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

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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

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

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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