeneous root system inputs belowground.

The success of permanent no-till management at the MCSE is illustrated by the No-till system's high grain yields (~8% more than Conventional management) and soil C gains (Table 15.3). It is notable that no-till was implemented with no increase in fertilizer N inputs and only a modest increase in herbicide inputs compared to conventional management. Energy inputs are substantially lower with reduced reliance on tillage (e.g., 4.9 GJ ha^{-1} yr^{-1} in the MCSE No-till system compared to 7.1 GJ ha^{-1} yr^{-1} in the Conventional system, Table 15.2), despite modest increases in herbicide use in No-till. Declining fossil fuel supplies and high energy costs are important arguments for the adoption of conservation tillage equipment and practices.

Published studies that have evaluated crop diversification and conservation tillage have shown that only the combination of rotational diversity and reduced tillage is an effective means to enhance soil C and N over the long term (West and Post 2002, Govaerts et al. 2009). Overall, the MCSE showed that permanent no-till management of a corn–soybean–wheat rotation was an effective means to modestly improve a broad range of ecosystem services. It is important to note that this was the only alternative practice that enhanced grain yield relative to conventional management, which may in large part explain the broad adoption of conservation tillage practices. The reduction in number of field operations, leading to reduced fuel and time requirements, may also play a significant role in farmer adoption. However, adoption has not been universal nor, where it has been adopted, is it usually permanent (Horowitz et al. 2010). This is particularly so among farmers who produce on heavy (clayey) soils, or without ready access to herbicides. Another constraint to continued and future adoption of no-till is the increasing number of weed species that are evolving resistance to the primary herbicides used in no-till cropping systems (i.e., glyphosate), which threaten to reduce the longer-term viability of no-till production practices (Johnson et al. 2009) or increase the use of older herbicide chemistries that have greater potential for nontarget impacts and ecosystem disservices (Mortensen et al. 2012).

A first step in promoting conservation agriculture might include improved knowledge about farmer adoption of management practices such as tillage and extended cover. Policies that support innovative conservation practices might include instruments that mitigate risk associated with adoption and adaptive research—these could go far toward enhancing the adoption of conservation agriculture (Feinerman et al. 1992). Innovative research will be required to support adoption by organic farmers and smallholder farmers in developing countries, groups that have thus far been left behind by the conservation agriculture movement (Giller et al. 2009). Long-term research on different types of conservation practices, and associated ecosystem services, is also urgently required. There is a tremendous variety of tillage equipment and integrated practices that can be pursued in combination with manure, cover crops, and rotational crop sequences; all are expected to influence the ecosystem services that are generated.

Organic Agriculture

The principles of organic (biologically based) management are closely aligned with a "semi-closed" system that mainly relies on biological processes to regenerate soil resources and support the growth of healthy plants and animals (Pearson 2007). The duration and diversity of active plant growth and the synchronization of N availability with plant N demand are important features of biologically based management. Following these principles in the MCSE Biologically Based system resulted in enhanced biological N fixation (almost 2-fold higher than in the Conventional system, Fig. 15.1) and soil C gains (25% more than in the Conventional system) that were slow to accrue but occurred in spite of more frequent soil disturbance. Evidence also exists that available soil P has been maintained despite low P inputs (Fig. 15.1). Energy inputs were low in the Biologically Based system compared to Conventional (4.8 GJ ha^{-1} yr^{-1} vs. 7.1 GJ ha^{-1} yr^{-1} in Conventional, Table 15.2). Biologically based crops used no fossil fuel–derived agrochemicals other than fuel for field operations, so total farming energy inputs were equivalent to those of the No-till system.

The yield reductions of cereals observed in the Biologically Based system could be considered a worthwhile trade-off for enhanced ecosystem services, although yield trade-off estimates for nitrate leaching and soil C sequestration in the MCSE indicate that gains in those ecosystem services are negated by the loss in yield (Table 15.3). There are also additional costs incurred for this system and for the Reduced Input system, including labor, tillage, and cover crop establishment, offset somewhat by the lower costs associated with reduced pesticide and fertilizer use. The energy balance conducted for the MCSE systems reflects the lower yield of cereals and net change in inputs associated with the Biologically Based system (Table 15.2).

A significant challenge associated with biologically based management is the labor and land investment in growing cover crops that fix N and build soil C (Drinkwater and Snapp 2007). Not only does this incur seed and management costs for a plant that provides little or no cash value, it also involves opportunity costs. That is, planting diverse crops can infringe on the window of time and resources required to grow higher value crops. For example, cover crops enhance ecosystem services by providing soil cover and active rooting throughout the year. However, planting a summer cash crop is necessarily delayed by the need to first kill and plow under the cover crop. It is also important to allow cover crop residues time to decompose, and the result is an even later planting window. This reduces the length of the growing season, and may require planting shorter season varieties that can have lower yields. This is one likely cause of the lower corn and wheat yields observed in the MCSE Reduced Input and Biologically Based systems.

Opportunity costs are particularly acute challenges for farmers operating in short growing season environments, such as the temperate U.S. Great Lakes region and unimodal rainfall systems in other parts of the world. Farmers have developed systems that maximize use of the biophysical environment (e.g., light, temperature, and moisture) to produce marketable crops. In locations where there is a longer growing season, such as in the southeastern United States, farmers develop double cropping systems with two cash crops per season, rather than following a cash crop with a biology-promoting cover crop (Cavigelli et al. 2008). This reflects the reward structure of current policies, and indeed is a requirement for farm survival in many socioeconomic environments. Overall, the costs and benefits associated with biodiversity are complex and interact with management practices.

Organic row-crop production makes up a very small proportion of midwestern agriculture, but organic acreage is increasing rapidly, even in the absence of policy support for broader adoption (Dimitri and Greene 2002). This would seem to suggest that organic row crops could be promoted in the United States without radically altering policy instruments or incentives. However, we note that as the supply of organic products increases, prices are expected to decline, reducing the premium that now compensates for lower yields.

On the other hand, the Reduced Input system has yields much closer to Conventional, and shares most of the environmental benefits of the Biologically Based system. Cropping systems based on the substitution of biological management for most rather than all chemical inputs could be an attractive hybrid system that optimizes yield and services. Such a system could be widely adopted with proper incentives for farmers' providing desirable services.

Perennial Vegetation

The cumulative effect of perennial vegetation in agroecosystems is dramatic, particularly belowground. In a Russian study, substantial soil C gains to 2 m were observed in grassland and forage systems compared to annual cropping systems (Mikhailova et al. 2000). Perennial legume and grass plantings have been shown to improve soil organic C by 35 to 58% compared to annuals (Bremer et al. 1994), which is comparable to the 45% increase in soil C we observed in our MCSE continuous Alfalfa system (Fig. 15.1).

Nitrogen leaching losses in perennial vegetation vary, influenced by species growth patterns and the importance of biological N fixation. Farming system management is also important, including reactive N inputs and harvest operations. In the MCSE Early Successional community, very low levels of inorganic N have been observed in soil, which is consistent with tight N cycling (Robertson et al. 2000). Alfalfa is intensively managed compared to this Early Successional system, with biomass harvested three times per year, on average, and lime and fertilizers other than N are applied as needed. Nitrogen leaching from the alfalfa system was lower than from any of the annual cropping systems (Syswerda et al. 2012), as has been shown in other shorter-term studies (Randall et al. 1997) despite high levels of biological N fixation. Nitrous oxide production, on the other hand, was as high from the Alfalfa system as from any of the annual cropping systems (Gelfand and Robertson 2015, Chapter 12 in this volume, Millar and Robertson 2015, Chapter 9 in this volume). Randall and colleagues proposed alfalfa plantings as a means to reduce tile drainage nitrate pollution across the U.S. Midwest. A review by Ledgard (2001) found that grazed grassland-legume mixed systems, with minimal fertilizer inputs, were associated with modest N losses from denitrification (6 kg N ha^{-1}) and leaching (23 kg N ha^{-1}).

Generally, perennial crops are confined to marginal farming areas with steep terrain, variable topography, or shallow, infertile soils. In the Midwest—and throughout temperate agricultural regions—alfalfa is the most important perennial crop. In southwest Michigan alfalfa has been grown on ~15% of agricultural land since the 1930s (Sylvester and Gutman 2008). This is presumably due to the species' high-quality residues and high productivity, together with access to ready markets provided by the state's dairy industry. Alfalfa is adapted to a broad range of environments, and there are varieties that can be grown under intensive irrigated and fertilized management.

Perennial vegetation is currently the fastest means for capturing C and reducing farm nitrate losses on a significant scale, and it thus could profoundly improve the delivery of ecosystem services generated from agriculture. Perennial crops grown for cellulosic biofuel on lands now not suited for food crops offer a major opportunity for agriculture to contribute to climate stabilization, soil and N conservation, pest suppression, and other ecosystem services including societal benefits such as national fuel security (Robertson et al. 2008, 2011). Planting perennial forages on land now used for food crops would also provide benefits, but promoting this for broad adaption would require radical changes in agricultural policies and marketing systems.

Cover crop integration is a small step in the direction of perennializing grain crops, and cover crop use could be promoted with existing agricultural policy instruments. An example of wide-scale cover crop adoption is available from the south of Sweden where row-crop farmers were paid to grow cover crops, resulting in a reduction of nitrate leaching (Kirchmann et al. 2002). Another way forward may be to develop grains such as wheat or sorghum that have a perennial life cycle (DeHaan et al. 2005, Glover et al. 2010). Both of these approaches to perennialization deserve support through agricultural policies that promote cover crop integration for incremental improvements in existing systems and research to develop a portfolio of perennial crops that could help to further diversify rural landscapes.

Summary

Row crops can be managed to deliver ecosystem services in addition to yield. KBS LTER results illustrate the delivery of services by current farming systems as well as the principles that can be used to design future systems to enhance the delivery of these and other services. Documented services other than yield include (1) soil C accretion with its positive effects on soil fertility, water-holding capacity, and climate stabilization; (2) nitrate conservation that improves water quality by reducing leaching of nitrate into ground and surface waters; (3) greenhouse gas mitigation including N_2O abatement and lower CO_2 emissions; (4) energy efficiency that saves fuel; and (5) pest suppression that reduces pesticide use.

No current agricultural system can maximize the delivery of all services—almost always the delivery of one service affects the potential delivery of others. Thus, trade-offs must be considered. The most important trade-off for farmers is profitability—the opportunity cost of providing a particular service. No-till management, for example, builds soil C, reduces fuel use, and reduces nitrate leaching, but it can compress the spring planting period and requires specialized equipment. Biologically based management conserves nitrogen, builds soil C, and reduces pesticide loading, but it has associated costs of timely labor requirements and yield reductions not recoverable without the price premiums provided by organic certification.

Key findings from over 20 years of KBS LTER row-crop research on ecosystem services include:

1. Crop (rotational) diversity—planting legumes, in particular—provides enhanced opportunities for biological N fixation and pest regulation.
2. Planting a forage or cover crop makes an annual row-crop system more perennial. Such plantings extend the duration of living cover, support soil C sequestration, reduce N losses, and can lower reliance on chemical inputs.
3. Reducing soil disturbance through conservation tillage enhances soil C sequestration, energy efficiency, and crop yield.

Economic trade-offs were also documented:

1. Compared with conventional crop management, direct costs associated with alternative management practices depend on requirements for extra inputs, labor, and associated costs, as well as any reduction in requirements for chemical inputs.
2. Indirect opportunity costs associated with cover crops include allowing time for biological decomposition to occur, which often requires late plantings of cash crops after cover crops, with associated yield penalties, particularly for corn.
3. Diversification is associated with lower production where moderate-yield crops or cover crops are substituted for high-yield crops such as corn, although economic returns can still be high from moderate-yield crops depending on product prices.

In summary, organic and reduced input management systems deliver more ecosystem services (Table 15.3). However, there is an apparent yield penalty, as shown for organic-managed corn relative to conventional in both the LFL and MCSE. In contrast, conservation tillage is consistently associated with high corn yields relative to conventional management. Further, biologically based soybean yields were consistently high. A simplistic approach to evaluating the yield trade-offs of environmental services provided by these management systems is to examine yield trends over time relative to annual estimates of soil C gain and nitrate leaching

(Table 15.3). In doing so, we find that nitrate leaching can be reduced substantially, albeit with a yield penalty for organic crops, or no penalty in the case of No-till and Reduced Input. Other disservices such as herbicide leaching have not been evaluated here. Given the suite of services considered, no-till is attractive—providing gains in crop yields in conjunction with soil C sequestration and reductions in nitrate leaching. However, the environmental services obtained from no-till are not in themselves sufficient to maximize services and minimize disservices from agriculture. Fine-tuning of N fertilizer application to take into account N fixation and other N inputs is also a promising approach that has many environmental advantages. Adopting a stepwise process would involve initial reliance on N fertilizer adjustments and conservation tillage, followed by more transformative types of alternative management that rely on the principles of diversity and perenniality.

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