Agriculture, Ecosystems and Environment 189 (2014) 28–35

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Ecosystem services along a management gradient in Michigan (USA) cropping systems

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ARTICLE INFO

Article history:
Received 11 March 2013
Received in revised form 28 February 2014
Accepted 3 March 2014

Keywords:
Ecosystem service
Climate change
Nitrate leaching
Organic agriculture
No-till
Diversity

ABSTRACT

To assess tradeoffs and synergies among different services provided by major ecosystems in agricultural landscapes, we examined agricultural yield, aboveground net primary productivity, global warming impact, soil quality, water conservation, water quality, and plant diversity in eight replicated ecosystems along a management intensity gradient on the same soil type in SW Michigan, USA. Ecosystems included four annual grain systems in a maize–soybean–wheat rotation, two perennial crops (alfalfa and hybrid poplar trees), an early successional community, and a late-successional deciduous forest. The annual grain systems included tilled and no-till treatments both managed with conventional chemical inputs; and reduced input and biologically based treatments both managed with tillage for weed control and leguminous winter cover crops for nitrogen. Radar diagrams illustrated the suite of services provided by each system. We found 13 significant interactions between ecosystem service indicators, seven being positive and six negative. Numerous trade-offs with grain yield were found, suggesting that by focusing on grain yield in these systems, land managers may be neglecting other ecosystem services. Management of nitrogen fertilizer, cover crops, and tillage (no-till) were particularly important determinants for the delivery of multiple ecosystem services.

1. Introduction

Understanding interactions among the services provided by agricultural systems requires understanding patterns and the individual trade-offs that occur when the delivery of one service is affected by the delivery of another. While it may be straightforward to assess trade-offs between two ecosystem services, it is more difficult to evaluate trade-offs among multiple services (Foley et al., 2005; Power, 2010). Trade-off curves (Antle and Valdivia, 2006; Stoorvogel et al., 2004) describe relationships between pairs of sustainability indicators.

Here we examine tradeoffs among several important ecosystem services in row crop agriculture in order to provide better knowledge for policy and farm level decision making. We use eight indicators to indicate the strength of ecosystem service delivery in our comparative ecosystems. Among them are (1) grain yield, to indicate the delivery of food and economic benefits; (2) drainage to indicate the delivery of regulating services related to flood control, groundwater discharge, and erosion avoidance; (3) global warming impact to indicate the delivery of climate mitigation services; (4) plant diversity to indicate the delivery of biological control, arthropod habitat, and other conservation benefits; (5) soil carbon to indicate services related to soil fertility, soil microbe and invertebrate habitat, filtration, and soil structure; (6) soil water content to indicate services related to soil water availability; (7) nitrate leaching to indicate services related to nitrogen conservation, nutrient mobility, and water quality in general; and (8) aboveground net primary productivity, as a supporting service, to indicate the overall function of the ecosystem.

Our overall objective is to investigate how agricultural systems can be managed to minimize the environmental impact of agriculture without sacrificing productivity—or conversely, to maximize the ecosystem services provided by agriculture, including productivity.

2. Material and methods

We compared ecosystem services from a field experiment that was established at the Kellogg Biological Station (KBS) in 1988 (Robertson and Hamilton, 2014). Multiple treatments

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Abbreviations: KBS, Kellogg Biological Station; LTER, Long-Term Ecological Research.

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http://dx.doi.org/10.1016/j.agee.2014.03.006
0167-8809/

Table 1
Management summary for the Kellogg Biological Station Long Term Ecological Research Site (KBS LTER).

	Tillage	Nitrogen fertilizer*	Weed control
Annual crops (maize, soybean, wheat rotation)			
Conventional	Conventional	Conventional	Chemical and mechanical
No-till	None	Conventional	Chemical
Reduced input	Conventional	1/3 Conventional with cover crop	1/3 Chemical and mechanical
Biologically based (organic)	Conventional	Cover crop	Mechanical
Perennial crops			
Alfalfa	None	None	None
Poplar	None	Starter[a]	None
Unmanaged communities			
Early successional	None	None	None
Deciduous forest	None	None	None

* Conventional refers to the recommended rate based on soil testing and best management practices.

[a] 60 kg N ha^{-1} in 1989 only.

at the KBS Long-Term Ecological Research (LTER) Site (www.lter.kbs.msu.edu) Main Cropping System Experiment form a management intensity gradient that is well suited to ecosystem comparisons. Kellogg Biological Station is located in SW Michigan, within the northern boundary of the U.S. corn belt (85° 24′W, 42° 24′N). The site lies on intermixed Kalamazoo (fine loamy) and Oshtemo (coarse loamy) soils, both mixed, mesic Typic Hapludalfs that mainly differ in the thickness of the Bt horizon. Annual rainfall at KBS is 1027 mm y^{-1}, is lowest in the winter (17%), and otherwise distributed evenly through the year (Robertson and Hamilton, 2014).

Seven of the eight experimental systems were established in 1989 in replicated 1-ha plots organized in a complete block design ($n = 6$ blocks), and additional offsite native deciduous forest sites on the same soil series were added in 1991 ($n = 3$ sites, see Table 1). Cropping systems included four maize (*Zea mays*)-soybean (*Glycine max*)-winter wheat (*Triticum aestivum*) rotations managed either (i) with conventional inputs and tillage, (ii) with conventional inputs and no tillage, (iii) with reduced chemical inputs and tillage, or (iv) biologically based (USDA certified organic) with no chemical inputs and tillage. The latter two treatments included a leguminous winter cover crop following the maize and wheat portions of the rotation to provide nitrogen (N) to the following grain crops. All cropping systems were planted and harvested during the same periods. Fertilizer application rates for the conventional input systems were based on soil-test recommendations. No manure or compost was added to any system.

Since 1993, all four of the annual grain crops have been in a maize–soybean–wheat rotation. The conventional, reduced input, and biologically based systems received primary tillage, which consisted of moldboard plowing in the spring from 1989 to 1998 and chisel plowing in the spring from 1999 onward. Secondary tillage consisted of disking before wheat planting, field conditioning with a soil finisher prior to soybean and maize planting, and inter-row cultivation for soybean and maize. The reduced input system received one-third of the N fertilizer and herbicide inputs applied to the conventional system; N fertilizer in this system was provided at reduced rates to supplement the N provided by legumes in the rotation, and herbicides were banded within rows rather than broadcast within and between rows as in the conventional and no-till systems. The reduced input and biologically based systems received additional inter-row cultivation and rotary hoeing as needed for weed control. Neither manure or compost nor insecticides were applied to any of the annual cropping systems during the course of this study.

The two perennial systems included alfalfa (*Medicago sativa*) and fast growing clonal poplar [*Populus deltoides* × *P. nigra*]. The alfalfa was harvested three to four times a year, and was re-established once during the study period. Fertilizer (P, K, B, and lime) and pesticides were applied according to Michigan State University Extension recommendations and soil test results. Insecticides were applied once to control a leafhopper (*Cicadellidae*) outbreak. Poplar trees were planted in 1989, with one starter fertilizer, creeping red fescue (*Festuca rubra*) being used as a cover crop to prevent soil erosion. Poplar trees were harvested in winter 1999, and allowed to coppice (regrow from the cut stems) the following spring.

The unmanaged systems included an early successional system that was abandoned from agriculture in 1989 when the Main Cropping System Experiment was established ($n = 6$) and a forest system that was added in 1991 ($n = 3$). The forest was a mature oak (*Quercus rubra*)-hickory (*Carya glabra*) forest; two of the replicate forest stands have never been logged and one was cut ca. 1900 and allowed to regrow; none have been plowed or cropped. The early successional system has been burned annually since 1997 to prevent tree colonization.

2.1. Nitrate leaching and drainage

We sampled all systems for 11 years (1996–2007) following an establishment period of seven years. Soil water draining from all eight ecosystems was sampled using quartz/PTFE tension samplers (Prenart, Fredriksburg, Denmark) installed in 1995. Three soil water samplers were installed in each of three replicate blocks of each ecosystem for a total of 72 samplers (eight ecosystems × three blocks × three samplers) as described in Syswerda et al. (2012). All samplers were installed at a depth of 1.2 m, approximately 20 cm into the unconsolidated sand of the 2Bt2 and 2E/Bt horizons. Samples were collected every two weeks April through October and monthly otherwise, except when freezing temperatures prevented sample collection. Stored samples were thawed and analyzed colorimetrically for nitrate on a continuous flow analyzer (OI Analytical, College Station, Texas) with a detection limit of 0.02 mg N L^{-1} for nitrate. All samples that were found to be below detection limits were recorded as half the detection limit, which did not change any statistical differences between treatments but was considered a more conservative estimate.

Nitrate concentrations were combined with modeled downward water drainage to provide estimates of nitrate leaching from the root zone. Water drainage was modeled using the Systems Approach for Land Use Sustainability (SALUS) model (Basso et al., 2006). SALUS is comprised of two plant growth modules, a simple module where growth and development are based on an input LAI curve and a thermal time calculation, and a complex module where crop growth and development are based on genetic characteristics of the species, radiation use efficiency, and thermal time. Both modules accommodate various crop rotations, planting dates, plant populations, irrigation, fertilizer applications, and tillage practices, and simulate plant growth and soil conditions every day during growing seasons and fallow periods. SALUS simulated the systems evaluated in this study using the simple module for forest and successional communities and the complex module for the annual crops and alfalfa.

The SALUS water balance submodel considers surface runoff, infiltration, surface evaporation, saturated and unsaturated water flow, drainage, root water uptake, soil evaporation and transpiration (Ritchie, 1998). The soil water balance module is based on that used in the CERES models (Ritchie and Basso, 2008) but incorporates a major revision for calculating infiltration, soil water drainage (Suleiman and Ritchie, 2004), evaporation (Suleiman and Ritchie, 2003), and runoff. We combined measured nitrate concentration data with each system's modeled water drainage to estimate total nitrate loss over the period 1996–2007. We modeled water drainage rates on a daily time step and interpolated daily nitrate concentrations between soil water sampling dates. Multiplying daily water drainage by interpolated nitrate-N concentrations provided daily nitrate-N loss in kg ha^{-1} at the 120 cm sampling depth.

2.2. *Soil carbon and C/N ratios*

Soil samples from all sites were taken sequentially by replicate from 31 May to 19 Oct. 2001 with a hydraulic sampler (Geoprobe, Salina, KS) that collected 6-cm diam. intact cores to a 1-m depth as described in Syswerda et al. (2011). Two cores were taken at each of five long-term sampling stations within each replicate plot, for a total of 60 cores per treatment in the annual grain, alfalfa, poplar, and early successional systems; and 30 in the deciduous forest treatment. Each core was analyzed for carbon (C) and N using a Carlo Erba NA1500 Series II C N Analyzer (Carlo-Erba Instruments, Milan, Italy). For all analytical replicates the coefficient of variation (CV) was 0.05; triplicate samples that exceeded 0.05 CV were reanalyzed. We used for soil calibration the standards O519 and O559 provided by USDA-ARS, Pendleton, OR.

2.3. *Global warming impact*

The global warming impact was calculated from 1989 to 2009 by combining the net global warming impact of soil C sequestration, agronomic N fertilizer application, lime application, fuel usage, nitrous oxide (N_2O) emissions, and methane (CH_4) oxidation for each of the systems, as described in detail in Gelfand et al. (2013). N_2O and CH_4 flux measurements were made using a static chamber approach (Livingston and Hutchinson, 1995) at weekly to monthly intervals during portions of the year when soils were not frozen. Chamber lids were placed on aluminum bases removed only for cropping activities; accumulated headspace was then sampled four times over the following 120 min. Collected samples were analyzed in the laboratory for N_2O and CH_4; flux for each chamber was calculated as the linear portion of the gas accumulation curve for that chamber. Single chambers were located in each ecosystem replicate (eight ecosystems × three to four replicate sites) except duplicate chambers were located in each of the three forests. All chambers were sampled on the same date, although not all sites were sampled each year. Due to cost constraints the low-input, alfalfa, and poplar systems were not sampled in 1998.

N_2O and CH_4 were analyzed by gas chromatography using Porapak QS columns in an 80 °C oven. N_2O was detected by electron capture (ECD), CH_4 by flame ionization (FID). Prior to analysis samples were stored over-pressurized in 3 mL crimp-top vials.

2.4. *Aboveground net primary productivity, plant diversity, and grain yields*

For each system, plant diversity as species richness was compiled from the same sampling regime as was used for aboveground net primary productivity, with all plant species counted in each replicate plot each year from 1991 to 2012. All systems were sampled for Aboveground Net Primary Productivity (ANPP) from 1996 to 2007, with samples divided and measured by species. Additionally, the annual cropping systems were sampled for grain yields. Grain yield was measured by plot using a John Deere 9410 combine with a Greenstar yield monitor (John Deere International, York, NE) as well as by hand harvesting. Hand harvesting for ANPP and species diversity was performed at five sampling stations in each plot by harvesting all the above ground portion of plants that were rooted within the bounds of a harvest quadrat (1 m^2 area). Plant biomass was then dried at 60 °C for at least 48 h and weighed. Crops were hand harvested at physiological maturity: for maize during black layer (early September), for soybeans during pre-leaf drop (early September), and for wheat when kernels entered dough stage (mid-July). The tissue was then threshed (Almaco corn or small grain thresher, Nevada, IA) to separate the seed from stover. Seed biomass was recorded and moisture subsampled using a Burrows Digital Moisture Computer 700 (Burrow Equipment, Evanston, IL). Seed and stover tissue subsamples were combined over stations by tissue type, and stored for further analysis.

Alfalfa was harvested three to four times per year, and five 1 m^2 samples per experimental plot were hand harvested to determine yield. Poplar trees were harvested by clear cut in January 1999 and 2007, and the total woody biomass in each 1 ha plot chipped and weighed. Litter fall was collected in traps placed on the ground throughout the period when leaves were falling. Traps were emptied, dried, and composited by plot over the season. Non-woody vegetation was hand harvested from at least two 1 m^2 sample areas per experimental plot at peak biomass in September or October.

Vegetation in the early successional system was hand harvested from five 1 m^2 sample areas per experimental plot at peak biomass in September. The deciduous forest annual woody growth increment was estimated by changes in stem diameter for all trees within the plot area within each of the three stands. Diameters were measured at three locations per tree to estimate individual tree mass based on allometric equations available in Tritton and Hornbeck (1982). Leaf litter was collected in litter traps placed on the forest floor throughout the period when leaves were falling. Traps were emptied, dried, and composited by plot over the season.

2.5. *Soil water content*

Soil was collected every two weeks when the ground was not frozen, and a 40 g subsample was taken from the composite soil sample of each plot. This subsample was weighed and then oven dried at 60 °C for 48 h. After drying the sample was reweighed. For the present study we used soil water content measurements taken during July, the most water limited part of the growing season.

2.6. *Data analysis and statistics*

Correlation analysis was used for each combination of ecosystem services in order to assess the degree to which there is a relationship between the provision of one ecosystem service and another. Each system was also represented with its own radar plot of ecosystem services. We constructed a diagram for each of the management systems using information for each measured indicator as a way to compare systems. The relative size of each axis denoted the proportional delivery of the group of services each indicator represents.

The experiment was analyzed as a completely randomized design (CRD) with eight treatments and three to six replicates of each treatment for each ecosystem service. Comparisons were completed using SAS (SAS Version 9.2, SAS Institute 2008). Levels of individual services were compared using PROC MIXED, and correlation analyses were performed using PROC CORR.

3. Results

Soil carbon levels to 1 m depth ranged from 6.5 (±0.8) kg C m^{-2} in the reduced input to 10.4 (±1.5) kg C m^{-2} in the alfalfa system (Table 2). Soil C/N ratios in the A/Ap horizon also showed a wide range of values, from 9.4 (±0.2) in the alfalfa system to 12.4 (±0.4) in the deciduous forest. Soil gravimetric water content in July was highest in the deciduous forest, no-till, and poplar systems, with 0.14, 0.13, and 0.13 g water g^{-1} soil, respectively. Average July soil water content was lowest in the conventional and early successional systems, at 0.11 and 0.11 g water g^{-1} soil, respectively.

Nitrate leaching levels varied widely across the treatments, with the highest leaching in the conventional system (62.2 ± 9.4 kg NO_3^-–N ha^{-1} y^{-1}) and the lowest levels in the poplar system (0.1 ± 0.0 kg NO_3^-–N ha^{-1} y^{-1}). All the annual systems had significantly different leaching levels, with the biologically based leaching the least nitrate (19.2 ± 0.8 kg NO_3^-–N ha^{-1} y^{-1}).

Drainage was highest in the no-till system (412 mm y^{-1}). Intermediate levels of drainage were seen in the conventional system and deciduous forest. The lowest levels were seen among the reduced input and biologically based annual systems as well as the alfalfa, poplar, and early successional systems.

Global warming impacts differed substantially by management. Negative values indicated net climate change mitigation potential, and the early successional system showed the largest potential for climate change mitigation with −387 g CO_2e m^{-2} y^{-1}. The conventional and poplar systems were the largest net emitters, with 82 g CO_2e m^{-2} y^{-1}.

Grain yield was highest in the no-till system (3.85 ± 0.07 t ha^{-1} y^{-1}) and lowest in the biologically based system (2.76 ± 0.10 t ha^{-1} y^{-1}). The no-till system had particularly higher yields during the corn years of the rotation. Average annual net primary productivity was lowest in the alfalfa (7.2 ± 0.1 t ha^{-1} y^{-1}) and highest in the deciduous forest system (10.8 ± 1.2 t ha^{-1} y^{-1}).

Plant diversity, measured as species richness, was highest in the early successional system (112.8 ± 2.9 species), and lowest in the conventional system (38.8 ± 2.3 species). The biologically based system had the highest plant species richness (83.8 ± 1.7 species) of all the annual systems, and the alfalfa had the highest plant species richness of the perennial systems (102.3 ± 1.9 species).

Radar plots of ecosystem services were created for each system (Figs. 1 and 2). A complete axis represented the maximum ecosystem service provisioning possible at our site, while a smaller portion represented a decrease in ecosystem service provisioning relative to that service as delivered by another ecosystem.

Significant correlations between several ecosystem services were identified (Table 3, Fig. 3). Soil C was negatively

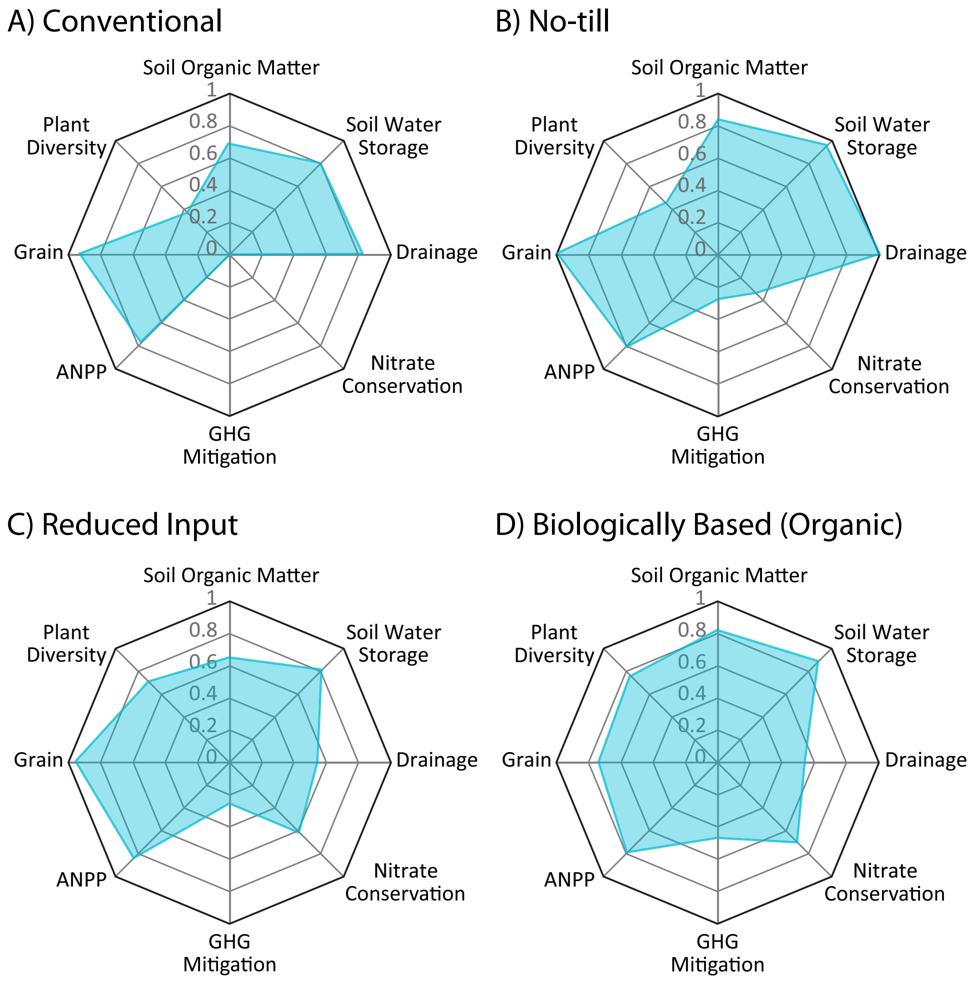

Fig. 1. Ecosystem service indicators for conventional, no-till, reduced input, and biologically based (USDA certified organic) systems of the KBS LTER site. The axes are (from the top clockwise): soil organic matter (soil C), soil water storage (soil water content in July), drainage, nitrate conservation (the inverse of nitrate leaching), greenhouse gas (GHG) mitigation (the inverse of global warming impact), annual net primary productivity (ANPP), grain yield, and plant diversity. Values are relative to maximum values for each service observed in our study.

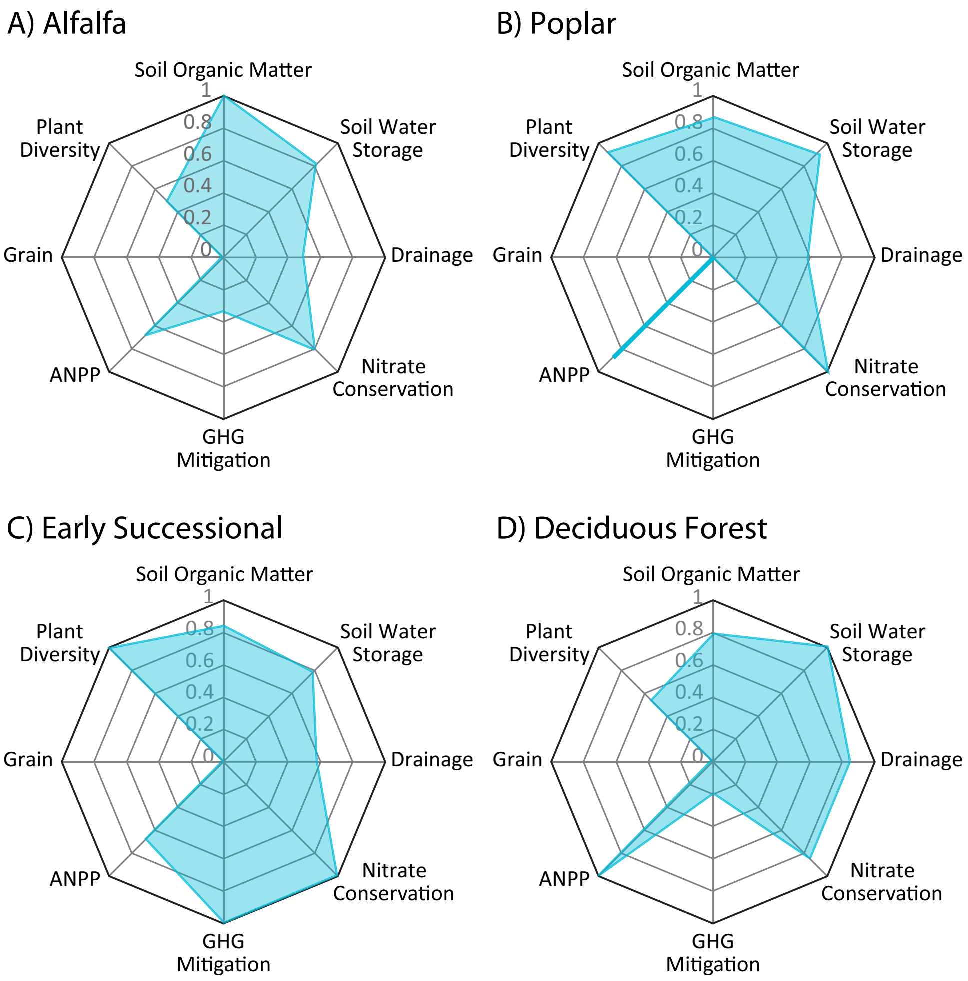

Fig. 2. Ecosystem services provided by alfalfa, poplar, early successional, and deciduous forest systems. See Fig. 1 legend for further information.

correlated with nitrate leaching. Soil water content was positively correlated with annual net primary productivity. Drainage was positively correlated with nitrate leaching and grain yield, and negatively correlated with plant diversity. Nitrate leaching was positively correlated with drainage and grain yield and negatively correlated with soil C and plant diversity. Global warming impact was positively correlated with nitrate leaching, annual net primary productivity, and grain yield, and negatively correlated with plant diversity. Annual net primary productivity was positively correlated with soil water content and global warming impact, and negatively correlated with plant diversity. Grain yield was positively correlated with drainage, nitrate leaching, and global warming impact, and negatively correlated with plant diversity. Plant diversity was negatively correlated with drainage, nitrate leaching, global warming impact, annual net primary productivity, and grain yield.

4. Discussion

Ecosystems along our management intensity gradient varied markedly in their delivery of ecosystem services, even within broad community types such as grain-based row crops or successional communities. Within row crops, for example, management caused large differences in the capacity of each system to deliver enhanced soil quality, climate regulation, groundwater recharge, plant diversity, and grain yield, even with similar levels of annual net primary productivity. Among the annual systems, nitrate leaching was largely reduced by switching to reduced input or biologically based management, likely due to the lower inputs of N in these systems. The no-till, reduced input, and biologically based systems also showed large reductions in global warming impact compared to the conventional system, due to a combination of improved soil C levels and reduced inputs in these systems. The annual systems also showed a marked increase in plant species richness under the reduced-input and biologically based systems, due in part to the use of cover crops and in part to reduced herbicide use, which led to greater weed populations and diversity. Grain production was highest in the no-till system, likely due to higher soil water contents in July relative to the conventional tillage system, and lowest in the biologically based system, likely due to nitrogen limitation.

The perennial crops excelled at the delivery of water quality protection, due to a combination of low N fertilization and lower drainage (higher transpiration). While alfalfa fixes atmospheric N, nitrate concentrations in the soil water of alfalfa were generally very low compared to those in the annual cropping systems. The poplar had the lowest nitrate leaching levels of any of the systems, due to the lack of N fixation and low fertilization rates. The alfalfa had the highest soil C contents of any of the systems and as well had one of the highest levels of plant species richness.

The early successional system delivered improved global warming impact and nitrate leaching, and provided the highest plant diversity of any of the systems we studied. The deciduous forest provided improvements in nitrate leaching, drainage, and soil water content relative to the annual systems. The deciduous forest

Table 2
Ecosystem services in KBS LTER systems. Values are means (standard error).

Treatment	Soil quality			Water quality		Climate regulation	Plant diversity	Productivity	
	Soil carbon to 1 m[a]	Soil C/N ratio in Ap horizon[a]	Soil water content[b]	Nitrate leaching[c]	Drain[d]	Global warming impact[e]	Species richness[f]	Annual net primary productivity[g]	Grain yield[g]
	kg C m^{-2}	C/N ratio	g H_2O g^{-1} soil	kg NO_3^-–N ha^{-1} y^{-1}	Mm y^{-1}	g CO_2e m^{-2} y^{-1}	Total number of species	t ha^{-1} y^{-1}	t ha^{-1} y^{-1}
Conventional	6.9 (0.6)ab	9.4 (0.4)a	0.11 (0.03)a	62.2 (9.4)a	336	82	38.8 (2.3)a	8.2 (0.5)ad	3.5 (0.2)a
No-till	8.5 (0.9)ac	9.6 (0.3)a	0.13 (0.02)a	41.4 (3.0)b	412	−42	49.0 (2.4)b	8.6 (0.3)a	3.9 (0.1)b
Reduced input	6.5 (0.8)a	10.1 (0.5)ab	0.11 (0.02)a	24.6 (0.7)c	220	−27	77.3 (1.7)c	8.9 (0.3)a	3.6 (0.1)a
Biologically based (organic)	8.3 (0.8)ac	10.6 (0.4)b	0.12 (0.01)a	19.2 (0.8)d	219	−134	83.8 (1.7)d	8.4 (0.3)a	2.8 (0.1)c
Alfalfa	10.4 (1.5)bc	9.4 (0.2)a	0.11 (0.01)a	12.7 (1.8)e	199	−65	102.3 (1.9)e	7.2 (0.1)b	n/a
Poplar	8.9 (0.8)bc	10.8 (0.3)bc	0.12 (0.01)a	0.1 (0.0)g	229	82	53.5 (1.9)b	9.2 (0.8)ac	n/a
Early successional	8.6 (0.3)c	11.0 (0.1)c	0.11 (0.01)a	1.1 (0.4)f	232	−387	112.8 (2.9)f	7.2 (0.6)bd	n/a
Deciduous forest	8.1 (1.5)ac	12.4 (0.4)d	0.14 (0.06)a	10.2 (4.0)e	344	−4	59.7 (7.1)b	10.8 (1.2)c	n/a

Statistical significance ($p = 0.05$) is indicated by different letters within the same column.

[a] Measured in 2001 to 1 m depth ($n = 6$ for all except the deciduous forest, where $n = 3$), results from Syswerda et al. (2011).

[b] As measured in July from 1989 to 2012, ($n = 6$ for all except the deciduous forest, where $n = 3$ replicates).

[c] Measured from 1996 to 2007 ($n = 3$ replicates for all treatments), results from Syswerda et al. (2012).

[d] Modeled values, from 1996 to 2007, results from Syswerda et al. (2012).

[e] Composite values, from 1989 to 2009, results from Gelfand et al. (2013).

[f] Measured from 1991 to 2012, ($n = 6$), except for deciduous forest ($n = 3$)

[g] Measured from 1996 to 2007 ($n = 6$), except for deciduous forest, which was sampled 1999–2007 ($n = 3$).

Table 3
Correlation matrix for indicators of ecosystem services in KBS LTER systems.

	Soil carbon	Soil water	Drainage	Nitrate leaching	Global warming impact	Annual net primary productivity	Grain yield	Plant species richness
Soil carbon	1.0	0.226 ($p = 0.135$)	0.050 ($p = 0.746$)	−0.296 ($p = 0.048$)	−0.213 ($p = 0.161$)	0.057 ($p = 0.712$)	0.075 ($p = 0.726$)	0.115 ($p = 0.451$)
Soil water		1.0	0.267 ($p = 0.077$)	−0.124 ($p = 0.418$)	0.199 ($p = 0.190$)	0.559 ($p < 0.001$)	0.133 ($p = 0.537$)	−0.2001 ($p = 0.186$)
Drainage			1.0	0.648 ($p < 0.001$)	0.290 ($p = 0.053$)	0.235 ($p = 0.120$)	0.661 ($p < 0.001$)	−0.679 ($p < 0.001$)
Nitrate leaching				1.0	0.440 ($p = 0.003$)	−0.040 ($p = 0.795$)	0.453 ($p = 0.026$)	−0.612 ($p < 0.001$)
Global warming impact					1.0	0.384 ($p = 0.009$)	0.554 ($p = 0.005$)	−0.794 ($p < 0.001$)
Annual net primary productivity						1.0	0.362 ($p = 0.082$)	−0.441 ($p = 0.002$)
Yield							1.0	−0.582 ($p = 0.003$)
Plant species richness								1.0

Values are listed as correlations and p-values.

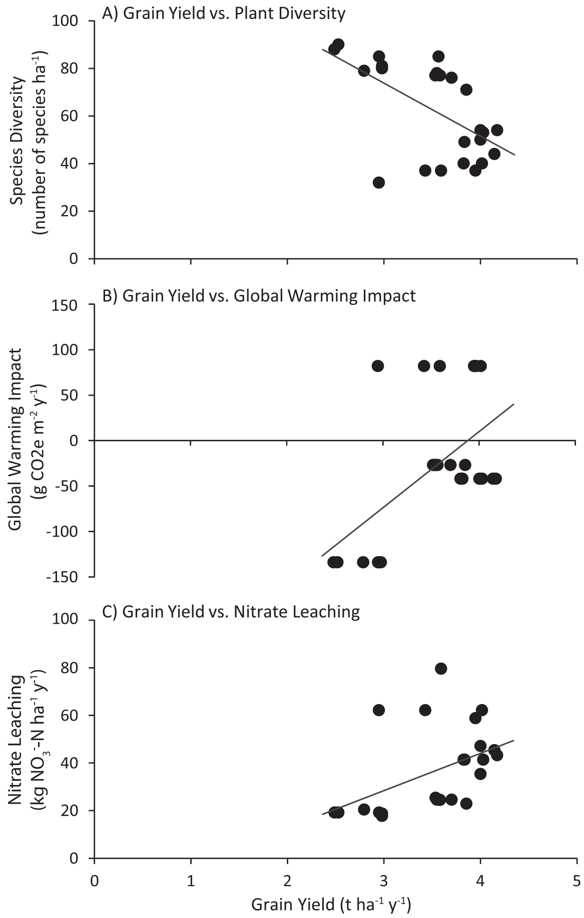

Fig. 3. Trade-off curves for the four annual cropping systems at the KBS LTER. (A) Grain yield vs. plant diversity, (B) grain yield vs. global warming impact, and (C) grain yield vs. nitrate leaching.

did not provide improved global warming impact, largely due to the fact that it is not accumulating large amounts of carbon in the soil.

Ecosystem service differences among systems, as gauged by our eight indicators, provided a basis for describing trade-offs among services. For some services, there were direct trade-offs with food production, while the delivery of other services synergistically increased as food production increased. Even within the annual cropping systems, the particular management of each system drove the production of ecosystem services. N fertilizer, cover crops, and tillage were particularly important determinants of the delivery of multiple ecosystem services.

Some ecosystem services can take years to develop or recover—soil C and the services it provides, for example, may take decades after the cessation of tillage to recover to levels that provide significant fertility and other benefits (Syswerda et al., 2011). Conversely, however, the climate mitigation benefits of soil C gain will be provided immediately but eventually will diminish as soil C saturates some 50–100 years post-tillage.

Grain yields were positively correlated with nitrate leaching and global warming impact, and negatively correlated with plant diversity. Grain production involved the use of inputs like phosphorus, potassium, lime, pesticides, fuel, and other chemicals with a significant C and therefore global warming impact cost. Nevertheless, despite these trade-offs against grain production goals, we found a wide range of outcomes for our four annual cropping systems, suggesting that farmers may be able to reduce the level of negative outcomes associated with conventional cropping systems without significantly reducing grain yields—or to design cropping systems that better maximize services in addition to grain yields.

Much research has been done on changing the suite of ecosystem services produced by ecosystems (Antle and Capalbo, 2002; Maier and Shobayashi, 2001; Robertson and Harwood, 2013) and on using a systems approach to analyze the complex mechanisms driving the delivery of multiple ecosystem services (Robertson et al., 2004). This sort of approach has a large potential modeling, and sites where many of the individual components of the system have been well studied could be used to parameterize models of ecosystem function.

Further research should focus on not only understanding the way ecosystems function, but also on the way farm managers make decisions (Swinton et al., 2007). With trade-offs between competing goals, it is important to understand the priorities of managers and how they make choices between alternative outcomes. Knowing the costs of producing various ecosystem services will allow policy makers to adjust incentives to correct imbalances in the provisioning of different services.

Acknowledgments

We thank S. VanderWulp, S. Bohm, S. Sippel, C. McMinn, J. Schuette, and many others for assistance in the field and lab. We also thank A.N. Kravchenko, M. Klug, A. Smucker, S. Swinton, and S.K Hamilton for many helpful suggestions and insightful comments. Financial support was provided by the US National Science Foundation LTER Program (DEB 1027253), the US DOE Office of Science (DE-FCO2-07ER64494), Michigan Sustainable Agriculture Research and Education Program, and Office of Energy Efficiency and Renewable Energy (DE-ACO5-76RL01830), and MSU AgBioResearch.

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