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ECOSYSTEM SERVICES FROM AGRICULTURE ACROSS A MANAGEMENT INTENSITY GRADIENT IN SOUTHWEST MICHIGAN

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SARA PARR SYSWERDA

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ECOSYSTEM SERVICES FROM AGRICULTURE ACROSS A MANAGEMENT INTENSITY GRADIENT IN SOUTHWEST MICHIGAN

By

Sara Parr Syswerda

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ABSTRACT

ECOSYSTEM SERVICES FROM AGRICULTURE ACROSS A MANAGEMENT INTENSITY GRADIENT IN SOUTHWEST MICHIGAN

By

Sara Parr Syswerda

I investigated how agricultural systems can be managed to minimize the environmental impact of agriculture without sacrificing productivity. Agricultural systems have a large impact on nutrient cycling, climate regulation, and fresh water and food provisioning, and I have used nitrate leaching, drainage, carbon sequestration, soil inorganic nitrogen, greenhouse gas fluxes, annual net primary productivity, and agronomic yield across a management intensity gradient as a measure of these services.

Research was conducted at Kellogg Biological Station's Long-Term Ecological Research site in southwest Michigan. Treatments included four annual maize-soybean-wheat rotations with conventional, no-till, reduced-input, and organic management; three perennial systems in alfalfa, poplar, and conifers; and four native successional systems ranging from early successional (~20 years since abandonment from agriculture) systems to old growth forest. All systems were replicated in the landscape on the same soil series.

Nitrate leaching over an 11 year period ranged from less than 1 kg NO_3^--N $ha^{-1}y^{-1}$ in poplars to 62 kg NO_3^--N $ha^{-1}y^{-1}$ in the conventional row-crop system. The no-till, reduced input, and organic systems leached 34%, 61%, and 68% less nitrogen, respectively, than did the conventional system. The alfalfa and conifer stands leached nitrogen at rates similar to the organic system. The successional and poplar systems leached the least amount of nitrogen. Drainage levels were highest in the no-till annual

system and deciduous forest. Our findings show that long-term water quality is substantially affected by crops and management practices.

Soil carbon levels 11 years post-establishment differed substantially among systems in the surface soil, where carbon contents were significantly greater than the conventional system in the no-till, organic, alfalfa, poplar, conifer, early successional, never tilled mid-successional, and deciduous forest systems. However, soil carbon levels in the deeper portions of the soil profile were more variable, and showed very few significant differences among treatments. Subsequently soil carbon levels in the total profile to 1 meter differed little among treatments. Deeper soil carbon was much more variable than carbon in upper soil layers, which suggests the need for more intensive sampling than has been undertaken to date.

The additional measured ecosystem services also differed by management system. As systems were managed more intensely, soil carbon levels decreased, nitrate leaching increased, methane oxidation decreased, and nitrous oxide production increased. Trade-off curves and flower diagrams provide a means to display these alternative services and their effects. Analyses of multiple ecosystem services are a first step towards better understanding the large scale trade-offs that occur with land management decisions. Trade-offs in multiple ecosystem services can be used to help develop models incorporating the complexity of the different components of the ecosystem. Future research might focus on using such models to predict the outcome of individual management decisions on the services delivered by managed systems.

Dedicated to my husband, Tim, who has been so supportive of my educational efforts.

This is also dedicated to Cynthia VanVleet, who instilled me with a love of science that went far beyond anything I had imagined before.

ACKNOWLEDGEMENTS

My thesis could not have been completed without the patient help of many caring individuals. I would first like to thank my advisor, Phil Robertson, who has provided guidance and much needed advice over the past five years. I would also like to thank my committee members, Steve Hamilton, Mike Klug, Al Smucker, and Scott Swinton. The helped me improve my research, gave helpful advice on proposals, and made my committee meetings quite enjoyable. I would also like to thank my collaborators on this work, including Bruno Basso, Andrew Corbin, Sasha Kravchenko, Delbert Mokma, and Jane Tausig. Without them, much of this work would not have been possible.

I would also like to thank the many people who have helped me with both laboratory analyses and field work. Two undergraduates, Matt Gorentz and Cole Smith, spent countless hours helping me with my research. Stacey Vanderwulp, Cathy McMinn, and the entire Kellogg Biological Station Long-Term Ecological Research Site field crew helped in the collection and analysis of much of the data that is shown in this work. I would like to particularly thank our data manager, Sven Bohm, for his help, and to our agronomic staff, especially Joe Simmons and Greg Parker, for their help with field operations. I would like to thank Barb Fox with all of her help with all sorts of problems.

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KEY TO SYMBOLS AND ABBREVIATIONS

Abbreviation	Definition
CH_4	Methane, a greenhouse gas
KBS	Kellogg Biological Station
LTER	Long-Term Ecological Research Station
N_2O	Nitrous Oxide, a greenhouse gas
NO_3^-	Nitrate, an anion, a form of nitrogen that is in the soil
NPP	Net Primary Productivity, the amount of biomass that is produced after the organism uses the energy necessary for cellular respiration and maintenance.

CHAPTER 1

INTRODUCTION

Background

Agriculture provides ecosystem services that are critical for human health and welfare. Ecosystem services have been defined in numerous ways, but are generally considered ecological outcomes that benefit humans (Ecological Society of America 1997, Daily 1997). The challenge for ecosystem managers and policy makers is to identify those services that are most important, to measure them, to systematically value them, and to then design and implement a management plan to maximize their delivery.

Ecosystem services from row crops are particularly important since these systems dominate the landscape, provide important economic benefits, and have well-known environmental costs. Row crops such as corn, soybean, and wheat are critical to our well-being and provide most of the US food supply (FAO, 2003). American row crops also use large amounts of energy and have high levels of chemical consumption and release, with concomitant environmental impacts that are both regional and global in scope (Vitousek et al. 1997, Pimentel et al. 2005, Swinton et al. 2007).

In part the environmental costs of agriculture are high because agricultural systems tend to be managed for a single ecosystem service—marketable yields. However, agricultural systems also provide other services that are valued by humans and important to the functioning of nearby ecosystems, including provisioning services such as food and fiber, regulating services such as climate regulation and water purification, cultural services such as aesthetic beauty and recreation, and supporting services such as nutrient cycling and soil formation (Robertson and Swinton 2005, Swinton et al. 2007, Millenium

Ecosystem Assessment 2005. In this dissertation, I examine tradeoffs among important ecosystem services in row crop agriculture in order to provide better knowledge for policy and farm level decision making.

My 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. Agricultural systems have a large impact on nutrient cycling, climate regulation, and fresh water and food provisioning, so I have chosen to focus on these services.

Organization of the dissertation

Chapter 2: In collaboration with Bruno Basso, Stephen Hamilton, Jane Tausig, and G. Philip Robertson, I combined measured values of nitrate concentrations in soil water with modeled water flux data to estimate nitrate leaching losses across a management intensity gradient. My findings show that nitrate leaching can change dramatically under different kinds of management. The poplar trees showed the lowest leaching losses, while the conventional agricultural system showed the highest losses. Changes in leaching levels were related to both the amount of drainage going through each system, as well as the level of nitrogen fertilizer application.

Chapter 3: In collaboration with Andrew Corbin, Delbert Mokma, Alexandra N. Kravchenko, and G. Philip Robertson, I examined carbon levels in deep soil layers across a management intensity gradient. My findings show that carbon levels are more variable at depth than in the surface. Carbon levels to 1 meter were lowest in the reduced-input, conventional, and poplar systems, and highest in the early successional system and alfalfa. Our results at the surface were similar to those in other studies at our site, but differences between treatments were less clear when considering the entire profile than when considering only the surface horizon.

Chapter 4: In collaboration with G. Philip Robertson, I examined trade-offs between a variety of ecosystem services across a management intensity gradient. These included soil quality, water quality, climate regulation, and productivity. My findings show that while some systems are better for grain production, others are preferable for other ecosystem services, such as water quality and climate regulation. These findings suggest that many ecosystem services are produced in tandem, and by impacting the production of one service (for example, climate regulation), you may also be impacting the production of several other ecosystem services (for example, water quality).

CHAPTER 2

LONG-TERM NITRATE LOSS FROM NO-TILL, ORGANIC, BIOFUEL, AND UNMANAGED ECOSYSTEMS.

ABSTRACT

Nitrate loss from intensively farmed cropland in the US Midwest is a long-standing, recalcitrant environmental problem that contributes to surface and groundwater pollution and coastal hypoxia. Efforts to identify cropping practices and systems that are productive and nitrate conservative have been stymied by a lack of information from well-equilbrated and appropriately replicated long-term experiments. Here we report nitrate leaching from ten replicated systems along a management intensity gradient in southwest Michigan, USA. Our systems include four annual corn-soybean-wheat rotations, three perennial crops (alfalfa, poplar trees, and conifer stands), and three unmanaged successional communities, including an early successional community analogous to a cellulosic biofuel system and a mature Eastern Deciduous forest. Measured nitrate concentrations were combined with modeled soil water export to provide estimates of nitrate leached over 11 years of cropping. Nitrate leached ranged from less than 1 kg NO_3^--N $ha^{-1}y^{-1}$ in poplars to 62 kg NO_3^--N $ha^{-1}y^{-1}$ in conventionally managed corn-soybean-wheat. Among annual row crops, average leaching losses followed the order conventional management > no-till > low-input > biologically based organic management. The alfalfa and conifers leached less than most row-crop systems, and the successional and poplar systems leached least. Our findings suggest that nitrate leaching could be altered substantially by substituting biological for chemical inputs in

annual grain crops and in biofuel systems by moving from grain-based to cellulosic-based feedstocks.

INTRODUCTION

Agriculture is the major contributor to reactive nitrogen levels in the biosphere, and reducing nitrogen loss from agricultural ecosystems is a longstanding environmental priority (Copeland 2000, Gruber and Galloway 2008). Agricultural nitrogen is derived from a variety of sources, but primarily from inorganic fertilizer, animal waste, and biological nitrogen fixation in row crops. Most crops take up only about 50% of nitrogen applied (Robertson 1997), leaving the remainder available for loss to the larger environment, including leaching loss to groundwater (Fenn et al. 1998, Sanchez et al. 2004, Basso and Ritchie 2005).

Nitrogen is leached from soils primarily in the form of nitrate, and in agricultural regions, nitrate often reaches high concentrations in ground water and groundwater-fed surface waters. Excessive nitrate can affect human health when ingested in drinking water; potential effects include infant methemoglobinemia (blue baby syndrome), cancer, and gastroenteritis (McCasland et al.1998). Leached nitrate can also cause eutrophication and associated algal blooms in some surface waters, which can kill fish and other wildlife (Buck et al. 1997, Frankenberger and Turco 2003) and promote the invasion of exotic species (Vitousek et al. 1997). Moreover, nitrate leached can be incompletely denitrified in soils, groundwaters or surface waters, resulting in partial conversion to nitrous oxide (Mulholland et al. 2008, Burgin and Hamilton 2007), an important greenhouse gas. Once nitrate reaches coastal areas it can contribute to marine hypoxia (NRC 2003, Rabelais et al. 2001). Costs to mitigate U.S. water quality impairment due to nitrate contamination have been estimated in the tens of billions of dollars (Ribaudo 2003).

Estimates of nitrate loss from different row crops in the U.S. vary widely, with reported values ranging from 25-146 kg N $ha^{-1}yr^{-1}$ in grain and forage systems (Fox et al. 2001, Power et al. 2001, and Basso and Ritchie 2005). To date, apart from a well-documented positive relationship between the rate of N applied and the rate of N loss (e.g. , Groffman et al. 1986, Andraski et al. 2000) consistent management-related patterns in nitrate leaching rates have been hard to detect. For example, comparisons of organic and conventional systems have shown that organically managed system can leach greater (Pimental 2005, Basso and Ritchie 2005), similar (Kirchmann and Bergstrom 2001), or less (Hansen et al. 2001, Kramer et al. 2006, Drinkwater et al. 1998, Martin et al. 2006) nitrogen as compared to conventional systems. Likewise, comparisons of no-till and conventional tillage systems have shown no differences (e.g. Cabrera et al. 1999, Mitsch et al., 1999; Smith et al., 1990), lower (e.g. Stinner et al. 1979), or higher (Kanwar et al. 1988, Tyler and Thomas 1977, Chichester 1977) rates of leaching.

This ambiguity may have two sources, the first related to management issues. Many times the cropping systems compared are not on the same rotation, receive different levels and/or types of nitrogen inputs, and receive different levels of mechanical tillage (Kirchmann and Bergstrom 2001). Different crop rotations imply different harvest and planting regimes, fertilization schedules, and tillage patterns, all of which can affect N use efficiency differently. The second source of ambiguity may be related to experiment duration. Many studies last only 2-3 years, and often begin shortly after treatment establishment. During short-term experiments, modest variation in interannual rainfall can mask long-term leaching differences if, for example, systems don't differ during periods of low rainfall differ greatly when rainfall is abundant (e.g. Cabrera et al. 1999). Additionally, prior to equilibration it is difficult to know whether even consistently different patterns will be maintained in the long-term (Rasmussen et al. 1998). Moreover, most studies have been performed in small plots, which cannot readily account for the effects of spatial variation present at the field scale (Robertson et al. 2007).

Here we report the results of a comprehensive study of the effect of management intensity on N leaching that avoids many of these shortcomings. This study compares 10 different replicated systems that include annual grain crops (tilled vs. no-till, organic vs. conventional), perennial crops (alfalfa, poplar, and conifer trees), and unmanaged communities in different stages of ecological succession (from recently abandoned crop fields to late successional forest). The successional systems provide a reference for assessing current vs. historical trends of N loss, and for judging the impact of converting cropland to biofuel-successional or Conservation Reserve Program (CRP) management. All of our annual crop systems are on the same rotation to avoid confounding rotation effects, and in the organic system biological nitrogen fixation provides the only external nitrogen addition. We sampled these systems for 11 years following an establishment period of greater than 6 years. Our cropping systems were established in large, one hectare plots that allowed the use of commercial-scale equipment to simulate on-farm conditions.

MATERIALS AND METHODS

Site Description

We compared nitrate leaching from a field experiment that was established at the Kellogg Biological Station (KBS) in 1988. Multiple treatments at the KBS Long-Term Ecological Research Site (LTER, www.lter.kbs.msu.edu) form a management intensity gradient. KBS 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 Kalamazoo (fine loamy) and Oshtemo (coarse loamy) soils, both mixed, mesic Typic Hapludalfs, which mainly differ in the thickness of the Bt horizon. The Kalamazoo has a thicker upper Bt horizon than the Oshtemo and therefore has a slightly greater water holding capacity (Table 2.1). Annual rainfall at KBS is 920 mm yr^{-1}, distributed evenly through the year. The water holding capacity of the soil is approximately 150 mm to 1.5 m depth (Crum and Collins 1999, unpublished data).

Experimental Design

Seven of our ten experimental treatments were established in 1989 in replicated 1-ha plots organized in a complete randomized block design (n=6). Three treatments (mid-successional field, old-growth deciduous forest, and coniferous forest) had already been in existence nearby (within 3 km radius) on the same soil series, and experimental plots were established in these systems as well (n=3). Maps of sites and experimental design are available at www.lter.kbs.msu.edu.

Three low tension lysimeters were installed in all treatments in each of three blocks (10 treatments x 3 blocks x 3 lysimeters = 90 lysimeters total). Cropping systems include maize (*Zea mays*)-soybean (*Glycine max*)-wheat (*Triticum* spp.) rotations

Table 2.1. Soil profile characteristics at the KBS LTER site. The dominant KBS soil series are the Kalamazoo (fine-loamy, mixed, mesic Typic Hapludalfs) and Oshtemo (coarse-loamy, mixed, mesic Typic Hapludalfs) series. Data are from Crum and Collins (1995). Abbreviation nd denotes missing data.

Horizon	Depth	Texture			Bulk Density	pH
		Sand	Silt	Clay		
			($g\ kg^{-1}$)		*($mg\ m^{-3}$)*	
Kalamazoo Series						
Ap	0-30	43	38	19	1.6	5.5
E	30-41	39	41	20	1.7	5.7
Bt1	41-69	48	23	29	1.8	5.3
2Bt2	69-88	79	4	17	nd	5.2
2E/Bt	88-152	93	0	7	nd	5.6
Oshtemo Series						
Ap	0-25	59	27	14	1.6	5.7
E	25-41	64	22	14	1.7	5.7
Bt1	41-57	67	13	20	1.8	5.8
2Bt2	57-97	83	4	13	nd	5.8
2E/Bt	97-152	92	0	8	nd	6.0

managed either i) with conventional inputs and tillage, ii) with conventional inputs and no tillage, iii) with reduced chemical inputs and tillage, or iv) organically with no chemical inputs and tillage. The latter two treatments include a leguminous winter cover crop grown following the maize and wheat portions of the rotation to provide N to the subsequent grain crops. All cropping systems were planted and harvested during the same periods according to best management practices for each system. Fertilizer application rates for the conventional input systems were based on soil-test recommendations and are shown in Table 2.3.

From 1989 to 1992, the conventional till and no-till systems were on a maize-soybean rotation, and the reduced-input and organic systems were on a maize-soybean-wheat rotation. Since 1993, all four of the annual grain crops have been in the same maize-soybean-wheat rotation. The conventional, reduced-input, and organic 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 and organic systems received additional inter-row cultivation and rotary hoeing as needed for weed control.

The three perennial systems included alfalfa (*Medicago sativa*), fast growing clonal poplar trees (*Populus xeuramericana*), and conifer stands established c. 1950. The alfalfa was harvested 3-4 times a year, and was reestablished 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. Poplar trees were planted in 1989, and starter fertilizer (only) was added at that time. Creeping red fescue was used as a cover crop to prevent soil erosion. Poplar trees were harvested in 1999, and allowed to coppice (regrow from the cut stems).The conifer stands were 50-70 years old at the time of this study and were mixed stands containing Red and White Pine (*Pinus resinosa and strobes)*, Norway spruce (*Picea abies)*, and some understory Black Cherry (*Prunus serotina);* herbaceous ground cover was generally sparser under the conifers than in the other forest treatments.

The three unmanaged successional systems included: 1) an early successional system that was abandoned from agriculture in 1989, 2) a mid-successional system that was released from agriculture in the 1950's, and 3) a late-successional oak-hickory forest that has never been cleared or plowed. The early successional system has been burned annually in the spring since 1997 to prevent tree colonization.

Sampling Protocols

Nitrate was sampled in water that leached from these systems using quartz/PTFE tension samplers (Prenart; Frederiksburg, Denmark) installed in 1995 at a depth of 1.2 m, approximately 20cm into unconsolidated sand of the 2Bt2 horizon. Sampled water is thus presumed to represent water that would otherwise freely leave the soil profile. The three soil water samplers per plot were installed by coring at an angle in locations 3 meters apart and at least 10 meters from the plot edge. Each soil water sampler was sampled by applying 0.5 atm of vacuum for 24 hours, during which time leachate was collected in a clean flask. Samples were filtered through Pall Type A/E glass fiber filters (East Hills, NY) and then frozen until analysis. Samples were collected every two weeks April

Table 2.2. Management summaries for cropping systems and successional communities at Kellogg Biological Station Long-Term Ecological Research Site.

	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
Organic	Conventional	Cover crop	Mechanical
Perennial Crops			
Alfalfa	None	None	None
Poplar	None	Starter[1]	None
Conifers	None	None	None
Unmanaged Communities			
Early Successional	None	None	None
Mid-Successional	None	None	None
Deciduous Forest	None	None	None

* see Table 2 for Nitrogen Fertilizer Application Rates
[1] 60 kg N ha^{-1} in 1989 only.

Table 2.3. Nitrogen fertilizer applications to the annual grain crops. Detailed information about annual applications can be found at http://lter.kbs.msu.edu. Lime, N, P, and K were applied as needed according to Michigan State University Soil Testing Lab recommendations.

Cropping Year	Conventional*	No-till*	Reduced Input	Organic
		kg N ha^{-1}		
1995-wheat	56	56	34 + covercrop	covercrop
1996-maize	163	163	28 + covercrop	covercrop
1997-soybeans	0	0	0	0
1998-wheat	56	56	28 + covercrop	covercrop
1999-maize	163	163	28 + covercrop	covercrop
2000-soybeans	0	0	0	0
2001-wheat	71	71	31 + covercrop	covercrop
2002-maize	153	153	28 + covercrop	covercrop
2003-soybeans	0	0	0	0
2004-wheat	90	90	54 + covercrop	covercrop
2005-maize	155	155	31 + covercrop	covercrop
2006-soybeans	0	0	0	0

* MSU Soil Testing Lab recommended rates

through October and monthly otherwise, except when soil temperatures were below freezing. Frozen samples were thawed and analyzed colorimetrically for nitrate on an OI Analytical Flow Solution IV continuous flow analyzer (OI Analytical, College Station, TX) with a detection limit of 0.02mg N/L for nitrate. All samples that were found to be below detection limits were recorded as half the detection limit.

Nitrate concentrations were combined with modeled downward water flux to provide estimates of nitrate leaching from the root zone. Water flux was modeled using the Systems Approach for Land Use Sustainability (SALUS) model (Basso et al. 2006). SALUS is designed to simulate continuous crop, soil, water, and nutrient conditions under different management strategies for multiple years (Basso et al. 2006). SALUS accommodates various crop rotations, planting dates, plant populations, irrigation and fertilizer applications, and tillage practices, and simulates plant growth and soil conditions every day during both growing seasons and fallow periods. For each simulation, all major components of the crop-soil-water model are executed, including management practices, water balance, soil organic matter change, nitrogen and phosphorus dynamics, heat balance, plant growth, and plant development. For this study, daily water fluxes were generated.

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 and Basso 2008). The soil water balance module is based on that used in the CERES models (Ritchie 1998) but incorporates a major revision for calculating infiltration (Basso et al. 2008), soil water export (Suleiman and Ritchie 2004), evaporation (Suleiman and Ritchie 2003), and runoff (Basso et al. 2008). In

SALUS, a time-to-ponding (TP) concept is used to replace the previous runoff and infiltration calculations that were based on SCS runoff curve numbers (Basso et al. 2008). The simulation of soil water export produced by SALUS has been tested extensively at KBS using monolith drainage lysimeters (Basso 2000, Basso and Ritchie 2005).

We combined measured nitrate concentration data with each treatment's modeled water flux to estimate total nitrate leaching over the period November 1995 to October 2006. We modeled water fluxes on a daily time step and interpolated daily nitrate concentrations between lysimeter sample dates. Multiplying daily water flux by interpolated nitrate concentrations provided a daily nitrate leaching value.

Statistical Analysis

The experiment was analyzed as a completely randomized design (CRD), with 10 treatments and three replicates of each treatment. Data were log-transformed to provide a more normal distribution and more homogeneous variance. Treatments were compared with analysis of variance (ANOVA) of the 12 year cumulative leaching values for the 3 replicate blocks per treatment. All comparisons were completed using SAS (SAS Version 8.2, SAS Institute 1999).

RESULTS

Patterns of Nitrogen Loss

Total soil water export and associated nitrate leaching over the 11 years of this experiment are summarized in Figures 1 and 2. The eleven year period corresponded to three and a half full rotations of the annual crops. Soil water export rates were highest in the coniferous forest, old-growth deciduous forest, and no-till system (Figure 2). Soil water export from alfalfa was least.

Among the cropping systems, the conventional agricultural system leached the most nitrate(685 kg NO_3^-N ha^{-1}), while the organic system leached the least (209 kg NO_3^- N ha^{-1}). The no-till and reduced-input systems leached intermediate amounts (458 and 267 kg NO_3^-N ha^{-1}, respectively). The perennial poplars leached less nitrate than the annual systems (<1 kg NO_3^-N ha^{-1}, respectively), while leaching in the alfalfa and coniferous forest was similar to the organic annual treatment (190 kg NO_3^-N ha^{-1}). The unmanaged systems leached less nitrate than did the annual systems.

Rates of leaching (in kg^{-1} NO_3^-N mm^{-1}) were dramatically different for each of the treatments (Tables 6, 7, and 8). We found the highest rates of leaching in the conventional annual cropping system, where 186 g of NO_3^-N were lost for each mm of exported soil water. All of the other annual cropping systems showed lower levels of nitrate leaching, although rates were much higher than were rates in the unmanaged and perennial systems.

In the annual crops (Table 6), the largest nitrate leaching losses occurred during the fallow period after corn and prior to soybean. In the conventional system, 52% of all nitrate lost (357 kg NO_3^-N ha^{-1}) was lost during this period. The no-till, reduced-input, and organic systems also experienced dramatic losses during the fallow period post-corn, contributing to 50, 46, and 42% of their leaching losses, respectively. Leaching losses were lowest during soybean periods.

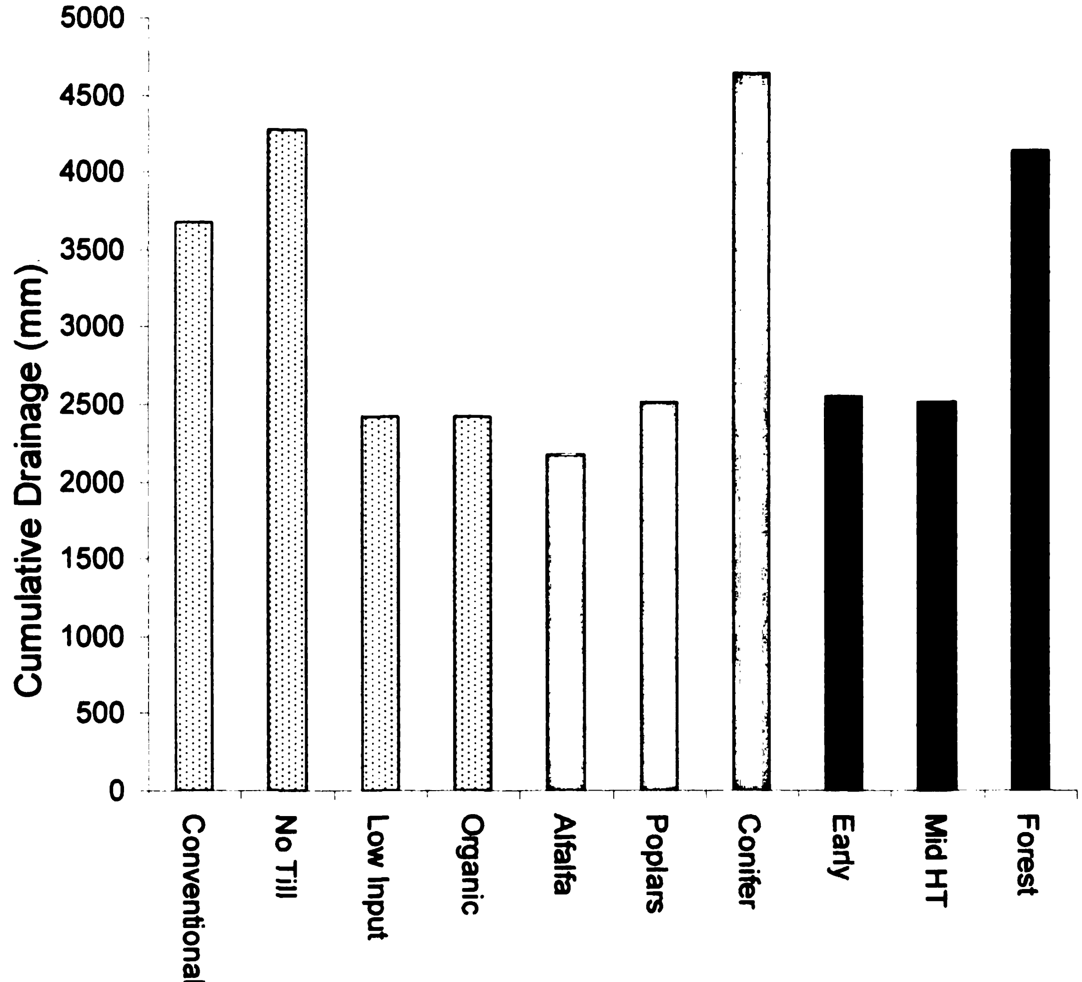

Figure 2.1 Cumulative drainage in all treatments from November 1995 to October 2006 in millimeters. Total precipitation for the period was 8985 millimeters during this period.

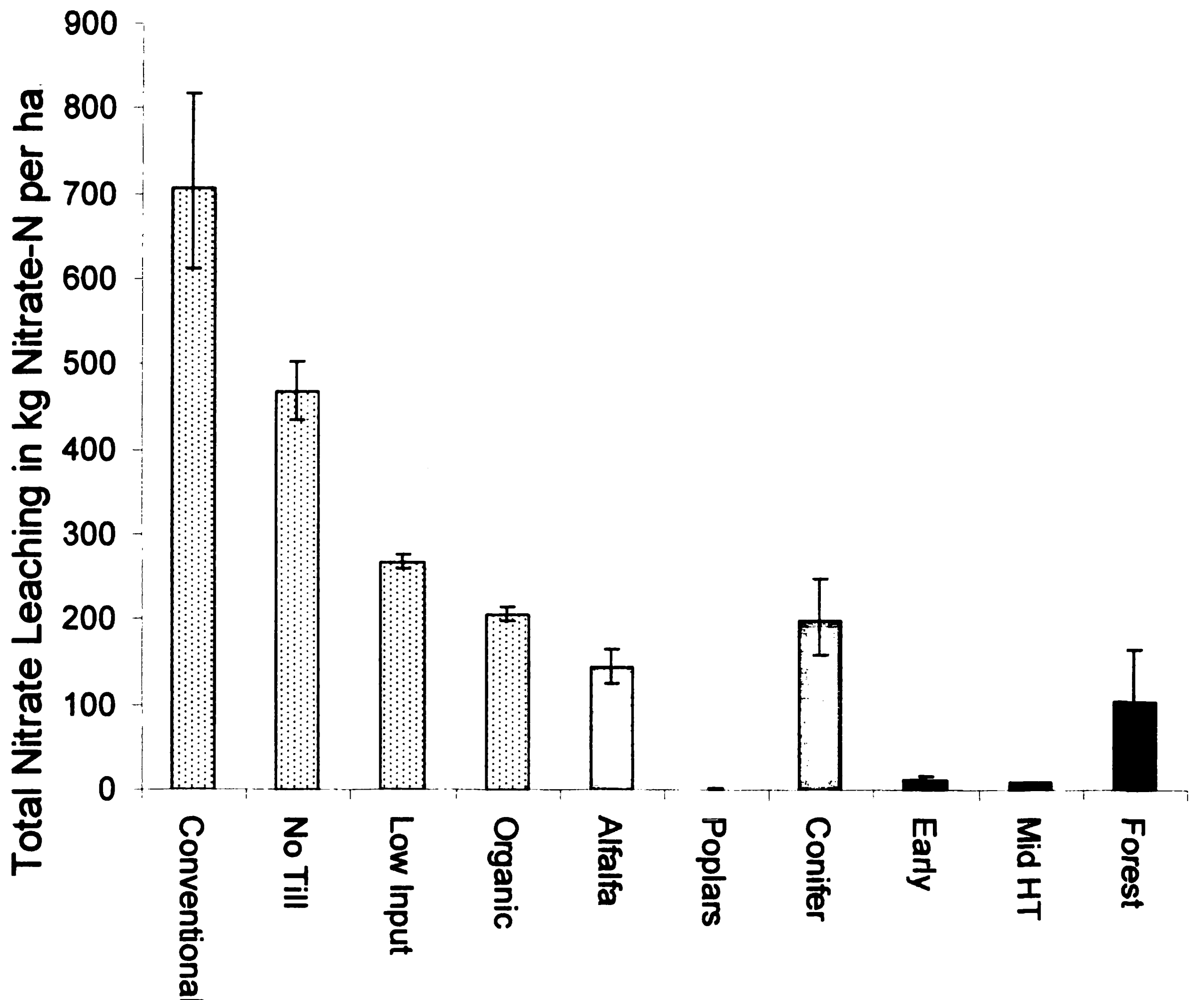

Figure 2.2 Cumulative nitrate leaching in all treatments from November 1995 to October 2006 in kg NO_3^--N ha^{-1}.

Table 2.4. Precipitation and crop timing by cropping year in the annual treatments. The planting date is when the particular crop was planted (or in the case of 1995, when observations began for that crop). The harvest date was when the crop was removed from the field, and the duration is the number of days between the planting of the focal crop until the next crop is planted.

Crop Year	Crop	Planting Date	Harvest Date	Duration (days)	Growing Season Precip (mm)	Post-Harvest Precip (mm)	Total Precip (mm)
1995	Post Wheat	11/1/1995	*	199	*	296	296
1996	Maize	5/18/1996	10/31/1996	372	396	394	790
1997	Soybeans	5/25/1997	10/17/1997	159	405	28	433
1998	Wheat	10/31/1997	7/10/1998	560	502	519	1021
1999	Maize	5/14/1999	10/5/1999	391	265	468	734
2000	Soybeans	6/8/2000	10/11/2000	146	409	19	428
2001	Wheat	11/1/2000	7/16/2001	561	608	799	1407
2002	Maize	5/16/2002	10/28/2002	379	412	390	802
2003	Soybeans	5/30/2003	10/6/2003	137	315	2	316
2004	Wheat	10/14/2003	7/12/2004	577	811	656	1467
2005	Maize	5/13/2005	10/10/2005	396	368	578	947
2006	Soybeans	6/13/2006	10/15/2006	135	422	88	509

*The experiment started after wheat had been harvested, so the first entry point is the post-wheat fallow period

Table 2.5. Nitrate leaching and drainage in the annual cropping systems, by crop.

Crop Year	Crop	Conventional			No-Till			Reduced-Input			Organic		
		Total Drain (mm)	Total Leach (kg NO_3^--N ha^{-1})	Leach/ Yield (g NO_3^--N kg yield^{-1})	Total Drain (mm)	Total Leach (kg NO_3^--N ha^{-1})	Leach/ Yield (g NO_3^--N kg yield^{-1})	Total Drain (mm)	Total Leach (kg NO_3^--N ha^{-1})	Leach/ Yield (g NO_3^--N kg yield^{-1})	Total Drain (mm)	Total Leach (kg NO_3^--N ha^{-1})	Leach/ Yield (g NO_3^--N kg yield^{-1})
1995	Post Wheat	139	7	*	150	9	*	52	2	*	49	1	*
1996	Maize	541	139	43.4	536	83	20.5	324	58	13.9	313	46	18.2
1997	Soybeans	189	24	15.9	202	19	9.3	152	17	9.4	155	12	7.3
1998	Wheat	355	37	12.3	442	32	11.4	201	17	7.7	201	10	9.0
1999	Maize	328	70	17.4	373	36	9.5	161	40	9.1	165	18	4.3
2000	Soybeans	83	10	3.8	90	5	1.7	82	13	4.5	83	6	2.1
2001	Wheat	543	58	13.8	601	53	14.2	365	25	6.8	365	18	6.6
2002	Maize	321	152	28.2	308	113	21.6	182	34	5.3	184	22	4.0
2003	Soybeans	16	14	8.6	20	4	2.2	38	2	1.7	39	10	9.9
2004	Wheat	715	136	33.4	754	65	15.6	515	31	8.1	515	30	13.0
2005	Maize	304	28	4.3	501	24	3.1	241	20	3.0	239	25	5.7
2006	Soybeans	139	10	3.5	296	16	4.4	106	9	2.8	106	10	3.4
	Total	3674	685	17.6	4273	458	10.9	2419	267	6.6	2415	209	6.7

*Since wheat was harvested before measurements were initiated, yield is not included in this analysis.

Table 2.6. Nitrate leaching in season (when the crop is present) and off season (fallow period) in the annual cropping systems, with rates of nitrate leaching per mm of drainage.

Crop Year	Crop	Conventional			No-Till			Reduced-Input			Organic		
		In Season	Off Season	Rate of Leach	In Season	Off Season	Rate of Leach	In Season	Off Season	Rate of Leach	In Season	Off Season	Rate of Leach
		(kg NO_3^--N ha^{-1})	(kg NO_3^--N ha^{-1})	(g NO_3^--N mm^{-1})	(kg NO_3^--N ha^{-1})	(kg NO_3^--N ha^{-1})	(g NO_3^--N mm^{-1})	(kg NO_3^--N ha^{-1})	(kg NO_3^--N ha^{-1})	(g NO_3^--N mm^{-1})	(kg NO_3^--N ha^{-1})	(kg NO_3^--N ha^{-1})	(g NO_3^--N mm^{-1})
1995	Post Wheat	*	7	50.9	*	9	57.2	*	2	35.2	*	1	26.5
1996	Maize	17	122	257.5	16	66	154.1	13	45	179.9	11	35	146.0
1997	Soy	23	1	125.8	18	1	95.8	17	0	111.0	12	0	80.1
1998	Wheat	28	9	105.3	22	11	72.6	14	3	85.6	9	1	50.6
1999	Maize	3	68	214.6	2	34	95.3	2	38	248.5	1	18	111.5
2000	Soy	8	2	124.5	4	1	59.8	12	1	156.7	6	0	77.1
2001	Wheat	21	37	106.4	15	38	87.9	20	5	68.2	13	5	49.0
2002	Maize	6	146	472.0	3	110	367.4	10	25	189.3	8	14	118.2
2003	Soy	2	12	864.3	1	3	216.3	2	0	44.4	9	1	251.0
2004	Wheat	125	12	190.8	52	13	86.2	29	1	59.3	29	1	58.5
2005	Maize	7	21	90.6	7	17	48.2	4	15	81.2	4	21	104.1
2006	Soy	6	4	68.5	12	3	52.8	9	0	85.0	10	0	95.2
	Total	245	440	186.5	152	306	107.3	132	135	110.4	112	97	86.5

Table 2.7. Annual Drainage and Leaching in Perennial crops.

Year	Annual Precip mm	Alfalfa Total Drain (mm)	Alfalfa Total Leach (kg NO_3^--N ha^{-1})	Alfalfa Rate of Leach (g NO_3^--N mm^{-1})	Poplar Total Drain (mm)	Poplar Total Leach (kg NO_3^--N ha^{-1})	Poplar Rate of Leach (g NO_3^--N mm^{-1})	Coniferous Forest Total Drain (mm)	Coniferous Forest Total Leach (kg NO_3^--N ha^{-1})	Coniferous Forest Rate of Leach (g NO_3^--N mm^{-1})
1996	694	173	13.73	79	198	0.29	1.50	378	8.21	22
1997	776	237	3.26	14	283	0.07	0.24	470	18.69	40
1998	723	123	0.83	7	147	0.10	0.71	325	14.62	45
1999	608	56	9.52	170	102	0.28	2.70	311	13.14	42
2000	937	201	53.01	260	233	0.02	0.10	444	22.59	51
2001	1032	283	42.50	150	306	0.03	0.11	531	15.38	29
2002	731	67	0.36	5	99	0.01	0.12	292	5.94	20
2003	908	272	8.92	33	290	0.03	0.12	454	27.85	61
2004	959	227	0.40	2	254	0.03	0.12	495	15.24	31
2005	700	126	0.67	5	159	0.03	0.18	295	2.59	9
2006	1150	408	8.39	21	438	0.04	0.10	648	46.53	72
Total	9218	2174	141.59	65	2507	0.95	0.38	4642	190.78	41

Table 2.8. Nitrate leaching in the perennial crops in the summer growing season (May 1-Oct. 1) and during the rest of the year.

Year	Alfalfa			Poplar			Coniferous Forest		
	Summer ($kg\ NO_3^-$-N ha^{-1})	Off-Season ($kg\ NO_3^-$-N ha^{-1})	Total Leach ($kg\ NO_3^-$-N ha^{-1})	Summer ($kg\ NO_3^-$-N ha^{-1})	Off-Season ($kg\ NO_3^-$-N ha^{-1})	Total Leach ($kg\ NO_3^-$-N ha^{-1})	Summer ($kg\ NO_3^-$-N ha^{-1})	Off-Season ($kg\ NO_3^-$-N ha^{-1})	Total Leach ($kg\ NO_3^-$-N ha^{-1})
1996	0.4	13.3	13.7	0.2	0.11	0.29	2.7	5.6	8.2
1997	0.2	3.1	3.3	0.1	0.02	0.07	11.7	7.0	18.7
1998	0.0	0.8	0.8	0.0	0.08	0.10	2.7	11.9	14.6
1999	1.1	8.4	9.5	0.0	0.24	0.28	6.5	6.6	13.1
2000	38.4	14.6	53.0	0.0	0.01	0.02	14.1	8.5	22.6
2001	28.4	14.1	42.5	0.0	0.02	0.03	9.1	6.3	15.4
2002	0.1	0.3	0.4	0.0	0.00	0.01	2.6	3.4	5.9
2003	2.2	6.7	8.9	0.0	0.03	0.03	10.5	17.3	27.9
2004	0.1	0.3	0.4	0.0	0.02	0.03	8.8	6.4	15.2
2005	0.2	0.5	0.7	0.0	0.02	0.03	1.4	1.2	2.6
2006	1.0	7.3	8.4	0.0	0.03	0.04	27.0	19.6	46.5
Total	72.2	69.4	141.6	0.4	0.57	0.95	97.0	93.8	190.8

Table 2.9. Annual drainage and nitrate leaching in the unmanaged systems.

		Early Successional			Mid-Successional			Old-Growth Forest		
Year	Annual Precip (mm)	Total Drain (mm)	Total Leach (kg NO_3^--N ha^{-1})	Rate of Leach (g NO_3^--N mm^{-1})	Total Drain (mm)	Total Leach (kg NO_3^--N ha^{-1})	Rate of Leach (g NO_3^--N mm^{-1})	Total Drain (mm)	Total Leach (kg NO_3^--N ha^{-1})	Rate of Leach (g NO_3^--N mm^{-1})
1996	694	208	2.84	14.0	198	0.42	2.1	345	7.81	23
1997	776	296	1.89	6.4	283	0.27	0.95	436	6.60	15
1998	723	152	0.27	1.8	147	0.17	1.2	268	9.49	35
1999	608	107	0.37	3.5	102	0.13	1.3	269	13.41	50
2000	937	235	1.31	5.6	233	0.62	2.7	384	23.32	61
2001	1032	308	3.14	10.0	306	2.27	7.4	505	16.38	32
2002	732	98	0.76	7.7	100	0.29	2.9	249	8.68	35
2003	908	290	0.61	2.1	289	0.79	2.7	428	17.00	40
2004	959	253	0.28	1.1	254	1.15	4.5	414	5.01	12
2005	700	159	0.19	1.2	159	1.27	8.0	225	3.05	14
2006	1150	438	0.50	1.1	438	1.98	4.5	614	10.64	17
Total	9218	2543	12.16	4.8	2507	9.36	3.7	4137	121.37	29

Table 2.10. Leaching in the unmanaged systems in the summer growing season (May 1-Oct. 1) and during the rest of the year.

Year	Early Successional			Mid-Successional			Deciduous Forest		
	Summer	Off-Season	Total Leach	Summer	Off-Season	Total Leach	Summer	Off-Season	Total Leach
	(kg NO_3^--N ha^{-1})	(kg NO_3^--N ha^{-1})	(kg NO_3^--N ha^{-1})	(kg NO_3^--N ha^{-1})	(kg NO_3^--N ha^{-1})	(kg NO_3^--N ha^{-1})	(kg NO_3^--N ha^{-1})	(kg NO_3^--N ha^{-1})	(kg NO_3^--N ha^{-1})
1996	0.27	2.56	2.84	0.26	0.16	0.42	4.72	3.09	7.81
1997	0.43	1.46	1.89	0.21	0.06	0.27	2.14	4.47	6.60
1998	0.10	0.18	0.27	0.04	0.13	0.17	0.69	8.80	9.49
1999	0.08	0.29	0.37	0.06	0.08	0.13	2.48	10.93	13.41
2000	0.71	0.60	1.31	0.46	0.16	0.62	8.88	14.44	23.32
2001	1.72	1.43	3.14	1.29	0.98	2.27	2.49	13.88	16.38
2002	0.44	0.31	0.76	0.27	0.03	0.29	3.04	5.64	8.68
2003	0.21	0.40	0.61	0.17	0.62	0.79	6.33	10.66	17.00
2004	0.10	0.17	0.28	0.41	0.74	1.15	1.96	3.05	5.01
2005	0.01	0.18	0.19	0.44	0.83	1.27	0.27	2.77	3.05
2006	0.10	0.40	0.50	0.78	1.20	1.98	1.74	8.90	10.64
Total	4.17	7.99	12.16	4.39	4.98	9.36	34.74	86.64	121.37

DISCUSSION

Managing agricultural systems to reduce the amount of nitrate leached from these systems could reduce their environmental impact. For example, highest nitrate losses typically occur when soil nitrogen is available, water is plentiful, and plants are not present or inactive in uptake of water or nitrogen. Agricultural practices that minimize available nitrogen when water infiltrates through the soils would thus be expected to leach less nitrogen.

Nitrate leaching varies both seasonally and throughout the rotation cycle of cropping systems as a function of available nitrogen concentrations and soil water mobility (Watts and Martin 1981, Martin et al. 1994, Rasse et al. 1999). Pimentel et al. (2005), for example, showed that in manure-based and legume-based organic grain systems nitrate concentration in leachate varied from 0-28 mg NO_3^--N L^{-1}ppm, and was highest in June and July. Concentrations of nitrate were probably highest when soil moisture levels were lowest.

However, nitrate leaching is a function of the concentration of nitrate in the soil solution and the amount of water moving through the profile. Nitrate leaching should increase during months when soil moisture is highest, since water is needed to carry the nitrate through the profile. Nitrate leaching should also increase during the months when plants are absent or inactive, since roots remove both water and nitrate from soil. Nitrate leaching should thus increase during cool seaseons following nitrogen fixing crops or crops that are highly fertilized, since this is when most infiltration occurs and leachable nitrate exists in the soil.

General Patterns of Leaching

This study has shown that cropping systems receiving more intensive management leach more nitrate into groundwater. The systems showing the greatest amounts of leaching were the annual cropping systems. These systems have higher nitrogen inputs than the other systems, and the conventional and no-till annual systems also have longer fallow periods than many of the other systems. The early and mid-successional and poplar systems showed the lowest amounts of leaching, mainly due to the low concentrations of nitrate in the leachate.

Leaching rates ranged from less than 1 kg NO_3^-N ha^{-1} yr^{-1} in the poplars to 62 kg NO_3^-N ha^{-1} yr^{-1} in the conventional cropping system, similar to rates reported in previous studies of agricultural systems (Fox et al. 2001, Power et al. 2001, and Basso and Ritchie 2005). Soil water export values ranged from 198 to 422 mm yr^{-1}, representing 24 to 52 percent of precipitation. Previous studies in KBS agricultural systems had 31 and 36% of precipitation lost as soil water export (Basso and Ritchie 2005 and Smeenk 2003 respectively). The leaching rate (nitrate lost per unit soil water export) of the systems showed wide variation, from poplar's losing virtually no nitrogen for each mm of soil water export (0.38 g NO_3^-N mm^{-1}) to the conventional system's losing far more (17.6 g NO_3^-N mm^{-1}). Most of the differences in the systems were attributable to higher nitrate concentrations in combination with longer fallow periods, which resulted in higher soil water exports.

Effects of Tillage

The no-till system leached 35% less nitrogen than the conventional cropping system (458 vs. 685 kg NO_3^--N ha^{-1} respectively). Leached nitrate N represented 50 and 76%, respectively, of the total N applied to these two systems over the eleven year period. The no-till system showed higher soil water export throughout the period as compared to the conventional system, as has been found in other studies (Rasse and Smucker 1999, and Ogden et al. 1999). The leaching rate was reduced by 42% in the no-till system, with the conventional system losing 187 g NO_3^--N mm^{-1} compared to 107 g NO_3^--N mm^{-1} in the no-till system.

The environmental impact of grain production, measured as the amount of nitrogen lost relative to grain yield, also varied among annual crops. The no-till system had less nitrogen loss per unit yield, losing only 10.9 g NO_3^--N kg^{-1} yield compared to 17.6 g NO_3^--N kg^{-1} yield in the conventional system. The decreased nitrate losses shown in the no-till system agreed with some studies (Stinner et al. 1979), but not all (Kanwar et al. 1988, Tyler and Thomas 1977, Chichester 1977). This difference in soil water export and nitrate leaching may be due to the well drained nature of KBS soils. Also, the no-till plots also showed higher yields in some years than the conventional plots (Grandy et al. 2006), which may contribute to reductions in nitrate availability in these soils.

Conventional, Organic, and Reduced Input Systems

The conventional till system also leached more nitrate than the organic cropping system: 685 vs. 209 kg NO_3^--N ha^{-1}, respectively. The organic system had both lower soil water export than the conventional system as well as lower nitrate concentrations in the exported soil water throughout the study. Lower nitrate leaching and soil water export in the organic systems are likely the result of cover crops, which increase evapotranspiration and take up free nitrogen from the soil. The leaching rate in the organic system was less than half that of the conventional system (86.5 vs. 186.5 g NO_3^--N mm^{-1} respectively).

The organic grain production system had a lower environmental impact per unit yield than the conventional system, losing only 6.7 g NO_3^--N kg yield^{-1} compared to 17.6 g NO_3^--N kg yield^{-1} in the conventional system. The organic system would be expected to lose less nitrogen per unit yield, since the system was nitrogen limited. The results found here are similar to some studies showing less nitrate leaching in organic systems (Hansen et al. 2001, Kramer et al. 2006, and Drinkwater et al. 1998), but not all (Pimental et al. 2005). Since we did not use manure in our system, our organic system had much lower nitrogen than many other organic systems.

Our reduced input system showed a large reduction in nitrate leaching compared to the conventional system (267 kg NO_3^--N ha^{-1}). This system also showed improvements in leaching rate (110.4 g NO_3^--N mm^{-1}) and efficiency (6.6 g NO_3^--N kg yield^{-1}). This system also showed lower soil water export rates than the conventional system due to the use of cover crops, but had higher nitrogen applications and resultant yields than the organic system.

Alfalfa

The alfalfa lost less nitrate than the conventional, no-till, and reduced-input cropping systems but more nitrate than the poplar, early successional, and mid-successional systems. The majority of the losses in alfalfa were in 2000 and 2001, during a period when the alfalfa stand was being reestablished following plowing in 2000. About two thirds of the nitrogen from the system was leached during this period. If 2000 and 2001 were excluded from the analysis, the total leaching would have been 46.1 kg NO_3^--N ha^{-1}, or 5.1 kg NO_3^--N ha^{-1} yr^{-1}. Nonetheless, periodic re-establishment of alfalfa is typically required due to auto-toxicity from previous plants. Alfalfa had the lowest soil water export of any of the systems, 2174 mm, and a higher leaching rate than any of the perennial and unmanaged systems (65g NO_3^--N mm^{-1}).

Poplar and Conifer Stands

The poplar system leached the least nitrogen of all the treatments, losing less than 1 kg NO_3^--N ha^{-1} over the 11 year period. The poplar system had intermediate rates of soil water export, with often undetectable levels of nitrate in the exported soil water from this system. The nitrate loss rate in this system was also the lowest among all of our systems, only 0.38 g NO_3^--N mm^{-1}. The low nitrate leaching in the poplars was most likely due to the lack of fertilization in these plots. Other studies have shown the potential for nitrogen loss in irrigated and fertilized poplar stands in the United States (McLaughlin 1985), but there are many environmental programs, both in the US and abroad, that use poplar to reduce nitrate availability in riparian areas, waste water treatment, or confined animal feeding operations (Ball et al. 2005).

The coniferous forest stand lost far more nitrogen than the poplar system: 191 kg NO_3^--N ha^{-1} over the 11 year period. The soil water export in this system was also much higher (4642 mm) than in the poplars (2507 mm). The overall rate of leaching was 42 g NO_3^--N mm^{-1}, which is higher than in the poplars and the unmanaged systems, but lower than in the alfalfa and annual cropping systems. Other researchers have found that there is the potential for nitrate leaching in nitrogen saturated coniferous forest stands like the one at KBS (Jussy et al. 2004, Tietema et al. 1997).

Unmanaged Successional Systems

The unmanaged systems showed a gradient of leaching, with the early and mid-succesional systems leaching very little nitrate (12.16 and 9.36 kg NO_3^--N ha^{-1} over the 11 year period, respectively), while the old growth forest leached an order of magnitude more nitrate (121.37 kg NO_3^--N ha^{-1} over the 11 year period). The soil water export in the early and mid-successional systems was also lower than in the old growth forest (2543, 2507, and 4137 mm respectively), implying greater evapotranspiration in these systems. The old growth forest also had the highest rate of leaching of the three unmanaged systems, losing 29 g NO_3^--N mm^{-1} compared to 4.8 and 3.7 g NO_3^--N mm^{-1} in the early and mid-successional systems, respectively. Since the early and mid-successional systems are still accumulating biomass, it would be expected that they would lose very little nitrogen (Vitousek and Reiners 1975). Since the old growth forest would be expected to be at equilibrium biomass, it would be expected that annual losses would be in approximate equilibrium with the amount of nitrogen that is deposited on the site annually through both dry and wet deposition. The KBS site received on average 6 kg N ha^{-1} yr^{-1} in wet precipitation during this study (National Atmospheric Deposition Program 2008), so the loss rate of 11 kg $NO3^-$-N ha^{-1} yr^{-1} suggests equilibrium depending on denitrification and dry deposition, and is well within the range of reported values of nitrate leaching from forest systems (Borken and Matzner 2004), though higher than some studies in forested sites (Schleppi et al. 2004).

Intra-annual variability and temporal trends

There was a great deal of variability in annual precipitation in our study (Table 7), ranging from 608 mm of precipitation in 1999 to 1150 mm in 2006. The total precipitation was 9218 mm from 1996-2006, with an average annual precipitation of 838 mm. Years with higher amounts of precipitation led to higher soil water export in all systems, with peaks in soil water export during 2006 for the perennial and unmanaged systems, while the wheat year of 2004 (with 1467 mm of precipitation from planting of wheat until the subsequent planting of corn) showed the highest soil water export of the annual systems.

The annual crops showed marked differences in nitrate leaching depending on the crop that was growing and the amount of precipitation received. Due to the variation in the amount of time a crop was on the field, management the crop including the amount of nitrogen received, particular crops contributed disproportionally to the total leaching losses. The soybeans were on the field the shortest amount of time (144 days on average), while maize and wheat were in place for much longer periods (385 and 566 days, respectively). The highest level of leaching occurred during the maize years, representing 53 to 57% of the total nitrate lost in these systems, even though maize only occupied 35% of the rotation cycle. Most of this loss occurred during the post-harvest period after maize was removed and before soybeans were planted, which accounted for 42 to 52% of the total nitrate loss in these systems over the 11 year period. This indicates that cover crop usage during long fallow periods, like those between corn harvest and soybean planting, could be very useful for reducing nitrate leaching into groundwater.

In the perennial systems, the poplars consistently lost very little nitrate, and leaching was not responsive to variation in precipitation due to the low nitrate levels in the exported soil water. The alfalfa showed the greatest losses due to stand re-establishment in 1999-2001. The coniferous forest showed a positive relationship between soil water export and the amount of nitrate leached from the system, a trend that has been shown in irrigated forest plots elsewhere (Jussy et al. 2004, Tietema et al. 1997).

In the unmanaged systems, precipitation and soil water export seemed to be less correlated with nitrate leaching. Only in the mid-successional field was there a trend of increased nitrate leaching with high soil water export. This may be due to the generally lower leaching overall in these systems. Particularly in the early and mid-successional systems, leaching was never more than 4 kg NO_3^--N ha^{-1} yr, so changes in leaching rates may have been more closely tied to changes in N deposition rates or other environmental factors.

Over the 11 year study, striking patterns emerged when comparing periods when the plants are actively growing and when they are dormant. Leaching losses during the off season when no crops were on the field accounted for 67 and 64 % of the total for the conventional and no-till systems, respectively. In the reduced input and organic systems, this was reduced to 51 and 46% of losses, respectively, presumably due to the use of cover crops in these systems. The perennial systems seemed to show a similar pattern, losing 49, 49, and 60% of their nitrate losses in the alfalfa, conifers, and poplars during the winter season (Oct.-Apr.). The unmanaged systems also lost the majority of their nitrogen during the winter offseason, losing 66, 53, and 71% in the early successional, mid-successional, and old growth forest, respectively, during this period.

Management Implications

This information on nitrate leaching in different management systems has many potential applications. Most importantly, this research shows that there is a wide range of nitrate leaching levels from row crop systems, and that leaching can be significantly reduced by changing management. This research suggests that cover crops, reduced tillage, and reduced inputs could all help to reduce nitrate leaching. Particularly with the expansion of biofuel production in the United States and elsewhere, implications for ground water quality should be considered. With the landscape in North America rapidly changing, the fate of the remaining fresh water supplies depends on the way in which we manage the lands around them.

Further research should be conducted looking at the impact of CRP and prairie land conversion to biofuel crop production on nitrate leaching, and the potential for crops like poplar to mitigate impaired water quality around the US, particularly in areas with high nitrogen deposition or manure management issues. Additionally, research should also look at the temporal management that might be used to alleviate the losses of nitrate during particularly vulnerable portions of the rotation in annual cropping systems.

CHAPTER 3

ECOSYSTEM MANAGEMENT AND CARBON STORAGE IN DEEP SOIL LAYERS

ABSTRACT

Soil carbon sequestration is one of several carbon capture methodologies proposed to mitigate atmospheric CO_2 increases, principally through the adoption of no-till or conservation tillage technologies. Historically, soil carbon sequestration research has focused on the top 10-30 cm of the soil profile, ignoring deeper portions that might also change due to management. In this study we sampled soils in eleven treatments along a management intensity gradient to 1 meter depth. Experimental treatments on the same soil series included four annual grain cropping systems in a maize-soybean-wheat rotation, three perennial cropping systems, and four unmanaged successional systems. The annual grain systems included conventionally tilled and no-till treatments managed with conventional levels of chemical inputs. A third annual grain system received reduced-inputs and a fourth, organic system received no chemical inputs; both of these latter systems used tillage for weed control and leguminous winter cover crops for nitrogen. Perennial crops included alfalfa, clonal poplar stands, and a mature conifer plantation. Successional treatments included a 12-year-old early successional community, two 50-year-old mid-successional communities, and a mature forest.

In surface soils, the no-till and organic systems had significantly higher carbon concentrations and total carbon than did the conventionally managed cropping system ($p \leq 0.05$). Likewise, the alfalfa, poplar, conifer, early successional, never-tilled mid-successional, and deciduous forest systems all showed significant gains in both carbon

concentrations and total carbon in the surface soil compared to the conventional system ($p \leq 0.05$). In contrast to surface soil trends, the B/Bt horizon had two times higher variability in carbon concentrations and total carbon than did surface soils, leading to very few significant differences among treatments. Likewise, the deeper Bt2/C horizon soil showed more than three times higher variability in carbon concentrations and total carbon than did surface soils, and very few significant differences among treatments. In the total profile to 1 meter, the conventional till maize-soybean-wheat system contained 7.0 kg C m^{-2}. The no-till system contained 1.5 kg C m^{-2} more carbon, but this gain was not statistically significant ($p=0.17$, NS) owing to variability in subsurface horizons. The reduced-input system contained 0.6 kg C m^{-2} less than the conventional system ($p=0.55$, NS), while the organic system contained 1.3 kg C m^{-2} more than the conventional system ($p = 0.16$, NS). The alfalfa had 3.5 kg C m^{-2} more total profile carbon than the conventional agricultural system ($p=0.06$), while the poplar system had 2.0 kg C m^{-2} more carbon than the conventional system ($p=0.07$). The early successional and never-tilled mid-successional systems showed higher carbon levels, with 1.7 and 2.7 kg C m^{-2} more than the conventional, respectively ($p \leq 0.05$). The conifers, historically tilled mid-successional system, and deciduous forest were not significantly different from the conventional system. High variability in subsurface soils suggests that detecting differences among treatments when including deeper soils will be more difficult and will require more intensive soil sampling and replication. Overall, 1) soil carbon concentrations were much more variable at depth than at the surface; 2) different cropping systems distribute their carbon differently throughout the profile; 3) systems that have more carbon at the surface do not necessarily have more carbon at depth; and 4) future research should focus on defining the distribution and variability of carbon with depth and under differential management.

INTRODUCTION

Soil carbon sequestration is a process by which plants remove carbon dioxide from the atmosphere through photosynthesis, to be stored as decaying plant material in the soil, leaving behind resistant organic matter that persists for variable lengths of time. Soils hold about 75% of the carbon stored on land, about twice that stored in the atmosphere, and play a large role in the global carbon cycle (Swift 2001). Carbon is sequestered when organic matter accumulates faster than it is respired to carbon dioxide by soil heterotrophs. Soil carbon storage promotes improved drainage, soil structure, water holding capacity, and other important soil properties that improve agricultural productivity (Lal et al. 2004).

Different types of organic matter are differentially resistant to microbial attack, with some materials showing resistance for hours and others for millennia (Kononova 1975, Schlesinger 1977, VanVeen and Paul 1981). Organic matter can also be protected by adsorption to clay surfaces and by residing inside soil aggregates, which prevent microbes from physically accessing the carbon (Six et al. 1998, DeGryze et al. 2004). Additionally, microbial decomposition requires appropriate environmental conditions—soils that are too cold or wet inhibit microbial growth and accumulate carbon (Schuur et al. 2008).

Agricultural soils are particularly important for carbon storage because of their potential for future sequestration (Schlesinger 1995, Murty et al. 2002). Conversion of native ecosystems to agriculture typically leads to 40-60% of soil carbon's conversion to carbon dioxide as disturbance accelerates heterotrophic activity. Globally, soils have contributed ca. 124 Pg of carbon to the atmosphere from 1850 to 1990 (Houghton and Hackler 2001). This contrasts to current rates of atmospheric increase that exceed 4.1 Pg C y^{-1} (Canadell et al. 2007).

Interest in restoring this lost carbon as a readily deployable, low cost option to help offset global climate change (IPCC 2001) has led to interest in management techniques that promote carbon storage. These include reduced or no-tillage technology to slow decomposition, cover crops that add extra (perhaps recalcitrant) residue to soil, and crop rotations that changes the biochemistry and quantity of crop residue. Other possible strategies to increase carbon storage include converting cropland from annual to perennial cropping systems, abandoning agricultural fields to succession, and planting long-rotation tree crops (West and Post 2002, Lal et al. 2004, Angers and Caron 1998, Martens 2000).

Conversion of cropland to perennial crops or to successional communities have been estimated to sequester as much as 60 g soil C m^{-2} y^{-1} (CAST 2004) and conversion to no-till annual crops have been estimated to sequester C at about half this rate (West & Post, 2002; Lal, 2003). However, most of these estimates of sequestration capacity are based on studies of soil carbon change in surface soils, and recent concerns that similar gains may not be occurring at depth (Baker et al. 2007, VandenBygaart et al. 2003, Carter 2005, Dolan et al. 2006) call into question the overall value of no-till and other management strategies for storing soil carbon. For example, of 67 studies reviewed by West and Post (2002) comparing soil carbon sequestration in different management systems, in only 2 studies were soils sampled below 30 cm. Sampling at depth is more difficult and expensive. It may also be harder to detect carbon changes at depth because carbon concentrations are lower and may be more variable due to the lack of homogenization that occurs with tillage.

Prior research on soil carbon at our site in southwest Michigan has shown soil carbon accumulation in the surface soil under no-till, perennial systems, and successional systems. Robertson et al. (2000) documented no-till carbon gains of 30 g C m^{-2} y^{-1} in the upper 7 cm of surface soil examined. Grandy and Robertson (2007) reported gains of soil carbon under no-till, perennial cropping, and successional systems to 5 cm depth. Subramanian (2008) sampled carbon to 15cm depth, and found carbon levels to be higher in no-till and organic management systems compared to conventional. But in this case, the no-till and organic systems had not shown any overall gain of carbon, but had avoided the loss of carbon that appear to have occurred in the conventional system. Documenting potential change in the entire soil profile is important for understanding the total effect of management on carbon sequestration, especially if decreases at depth due to no-till might offset increases in surface soils. Our objective in this study is to examine changes of accumulation of carbon at depth (to 1 meter) under different agricultural management regimes, and additionally to test the hypothesis that carbon gains that might be observed in surface soils of various treatments are offset by losses lower in the profile.

MATERIALS AND METHODS

Site Description

We collected soil cores to compare soil carbon storage from a field experiment that was established at the Kellogg Biological Station (KBS) in 1988. Multiple treatments at the KBS Long-Term Ecological Research Site (LTER, http//lter.kbs.msu.edu) form a management intensity gradient that is well suited to ecosystem comparisons. KBS is located in SW Michigan within the northern portion of the U.S. maize belt (85° 24'W, 42° 24'N). The site lies on Kalamazoo (fine loamy) and Oshtemo (coarse loamy) soils, both developed on glacial outwash and mixed, mesic Typic Hapludalfs, which mainly differ in the thickness of the B/Bt horizon. The Kalamazoo series has a somewhat thicker upper B/Bt horizon than the Oshtemo. Annual rainfall at KBS is 920mm/yr, distributed evenly through the year. The water holding capacity of these soils is approximately 150 mm to 1.5 m depth (Crum and Collins 1995).

Experimental Design

Seven experimental treatments were established in 1989 in replicated 1-ha plots organized in a complete block design (n=6). Additional offsite native deciduous forest plots were added in 1991 (n=3). For maps of the treatments and experimental design, see www.lter.kbs.msu.edu/. Cropping systems include four maize (*Zea mays*)-soybean (*Glycine max*)-wheat (*Triticum aestivum*) rotations managed either i) with conventional inputs and tillage, ii) with conventional inputs and no tillage, iii) with tillage and reduced chemical inputs, or iv) organically with tillage and no chemical inputs. The latter two treatments include a leguminous winter cover crop grown following the maize and wheat portions of the rotation to provide N to the following grain crops. All cropping systems

Table 3.1 Soil profile characteristics at the KBS LTER site. The dominant KBS soil series are the Kalamazoo (fine-loamy, mixed, mesic Typic Hapludalfs) and Oshtemo (coarse-loamy, mixed, mesic Typic Hapludalfs) series. Data are from Crum and Collins (1995). Abbreviation nd denotes missing data.

Horizon	Depth	Texture			Bulk Density	pH
		Sand	Silt	Clay		
			($g\ kg^{-1}$)		*($mg\ m^{-3}$)*	
Kalamazoo Series						
Ap	0-30	43	38	19	1.6	5.5
E	30-41	39	41	20	1.7	5.7
Bt1	41-69	48	23	29	1.8	5.3
2Bt2	69-88	79	4	17	nd	5.2
2E/Bt	88-152	93	0	7	nd	5.6
Oshtemo Series						
Ap	0-25	59	27	14	1.6	5.7
E	25-41	64	22	14	1.7	5.7
Bt1	41-57	67	13	20	1.8	5.8
2Bt2	57-97	83	4	13	nd	5.8
2E/Bt	97-152	92	0	8	nd	6.0

Table 3.2: Management summaries for cropping systems and successional communities at the Kellogg Biological Station Long Term Ecological Research Site. .

	Tillage	Nitrogen Fertilizer[1]	Weed Control
Annual Crops (maize-soybean-wheat rotation)			
Conventional	Conventional	Conventional	Chemical (Conventional Rate) and mechanical
No-Till	None	Conventional	Chemical (Conventional Rate)
Reduced Input	Conventional	1/3 Conventional with cover crop	Chemical (1/3 Conventional Rate) and mechanical
Organic	Conventional	Cover crop	Mechanical
Perennial Crops			
Alfalfa	None	None	None
Poplar	None	Starter[2]	None
Conifer	None	None	None
Unmanaged Communities			
Early Successional	None	None	None
Mid-Successional (HT)[3]	None	None	None
Mid-Successional (NT)[3]	None	None	None
Deciduous Forest	None	None	None

[1]Conventional refers to the recommended rate based on soil testing and best management practices.

[2]60 kg N ha^{-1} in 1989 only.

[3]HT = historically tilled, NT = never tilled

were planted and harvested during the same periods. Fertilizer application rates for the conventional input systems were based on soil-test recommendations.

From 1989 to 1992, the conventional tillage and no-till systems were in a maize-soybean rotation, and the reduced-input and organic systems were in a maize-soybean-wheat rotation. Since 1993, all four of the annual grain crops have been in a maize-soybean-wheat rotation. The conventional, reduced-input, and organic systems received primary tillage, which consisted of moldboard plowing from 1989 to 1998 and chisel plowing from 1999 onward, all in the spring. 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 and organic systems received additional inter-row cultivation and rotary hoeing as needed for weed control.

The three perennial systems included alfalfa (*Medicago sativa*), fast growing clonal poplar (*Populus* x *euramericana*) trees, and conifer stands established before 1950. The conifer stands were 50-70 years old at the time of this study and were mixed stands containing red and white pine (*Pinus resinosa* and *P. strobes, respectively*), Norway Spruce (*Picea abies*), and some understory Black Cherry (*Prunus serotina*). The alfalfa was harvested 3-4 times per year, and was reestablished 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. Poplar trees were planted in 1989, and starter fertilizer (only) was added at that time. Creeping red fescue was used as a cover crop to prevent soil erosion. Poplar trees were harvested in 1999, and allowed to coppice (regrow from the cut stems).

The four unmanaged successional systems included: 1) an early successional system that was abandoned from agriculture in 1989 (n=6), 2) a historically tilled, mid-successional system that was released from agriculture in the 1950's (n=3), 3) a never tilled pasture that was cleared from forest in 1960 (n=4), and 4) an old-growth oak-hickory forest that has never been cleared or plowed (n=3). The early successional system has been burned annually in the spring since 1997, and the never-tilled pasture is mown every fall with mown biomass left in place.

Soil Sampling and Analysis

Soils from all sites were taken sequentially by replicate from May 31 to October 19, 2001 with a hydraulic sampler (Geoprobe, Salina, Kansas) that collected 6 cm diameter intact cores to 1 meter depth. Cores were taken using the direct push method, which uses vibratory driving to avoid compaction. Each core was removed from the soil in its own acrylic sleeve and taken into the lab for classification into soil horizons. Two cores were taken at each of five long-term sampling stations within each replicate plot.

Soil profiles were classified according to soil horizon, and each horizon was measured for length and then split into individual profile segments. Segments were individually weighed and analyzed for soil carbon and nitrogen. Soil segments were first passed through a 4mm sieve and mixed. A subsample was then oven dried at 60 degrees C. Duplicate subsamples from each dried sample were then finely ground in a roller mill, 10 mg was weighed into each of three tin foil cups, and then analyzed for C and N using a Carlo Erba NA1500 Series II C N Analyzer (Carlo-Erba Instruments, Milan, Italy). The coefficient of variation (c.v.) was <5% for all analytical replications; triplicate samples that exceeded 0.05 analytical c.v. were re-analyzed. We used for soil calibration standards O519 and O559 provided by USDA-ARS Pendleton, OR. Subsamples were reacted with hydrochloric acid to test for the presence of carbonates in 440 of the 800 samples of different treatments and depths. A pressure transducer was used to measure changes in pressure due to the presence of carbonate minerals (Evangelou et al. 1984, Loeppert and Suarez 1996), with a detection limit of 0.1% inorganic carbon. No significant amounts were found.

Statistical Analysis

The experiment was analyzed as a completely randomized design (CRD), with 11 treatments and 3 to 6 replicates of each treatment. Treatments were compared based on bulk density, horizon length, carbon concentrations, and total carbon in each horizon as well as total carbon to 1 meter. Total carbon was calculated by multiplying the percent carbon times the average bulk density and horizon length for that depth increment. The deciduous forest and never-tilled mid-successional systems were analyzed separately due to their lack of historic lack of tillage. All comparisons were completed using SAS (SAS Version 8.2, SAS Institute 1999). Proc mixed was used with the lsmeans statement to determine treatment differences.

RESULTS

Horizon Depth

A/Ap horizon depths ranged from 14.2 cm to 22.3 cm and differed little by treatment except among plots that differed in plowing history (Table 3.3, Figure 3.1). All sites that had been plowed previously showed similar A/Ap horizon depths of 20.8 $\pm$ 0.3

cm, whereas the A/Ap horizons in the never-tilled mid-successional and deciduous forest systems had significantly different ($p \leq 0.05$) mean depths of 14.2 $\pm$ 0.2 cm and 16.9 $\pm$ 1.3 cm, respectively. The annual cropping systems had A/Ap horizons of 19.9 $\pm$ 2.3, 20.0 $\pm$ 1.0, 21.6 $\pm$ 1.4, and 19.5 $\pm$ 1.4 cm in the conventional, no-till, reduced-input, and organic systems, respectively. The perennial systems had A/Ap horizons of 21.2 $\pm$ 2.0, 21.3 $\pm$ 2.7, and 20.9 $\pm$ 1.0 cm in the alfalfa, poplar, and conifer systems, respectively. The early successional and historically tilled mid-successional system had A/Ap horizons of 22.3 $\pm$ 1.7 and 20.8 $\pm$ 2.2 cm, respectively.

The B/Bt horizon lengths were similar in all treatments except the poplars, which had the smallest B/Bt horizon (30.0 $\pm$ 2.2 cm) as compared to 35.9 $\pm$ 0.6 cm in all others. The annual systems had B/Bt horizons of 35.8 $\pm$ 3.9, 35.8 $\pm$ 2.0, 36.2 $\pm$ 3.2, and 36.7 $\pm$ 3.4 cm in the conventional, no-till, reduced-input, and organic systems, respectively. The alfalfa and conifer systems had B/Bt horizons of 35.9 $\pm$ 2.4 and 34.7 $\pm$ 4.6 cm, and the early successional, historically tilled mid-successional, never tilled mid-successional, and deciduous forest systems had B/Bt horizons of 35.8 $\pm$ 3.4, 33.2 $\pm$ 3.9, 35.0 $\pm$ 1.1, and 40.0 $\pm$ 4.3 cm, respectively.

All treatments had a similar Bt2/C horizon length of 42.2 $\pm$ 0.8 cm. The annual systems had Bt2/C horizons of 43.0 $\pm$ 2.3, 41.3 $\pm$ 1.9, 40.1 $\pm$ 2.8, and 41.6 $\pm$ 2.4 cm in the conventional, no-till, reduced-input, and organic systems, respectively. The alfalfa, poplar, and conifer systems had Bt2/C horizons of 40.5 $\pm$ 3.3, 46.1 $\pm$ 4.0, and 43.1 $\pm$ 6.0 cm, respectively. The early successional, historically tilled mid-successional, never tilled mid-successional, and deciduous forest systems had Bt2/C horizons of 41.1 $\pm$ 2.2, 38.9 $\pm$

6.5, 47.9 $\pm$ 2.8, and 40.6 $\pm$ 4.1 cm, respectively. None of the differences were statistically significant ($p \leq 0.05$).

Bulk Density

Bulk density was generally lower at the surface than in lower profile positions in all systems (Table 3.2). A/Ap bulk density was less in the never-tilled successional system (1.2 $\pm$ 0.03 g cm^{-3}, $p \leq 0.05$) than in all other systems (1.47 g cm^{-3} $\pm$ 0.03). The annual systems had bulk densities of 1.6 $\pm$ 0.05, 1.5 $\pm$ 0.05, 1.5 $\pm$ 0.02, and 1.5 $\pm$ 0.04 g cm^{-3} in the conventional, no-till, reduced input, and organic systems, respectively. The perennial crops had A/Ap horizon bulk densities of 1.5 $\pm$ 0.04, 1.4 $\pm$ 0.05, and 1.4 $\pm$ 0.05 g cm^{-3} in the alfalfa, poplar, and conifer systems, respectively. The early successional, historically tilled mid-successional, and deciduous forest systems had bulk densities of 1.5 $\pm$ 0.03, 1.5 $\pm$ 0.04, and 1.3 $\pm$ 0.03 g cm^{-3}, respectively.

Bulk density of B/Bt horizon soils showed very little variation among treatments (range 1.6-1.8 g cm^{-3}). The annual systems were most similar to one another, with the conventional, no-till, reduced input, and organic systems having a bulk density of 1.7 $\pm$ 0.05, 1.6 $\pm$ 0.03, 1.6 $\pm$ 0.03, and 1.6 $\pm$ 0.04 g cm^{-3}, respectively. The perennial treatments were equally similar, with 1.7 $\pm$ 0.05, 1.7 $\pm$ 0.03, and 1.7 $\pm$ 0.03 g cm^{-3} in the alfalfa, poplar, and conifer systems, respectively. The historically tilled mid-successional system had higher bulk density (1.8 $\pm$ 0.09 g cm^{-3}) than the early successional (1.6 $\pm$ 0.04 g cm^{-3}), never tilled mid-successional (1.6 $\pm$ 0.02 g cm^{-3}), and deciduous forest systems (1.7 $\pm$ 0.08 g cm^{-3}), but not all of these differences were significant at the $p \leq 0.05$ level: In only the early successional community was B/Bt bulk density significantly different from that in the conventional annual system ($p \leq 0.05$).

In the Bt2/C horizon, bulk densities ranged from 1.5 to 1.7 g cm^{-3}, with no consistent patterns with management (overall mean 1.64 ± 0.07 g cm^{-3}). The annual treatments had bulk densities of 1.6 ± 0.03, 1.6 ± 0.03, 1.7 ± 0.03, and 1.6 ± 0.04 g cm^{-3} in the conventional, no-till, reduced input, and organic systems, respectively. Of the perennial systems, the alfalfa, poplar, and conifers had bulk densities of 1.6 ± 0.05, 1.7 ± 0.03, and 1.7 ± 0.04 g cm^{-3}, respectively. In the successional systems bulk densities were 1.6 ± 0.03, 1.7 ± 0.01, 1.5 ± 0.02, and 1.7 ± 0.02 g cm^{-3} in the early successional, historically tilled mid successional, never tilled mid-successional, and deciduous forest system, respectively. As for the B/Bt horizon, in only a few cases were Bt2/C bulk density differences statistically significant ($p \leq 0.05$).

Soil Carbon Concentrations

Soil carbon concentrations ranged from 0.5 to 29.5 g C kg soil^{-1}. Concentrations were higher at the surface than at lower soil horizons, and also showed a pattern of increasing variability with depth (Table 3.4). We found highest carbon concentrations in the A/Ap horizons of the never tilled successional community (29.5 ± 1.1 g C kg soil^{-1}). We found the lowest A/Ap carbon concentrations in the conventional and reduced input row crop systems (10.4 ± 0.3 and 11.1 ± 0.4 g C kg soil^{-1}, respectively). Among the annual cropping systems, the no-till (11.5 ± 0.4 g C kg soil^{-1}) and organic (12.2 ± 0.4 g C kg soil^{-1}) systems had significantly greater C concentrations ($p \leq 0.05$) than the conventional system; the reduced input system (11.1 ± 1.2 g C kg soil^{-1}) was intermediate to these.

In the B/Bt horizon, carbon concentrations ranged from 2.6 ± 0.6 g C kg soil^{-1} in the historically tilled mid-successional field to 4.8 ± 0.3 g C kg soil^{-1} in the early successional field. Concentrations were statistically similar among all annual and perennial systems; in the annual systems carbon concentrations were 4.2 ± 0.7, $4.4 \pm 0.0.5$, 3.5 ± 0.5, and 4.6 ± 0.5 g C kg soil^{-1} in the conventional, no-till, reduced input, and organic systems, respectively. In the perennial systems concentrations were 4.5 ± 0.7, 3.9 ± 0.9, and 3.1 ± 1.2 g C kg soil^{-1} in the alfalfa, poplars, and conifers, respectively. The early successional, never-tilled mid-successional, and deciduous forest sites had similar ($p > 0.05$) carbon concentrations of 4.8 ± 0.3, 4.3 ± 0.4 and 4.0 ± 1.0 g C kg soil^{-1}, respectively. In the successional communities only in mid-successional historically tilled soils were C concentrations significantly different (2.6 ± 0.6 g C kg soil^{-1}, $p \leq 0.05$) from the others.

In the Bt2/C horizon, carbon concentrations ranged from 0.5 ± 0.2 g C kg soil^{-1} in the conifers to 6.0 ± 2.2 g C kg soil^{-1} in the alfalfa. The annual treatments all had similar ($p > 0.05$) carbon concentrations of 1.8 ± 0.2, 3.5 ± 1.4, 1.5 ± 0.3, and 2.7 ± 0.9 g C kg soil^{-1} in the conventional, no-till, reduced input, and organic systems, respectively. The alfalfa and poplar had similar carbon concentrations of 6.0 ± 2.2 and 5.2 ± 2.3 g C kg soil^{-1} respectively, which were significantly higher than in the conifer systems (0.5 ± 0.2 g C kg soil^{-1}, $p \leq 0.05$). Of the successional treatments, the historically-tilled mid-successional system (0.9 ± 0.1 g C kg soil^{-1}) had lower soil carbon concentrations than the early or never-tilled successional systems (1.9 ± 0.2 and 1.7 ± 0.2 g C kg soil^{-1}, respectively, $p \leq 0.05$), but concentrations were similar to those in the deciduous forest system (1.3 ± 0.4 g C kg soil^{-1}, $p > 0.05$).

Variability in carbon concentrations was lowest in the A/Ap horizon, ranging from a coefficient of variation (CV) of 0.02 in the alfalfa to 0.40 in the historically tilled mid-successional and poplar systems with a mean CV of 0.18 ± 0.14. The annual systems had CVs of 0.07, 0.09, 0.26, and 0.08 in the conventional, no-till, reduced input, and organic systems, respectively. The perennial crops had a wider range in CVs, with 0.02, 0.40, and 0.24 in the alfalfa, poplars, and conifers, respectively. The successional systems also had a wide range of CVs, with the early successional, historically tilled mid-successional, never tilled mid-successional, and deciduous forest systems having CVs of 0.09, 0.40, 0.07, and 0.25, respectively.

In the B/Bt horizon, CVs for carbon concentrations were about twice those in the A/Ap horizon (mean 0.37 ± 0.15), and ranged from 0.15 in the early successional system to 0.67 in the conifers. The annual systems had CVs of 0.41, 0.28, 0.35, and 0.27 in the conventional, no-till, reduced-input, and organic systems, respectively. The perennials had CVs of 0.38, 0.57, and 0.67 in the alfalfa, poplar, and conifers, and in the successional systems, the early successional, historically tilled mid-successional, never tilled mid-successional, and deciduous forest system had CVs of 0.15, 0.40, 0.19, and 0.43, respectively.

Spatial variability in carbon concentrations was highest in the Bt2/C horizon; CVs here were about 3.4 times those in the A/Ap horizon (mean 0.61 ± 0.31), ranging from 0.19 in the historically tilled mid-successional system to 1.08 in the poplars. In the annual crops CVs were 0.27, 0.98, 0.49, and 0.82 in the conventional, no-till, reduced-input, and organic systems, respectively. The perennial crops had CVs of 0.90, 1.08, and 0.69 in the alfalfa, poplar, and conifers, respectively. In the successional systems, the early successional, historically tilled mid-successional, never tilled mid-successional, and deciduous forest system had Bt2/C CVs of 0.26, 0.19, 0.47, and 0.53, respectively. Throughout the entire profile, the systems with fewer replicates (n=3, conifers, deciduous forest, and historically tilled mid-successional system) showed higher variation in carbon concentrations than the other systems (n=6).

Total Carbon

Total soil carbon is a function of bulk density, horizon length, and carbon concentration. Management changed the distribution of soil carbon throughout the soil profile (Table 3.4). In the A/Ap horizon, soil carbon levels ranged from 3.0 ± 0.5 kg C m^{-2} in the poplar system to 5.7 ± 1.2 kg C m^{-2} in the never tilled mid-successional system. Among annual crops, the no-till and organic systems had significantly more soil carbon in the A/Ap horizons than did the conventional till system (3.6 ± 0.1 and 3.8 ± 0.1 vs. 3.2 ± 0.1 kg C m^{-2}, $p \leq 0.05$); the reduced input system (3.5 ± 0.4 kg C m^{-2}) was intermediate to but not significantly different from the other annual crops ($p > 0.05$). Among the perennial systems, the conifers had higher A/Ap carbon levels than the alfalfa or the poplars (5.4 ± 0.7 vs. 3.6 ± 0.3 and 3.0 ± 0.5 kg C m^{-2}, $p \leq 0.05$, respectively). And in the successional communities, the never-tilled mid-successional system had greater A/Ap carbon levels than the early successional system (5.7 ± 0.2 vs. 4.5 ± 0.1 kg C m^{-2}, $p \leq 0.05$), though it was similar to the historically tilled mid-successional and deciduous forest systems (3.9 ± 0.9 and 4.7 ± 0.7 kg C m^{-2}, respectively).

In the B/Bt horizon, soil carbon levels ranged from 1.5 $\pm$ 0.4 kg C m^{-2} in the historically tilled mid-successional system to 2.8 $\pm$ 0.2 kg C m^{-2} in the early successional system. B/Bt carbon levels in the annual and perennial treatments were all similar, with the conventional, no-till, reduced input, and organic systems containing 2.4 $\pm$ 0.4, 2.5 $\pm$ 0.3, 2.0 $\pm$ 0.3, and 2.7 $\pm$ 0.3 kg C m^{-2}, and the alfalfa, poplars, and conifers containing 2.6 $\pm$ 0.4, 2.3 $\pm$ 0.5, and 1.8 $\pm$ 0.7 kg C m^{-2}, respectively. The early successional (2.8 $\pm$ 0.2 kg C m^{-2}) and never-tilled mid-successional systems (2.6 $\pm$ 0.3 kg C m^{-2}) had higher carbon levels than the historically tilled mid-successional system (1.5 $\pm$ 0.4 kg C m^{-2}, $p \leq 0.05$), but none differed significantly ($p \leq 0.05$) from the deciduous forest system (2.5 $\pm$ 0.6 kg C m^{-2}).

In the Bt2/C horizon, carbon contents ranged from 0.4 $\pm$ 0.1 kg C m^{-2} in conifer soils to 4.1 $\pm$ 1.6 kg C m^{-2} in alfalfa. The annual systems were statistically similar to one another ($p > 0.05$), with 1.2 $\pm$ 0.2, 2.4 $\pm$ 0.9, 1.0 $\pm$ 0.2, and 1.9 $\pm$ 0.6 kg C m^{-2} in the conventional, no-till, reduced input, and organic systems, respectively. The conifers had a lower Bt2/C soil carbon content (0.4 $\pm$ 0.1 kg C m^{-2}, $p \leq 0.05$) than either the alfalfa (4.1 $\pm$ 1.6 kg C m^{-2}) or the poplars (3.6 $\pm$ 1.5 kg C m^{-2}). The early successional (1.3 $\pm$ 0.2 kg C m^{-2}) and never-tilled mid-successional systems (1.2 $\pm$ 0.3 kg C m^{-2}) had higher carbon than the historically tilled mid-successional system (0.6 $\pm$ 0.1 kg C m^{-2}), but all were statistically similar to the deciduous forest system (0.9 $\pm$ 0.3 kg C m^{-2}, $p > 0.05$).

Over the entire profile to 1 meter, soil carbon levels ranged from 6.1 $\pm$ 1.3 kg C m^{-2} in the historically tilled mid-successional system to 10.4 $\pm$ 1.5 kg C m^{-2} in the alfalfa system. All of the annual treatments were similar to one another, with carbon levels of 6.9 $\pm$ 0.6, 8.5 $\pm$ 0.9, 6.5 $\pm$ 0.8, and 8.3 $\pm$ 0.8 kg C m^{-2}, respectively, in the conventional, no-till, reduced input, and organic treatments. The perennial systems were also similar, with 10.4 $\pm$ 1.5, 8.9 $\pm$ 0.8, and 7.6 $\pm$ 1.3 kg C m^{-2}, respectively, in the alfalfa, poplars, and conifers. The early successional (8.6 $\pm$ 0.3 kg C m^{-2}) and never-tilled mid-successional systems (9.6 $\pm$ 0.7 kg C m^{-2}) had more carbon than the historically tilled mid-successional system (6.1 $\pm$ 1.3 kg C m^{-2}, $p \leq 0.05$), but none had statistically different total carbon contents from the deciduous forest (8.1 $\pm$ 1.5 kg C m^{-2}).

Variability of total soil carbon was greater at depth than at the surface. In the A/Ap horizon, CVs for total carbon ranged from 0.05 in the early successional system to 0.41 in the poplars (mean 0.19 $\pm$ 0.13). The annual systems had CVs of 0.08, 0.07, 0.28, and 0.06 in the conventional, no-till, reduced-input, and organic system, respectively. In the perennial systems, CVs were 0.20, 0.41, and 0.22 in the alfalfa, poplar, and conifers, respectively. The early successional, historically tilled mid-successional, never tilled mid-successional, and deciduous forest system had total A/Ap carbon CVs of 0.40, 0.07, 0.26, and 0.19, respectively.

In contrast, variability in total carbon in the B/Bt horizon was about twice as high as in the A/Ap horizon, with CVs ranging from 0.17 in the early successional system to 0.67 in the conifers (mean 0.38 $\pm$ 0.14). The annual treatments had CVs of 0.41, 0.29, 0.37, and 0.27 in the conventional, no-till, reduced input, and organic systems, respectively. In the perennial crops CVs for total B/Bt horizon carbon were 0.38, 0.53, and 0.67 in the alfalfa, poplars, and conifers, respectively. The successional systems had B/Bt total carbon CVs of 0.17, 0.46, 0.23, and 0.42 in the early successional, historically tilled mid-successional, never tilled mid-successional, and deciduous forest system, respectively.

In the Bt2/C horizon, the CVs for total carbon were still higher, more than three times greater than in the A/Ap horizon, ranging from 0.29 in the historically tilled mid-successional field to 1.02 in the poplars (mean 0.61 $\pm$ 0.26). The annual systems all had high variability, with CVs of 0.41, 0.92, 0.49, and 0.77 in the conventional, no-till, reduced input, and organic systems, respectively. The alfalfa, poplar, and conifers had Bt2/C total carbon CVs of 0.96, 1.02, and 0.43 in the alfalfa, poplar, and conifers, respectively. The successional systems had somewhat lower variability, with CVs of 0.38, 0.29, 0.50, and 0.58 in the early successional, historically tilled mid-successional, never tilled mid-successional, and deciduous forest system, respectively.

Variation across the entire soil profile in total carbon to 1 meter ranged from a CV of 0.09 in the early successional system to 0.37 in the historically tilled mid-successional system (mean CV = 0.25 $\pm$ 0.09). The annual systems had CVs for the total profile of 0.21, 0.26, 0.30, and 0.24 in the conventional, no-till, reduced input, and organic systems, respectively. The alfalfa, poplar, and conifers had total profile carbon CVs of 0.35, 0.22, and 0.30 in the alfalfa, poplar, and conifers, respectively. The successional systems had CVs of 0.09, 0.37, 0.15, and 0.32 in the early successional, historically tilled mid-successional, never tilled mid-successional, and deciduous forest system, respectively.

Percent Nitrogen and C:N ratios

In the A/Ap horizon, all the annual and perennial treatments had similar concentrations of nitrogen in the soil (ranging from 1.12 to 1.35 g N kg^{-1} soil, see Table 3.5). The never tilled mid-successional field and deciduous forest had significantly more nitrogen than any of the other treatments, with 2.48 ($\pm$ 0.16 s.e.) and 2.05 ($\pm$ 0.19) g N kg^{-}

^{1} soil, respectively. The C/N ratio of the A/Ap horizon was highest in the conifers (14.01 (± 0.68)), although the deciduous forest and mid-successional systems also had high C/N ratios (range 11.51-12.42).

In the B/Bt horizon, the nitrogen concentrations in the soil ranged from 0.45 to 0.73 g N kg^{-1} soil. All the annual treatments were similar, while the conifers were significantly lower than the other perennial crops. The deciduous forest site had similar nitrogen concentrations to all the other successional treatments, with the historically tilled mid-successional treatment having the lowest nitrogen concentrations (0.45 g N kg^{-1} soil), and the never-tilled mid-successional treatment having the highest concentrations of the successional treatments (0.72g N kg^{-1} soil). The C/N ratio of the B/Bt horizon was more variable than in the A/Ap horizon, and ranged from 6.43 (± 0.29) in the never-tilled mid-successional treatment to 10.73 (± 2.33) in the deciduous forest treatment.

In the Bt2/C horizon, the nitrogen concentrations ranged from 0.19 g N kg^{-1} soil in the conifers to 0.53 g N kg^{-1} soil in the never-tilled mid-successional system. The C/N ratio of the Bt2/C horizon was more variable than the A/Ap or B/Bt2 horizons, and ranged from 4.46 (± 0.84) in the never-tilled mid-successional system to 13.15 in the no-till annual system.

Table 3.3 Cropping system and successional community effects on soil horizon thickness and bulk density to 100 cm soil depth at KBS LTER Site in 2001. Results are shown as mean (standard error). Replication is n=6 plots for annual crops, alfalfa, poplar, and early successional communities; n=4 mid-successional never-tilled (NT) sites, and n=3 sites for the conifers, mid-successional historically tilled (HT) communities, and deciduous forest. Systems with different lower case letters within columns are significantly different ($p \leq 0.05$).

	A/Ap		B/Bt		Bt2/C	
	Thickness	Bulk Density	Thickness	Bulk Density	Thickness	Bulk Density
	Cm	g cm^{-3}	Cm	g cm^{-3}	cm	g cm^{-3}
Annual Crops (Maize-Soybean-Wheat Rotation)						
Conventional	19.9 (2.30)[ab]	1.6 (0.05)[a]	35.8 (3.85)[ab]	1.7 (0.05)[ab]	43.0 (2.31)[a]	1.6 (0.03)[a]
No-till	20.0 (0.97)[ab]	1.5 (0.05)[a]	35.8 (1.99)[ab]	1.6 (0.03)[b]	41.3 (1.86)[a]	1.6 (0.03)[a]
Reduced Input	21.6 (1.43)[a]	1.5 (0.02)[a]	36.2 (3.24)[ab]	1.6 (0.03)[b]	40.1 (2.76)[a]	1.7 (0.03)[b]
Organic	19.5 (1.43)[ab]	1.5 (0.04)[a]	36.7 (3.43)[ab]	1.6 (0.04)[ab]	41.6 (2.41)[a]	1.6 (0.04)[ab]
Perennial Crops						
Alfalfa	21.2 (1.97)[ab]	1.5 (0.04)[ab]	35.9 (2.44)[ab]	1.7 (0.05)[ab]	40.5 (3.34)[a]	1.6 (0.05)[ab]
Poplar	21.3 (2.65)[ab]	1.4 (0.05)[ab]	30.0 (2.21)[b]	1.7 (0.03)[ab]	46.1 (3.95)[a]	1.7 (0.03)[b]
Conifers	20.9 (0.95)[a]	1.4 (0.05)[ab]	34.7 (4.56)[ab]	1.7 (0.03)[ac]	43.1 (5.96)[a]	1.7 (0.04)[b]
Successional Communities						
Early Succession	22.3 (1.67)[a]	1.5 (0.03)[ab]	35.8 (3.39)[ab]	1.6 (0.04)[bc]	41.1 (2.19)[a]	1.6 (0.03)[a]
Mid-Successional (HT)	20.8 (2.21)[ab]	1.5 (0.04)[ab]	33.2 (3.86)[ab]	1.8 (0.09)[a]	38.9 (6.54)[a]	1.7 (0.01)[b]
Mid-Successional (NT)	14.2 (0.20)[c]	1.2 (0.03)[c]	35.0 (1.06)[a]	1.6 (0.02)[b]	47.9 (2.80)[a]	1.5 (0.02)[c]
Deciduous Forest	16.9 (1.25)[b]	1.3 (0.02)[b]	40.0 (4.26)[a]	1.7 (0.08)[ab]	40.6 (4.13)[a]	1.7 (0.02)[b]

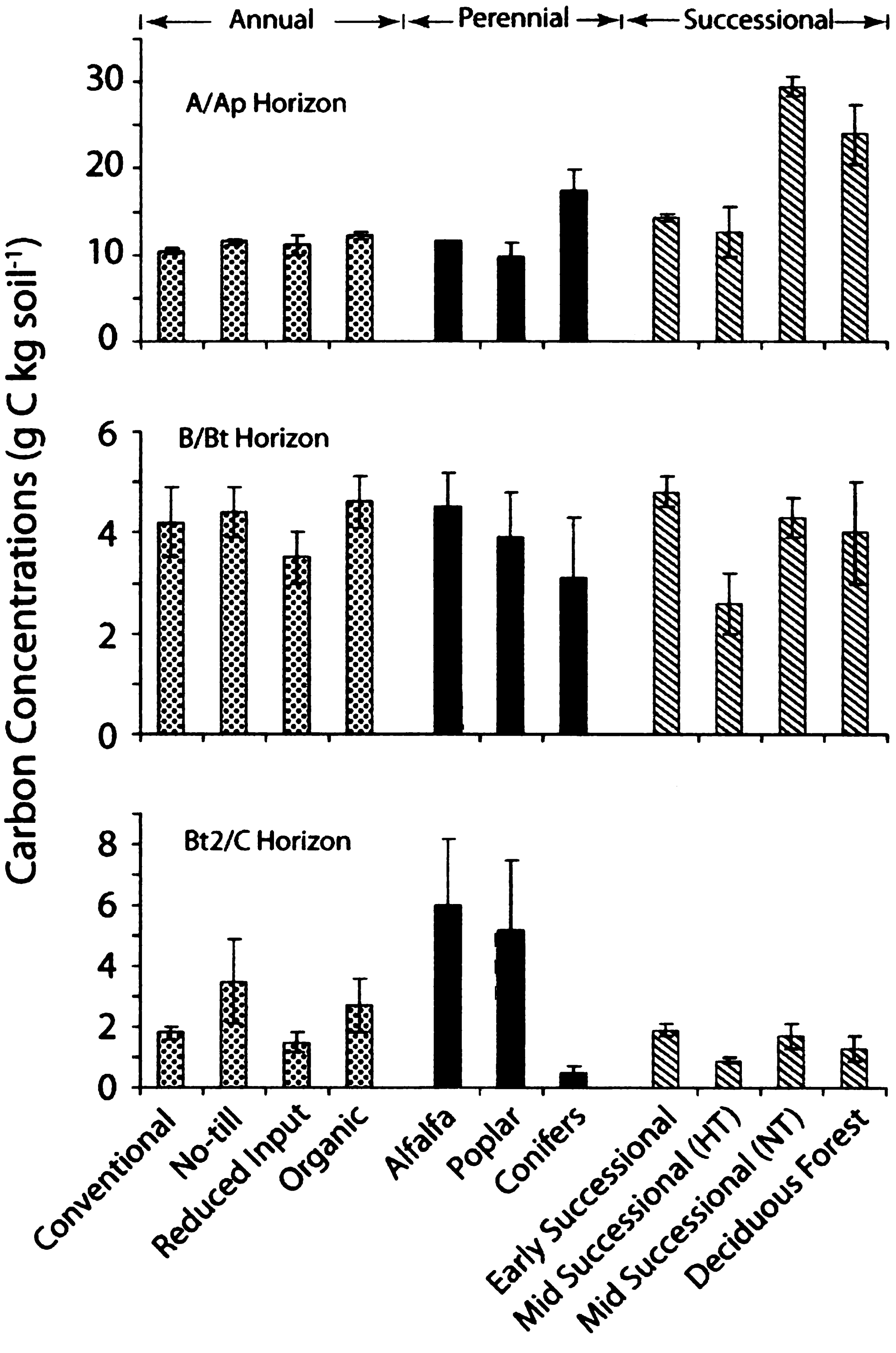

Figure 3.1: Carbon concentrations in the A/Ap, B/Bt, and Bt2/C horizon in the KBS LTER treatments (in g C kg soil^{-1}). Error bars represent standard errors. For significant differences among treatments see Table 3.4.

Table 3.4: Cropping system and successional community effects on soil carbon levels to 100 cm soil depth at the KBS LTER site in 2001. Values are given as mean (standard error).

	A/Ap		B/Bt		Bt2/C		Total
	g C kg soil^{-1}	kg C m^{-2}	g C kg soil^{-1}	kg C m^{-2}	g C kg soil^{-1}	kg C m^{-2}	kg C m^{-2}
Annual Crops (Maize-Soybean-Wheat Rotation)							
Conventional	10.4 (0.3)^{a}	3.2 (0.1)^{a}	4.2 (0.7)^{abc}	2.4 (0.4)^{abc}	1.8 (0.2)^{a}	1.2 (0.2)^{a}	6.9 (0.6)^{ab}
No-till	11.5 (0.4)^{b}	3.6 (0.1)^{b}	4.4 (0.5)^{ab}	2.5 (0.3)^{ab}	3.5 (1.4)^{ab}	2.4 (0.9)^{ab}	8.5 (0.9)^{ac}
Reduced Input	11.1 (1.2)^{ab}	3.5 (0.4)^{ab}	3.5 (0.5)^{bc}	2.0 (0.3)^{bc}	1.5 (0.3)^{ab}	1.0 (0.2)^{ab}	6.5 (0.8)^{a}
Organic	12.2 (0.4)^{b}	3.8 (0.1)^{b}	4.6 (0.5)^{ab}	2.7 (0.3)^{ab}	2.7 (0.9)^{a}	1.9 (0.6)^{a}	8.3 (0.8)^{ac}
Perennial Crops							
Alfalfa	11.6 (0.1)^{b}	3.6 (0.3)^{ab}	4.5 (0.7)^{ab}	2.6 (0.4)^{ab}	6.0 (2.2)^{a}	4.1 (1.6)^{a}	10.4 (1.5)^{bc}
Poplar	9.8 (1.6)^{b}	3.0 (0.5)^{ab}	3.9 (0.9)^{abc}	2.3 (0.5)^{abc}	5.2 (2.3)^{ab}	3.6(1.5)^{ab}	8.9 (0.8)^{bc}
Conifers	17.4 (2.4)^{cd}	5.4 (0.7)^{cd}	3.1 (1.2)^{abc}	1.8 (0.7)^{abc}	0.5 (0.2)^{c}	0.4 (0.1)^{c}	7.6 (1.3)^{ac}
Successional Communities							
Early Successional	14.3 (0.5)^{c}	4.5 (0.1)^{c}	4.8 (0.3)^{a}	2.8 (0.2)^{a}	1.9 (0.2)^{a}	1.3 (0.2)^{a}	8.6 (0.3)^{c}
Mid-Success. (HT)[1]	12.7 (2.9)^{ab}	3.9 (0.9)^{abcd}	2.6 (0.6)^{c}	1.5 (0.4)^{c}	0.9 (0.1)^{bc}	0.6 (0.1)^{bc}	6.1 (1.3)^{a}
Mid-Success. (NT)[1]	29.5 (1.1)^{d}	5.7 (0.2)^{d}	4.3 (0.4)^{ab}	2.6 (0.3)^{ab}	1.7 (0.4)^{a}	1.2 (0.3)^{a}	9.6 (0.7)^{c}
Deciduous Forest	24.0 (3.4)^{d}	4.7 (0.7)^{bcd}	4.0 (1.0)^{abc}	2.5 (0.6)^{abc}	1.3 (0.4)^{abc}	0.9 (0.3)^{abc}	8.1 (1.5)^{ac}

[1]HT=historically tilled, NT=never tilled.

Table 3.5: Cropping system and successional community effects on soil nitrogen concentrations and C/N ratios to 100 cm soil depth at the KBS LTER site in 2001.

	A/Ap		B/Bt		Bt2/C	
	g N kg soil^{-1}	C/N ratio	g N kg soil^{-1}	C/N ratio	g N kg soil^{-1}	C/N ratio
Annual Crops (Maize-Soybean-Wheat Rotation)						
Conventional	1.12 (0.05) ab	9.44 (0.37) a	0.64 (0.09) abd	6.66 (0.51) a	0.41 (0.07) abc	5.52 (1.02) abc
No-till	1.21 (0.02) ac	9.57 (0.32) a	0.67 (0.02) b	6.87 (0.65) abc	0.39 (0.04) abc	13.15 (5.16) abc
Reduced Input	1.24 (0.06) abc	10.14 (0.47). ab	0.60 (0.06) bcd	7.51 (1.03) abc	0.36 (0.05) ab	6.70 (2.06) ab
Organic	1.17 (0.06) ac	10.59 (0.42) b	0.55 (0.05) acd	9.10 (1.14) bc	0.32 (0.03) ad	11.52 (2.61) ad
Perennial Crops						
Alfalfa	1.35 (0.04) bc	9.40 (0.17) a	0.73 (0.06) b	6.95 (0.35) a	0.47 (0.06) bc	9.10 (2.96) b
Poplar	1.17 (0.07) ac	10.75 (0.32) bc	0.63 (0.06) bcd	8.19 (0.69) ab	0.35 (0.03) a	6.39 (0.63) ab
Conifers	1.34 (0.22) abc	14.01 (0.68) d	0.45 (0.04) a	7.12 (1.69) c	0.19 (0.04) d	6.59 (1.47) e
Successional Communities						
Early Successional	1.30 (0.05) c	11.04 (0.10) c	0.59 (0.03) d	8.45 (0.36) bc	0.32 (0.02) abe	8.21 (1.06) acd
Mid Success. (HT)[1]	1.36 (0.17) ac	11.51 (0.96) ce	0.45 (0.04) a	8.83 (1.89) c	0.24 (0.03) ce	10.35 (5.11) de
Mid Success. (NT)[1]	2.48 (0.16) d	11.92 (0.42) e	0.72 (0.05) b	6.43 (0.29) a	0.53 (0.06) c	4.46 (0.84) c
Deciduous Forest	2.05 (0.19) d	12.42 (0.41) e	0.50 (0.10) abd	10.73 (2.33) abc	0.31 (0.03) abe	7.98 (2.57) ad

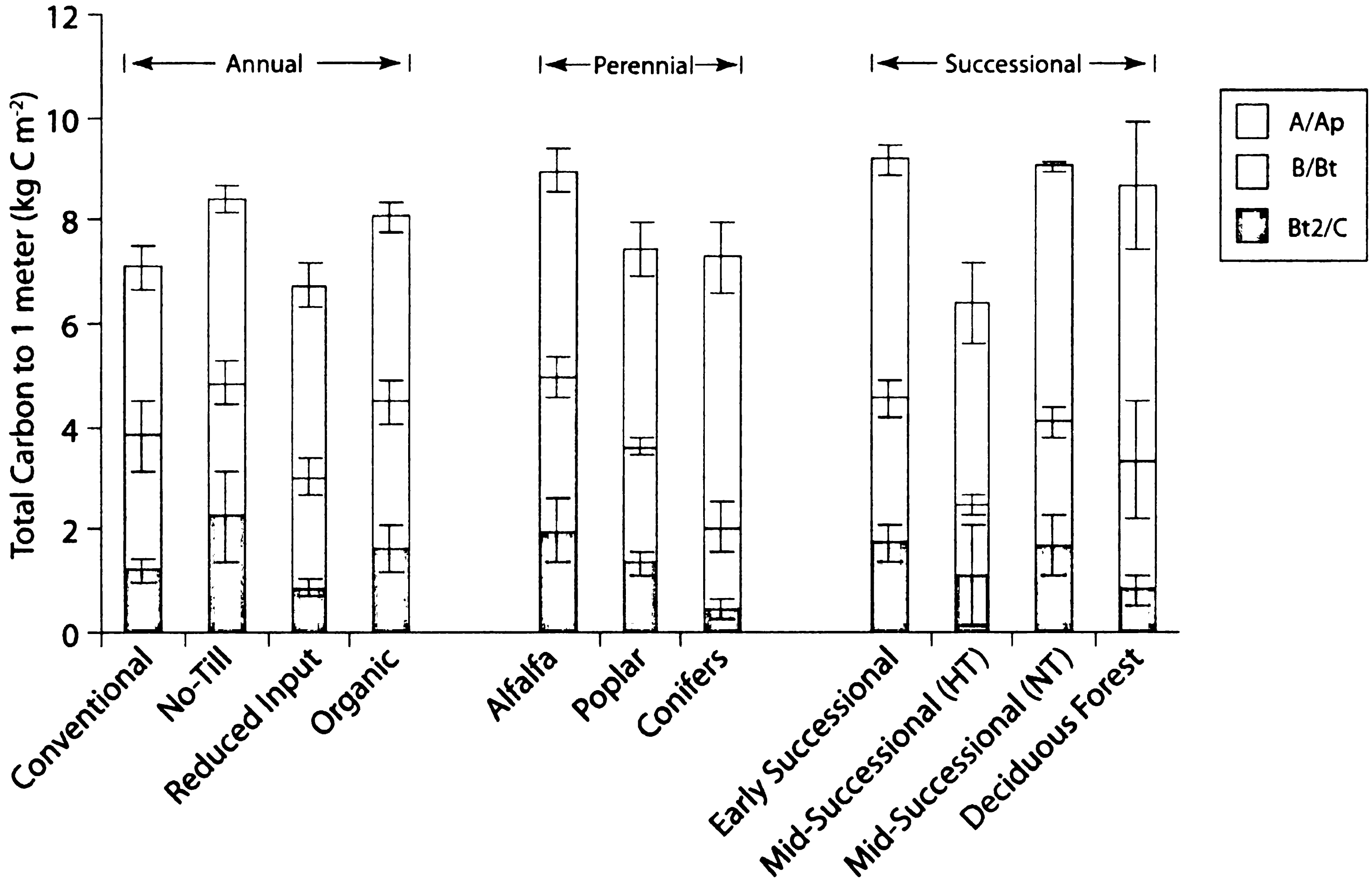

Figure 3.2: Total carbon to 1 meter in KBS LTER treatments (in kg C m^{-2}). Error bars represent standard errors. For significant differences among treatments see Table 3.4.

DISCUSSION

In general we found that surface soil carbon concentrations and total carbon differed significantly among our different systems, as did the distribution of carbon through our 1m profiles. We also found more variability in carbon concentrations and total carbon in the deeper soil horizons than in the surface soil horizons.

Annual treatments

Among the annual cropping treatments, differences in carbon concentrations and total carbon were only significant in the surface horizon. Surface soils in the no-till and organic systems had higher concentrations of carbon than in the conventionally managed system(11.5 and 12.2 vs. 10.4 g C kg soil^{-1}, $p \leq 0.05$), while the reduced input system had intermediate levels not significantly different from others. In total carbon, too, the no-till and organic systems had greater carbon than the conventional systems (3.6 and 3.8 vs. 3.2 kg C m^{-2}, $p \leq 0.05$), while the reduced input system had intermediate levels not significantly different from the other systems. At all other depths, including to one meter, we found no differences among treatments. Robertson et al. (2000), Grandy and Robertson (2007), and Subramanian (2008) also found that no-till systems had higher surface carbon than did the conventionally tilled system at this site, although in these studies surface soils were defined differently. These findings are consistent with global meta analyses of other long-term studies that have shown that no-till systems accumulate surface soil carbon relative to conventional tillage systems (Franzluebbers 2004, Puget and Lal 2005).

Total profile carbon was also greater in the no-till system than in the conventionally tilled system, but differences were not statistically significant (change of

1.5 kg C m^{-2}, p=0.17). The no-till system, for example, contained 1.2 kg C m^{-2} more than the conventionally tilled system in the Bt2/C horizon, but the carbon level was too variable among replicate plots to show statistical significance. The source of the variability in the entire profile is in the B/Bt and Bt2/C horizons, where variability among plots in total carbon was two to three times greater than in the A/Ap horizon (CV = 0.19 in the A/Ap horizon vs. 0.38 in the B/Bt and 0.61 in the Bt2/C horizon. In light of this variability plus the relatively small number of replicate plots (n=6), it is not surprising that we could not document statistically significant changes in carbon at depth. There either is no change in carbon occurring, or the change in carbon is happening very slowly in variable locations. In either case, it does not diminish our finding that carbon is accumulating in these systems in surface soils.

That other studies and reviews have also failed to find whole-profile carbon gains under no-till (Powlson and Jenkinson 1981, Machado et al. 2003, Baker et al. 2007, VandenBygaart et al. 2003, Carter 2005, Dolan et al. 2006) may also be due to lack of statistical power. Powlson and Jenkinson (1981) examined soils to 40cm at Rothamsted, UK, and could find no difference between long-term tillage treatments. Machado et al. (2003) also could find no difference between tillage treatments in a Rhodic Ferrasol in Brazil.

The carbon gain in our organic system is surprising but consistent with earlier studies (Robertson et al. 2000, Grandy and Robertson 2007, and Subramanian 2008) at our site. Even though the soils in this system are exposed to more frequent mechanical disturbance that breaks apart aggregates and exposes carbon therein to microbial attack (Grandy and Robertson 2007), the organic system may be gaining carbon due to cover crop composition. The fact that the reduced input system is accumulating carbon more slowly (or not at all) despite having the same cover crops as the organic system may be due to an interaction with nitrogen fertilizer that could be accelerating the decomposition of plant residue relative to rates of decomposition in the unfertilized soils of the organic system.

It is probably reasonable to assume that soil carbon in the conventional till treatment is at equilibrium, i.e. that it has already lost all of the carbon it is likely to lose while row-cropped and is maintaining its current carbon levels, since this system has been tilled for over a hundred years. If this is the case, then the carbon differences between the conventional system and the no-till and organic systems represent total sequestration rates of 145 and 127 g C m^{-2} y^{-1}. If, on the other hand, the conventional system is losing carbon (Subramanian 2008), then differences represent net sequestration. In this case carbon in the no-till and organic systems are losing carbon more slowly than in the conventional system. In either case no-till and organic management in these soils would represent effective CO_2 mitigation strategies.

Perennials

Our study found that alfalfa contained 3.5 ($\pm$ 1.5) kg C m^{-2} more carbon to 1 meter than the conventional system ($p \leq 0.05$), and contained as much or more carbon than any other system we measured. The other perennial systems did not show any significant gain in carbon compared to the conventional system ($p > 0.05$). The distribution of carbon through the profile in the perennial cropping systems was strikingly different from many of the other systems. The conifers stored most of its carbon in the surface, while the alfalfa and poplars had a much more even distribution of carbon with depth. The alfalfa and poplars also were the only systems that had their highest amounts of carbon in the Bt2/C horizon.

Previous studies at this site have shown that the alfalfa and poplar crops have higher surface carbon levels than the annual cropping systems (Grandy and Robertson 2007, Robertson et al. 2000). While the alfalfa has shown a gain in carbon, most likely due to its deep rooting depth and high root: shoot ratio, the poplar and conifer systems have not. The conifer plots are geographically separated from the alfalfa and poplar treatments, and may have had different initial carbon values than the other treatments. Thus they could have gained carbon, but since they might have started at a different, lower level, the carbon levels may not show a net gain when contemporary stores are compared. The poplar systems, on the other hand, were established at the same time as the other annual and perennial systems so their low carbon content is a treatment effect. The poplar stands seem to be nitrogen limited based on patterns of nitrate leaching (Chapter 2), soil inorganic nitrate (Chapter 4), and nitrous oxide losses (Chapter 4), and has also have lower rates of aboveground net primary productivity than the other systems studied here (Chapter 4), and thus could have lower soil carbon levels due to lower carbon inputs from litterfall and root inputs. Additionally, the lower stores of poplar soil carbon found here relative to those found in previous studies may be related to accelerated soil carbon oxidation in the year following cutting: earlier studies reported carbon contents prior to clearcutting; our findings represent carbon values in summer 2001, about 18 months after harvest in winter 1999. Soils during this period would likely have been warmer and wetter due to less shading and transpiration prior to canopy closure in 2002, and therefore would have experienced accelerated decomposition of accumulated inputs.

Successional Communities

The early successional and never-tilled mid-successional systems contained more total carbon than did the conventional and reduced input annual systems. The historically tilled mid-successional fields and deciduous forest contained similar levels of total carbon as compared to all of the annual cropping systems. Previous studies at this site have shown that the successional systems have higher carbon levels than did the annual and perennial systems (Grandy and Robertson 2007, Robertson et al. 2000). In all of these systems, except the early successional field, the number of replicates was smaller than f for other treatments, and this may have resulted in higher variability than in many of the other treatments. The variability patterns found in our study were similar to those shown in Grandy and Robertson (2007). It is also possible that the mid-successional systems and deciduous forest were not used for agriculture for fertility reasons. This may be particularly true for the historically tilled mid-successional system that was abandoned from agriculture in the 1950's. The complete history of these systems is unknown, but it seems possible that these were more marginal lands removed from production by previous land owners. The successional systems also tend to have higher spatial variability than the cropped systems due to differences in soil disturbance histories (Robertson et al. 1993 and Table 3.4); more samples should probably have been taken from these sites to compensate for this variability.

Spatial Variability

Soil carbon was more spatially variable at depth in all sites. In the Bt2/C horizon carbon concentrations were three times more variable than in the A/Ap horizon, which led to more variability in total soil carbon at depth. Carbon contents tend also to be smaller at depth. Higher variability combined with lower concentrations at depth leads to much greater difficulty finding treatment differences. This in turn leads to difficulty in finding differences between treatments when the entire profile to 1 meter is considered. In the surface horizon, on the other hand, lower variability combined with higher concentrations make it easier to find treatment differences.

Overcoming the difficulty of documenting subtle carbon change at depth requires increasing statistical power. This can be achieved either by increasing the sample size or increasing the effect size, i.e. the difference between the control and treatment groups. In the case of soil carbon, both options are important. The effect size can be increased by waiting more time for carbon levels to change, although for soil carbon this can take decades. The other option is increasing replication. In our study, a retrospective power analysis suggests that more than 40 soil cores per plot would have been needed to achieve a 40% chance of documenting a statistically significant management effect in Bt2/C horizon soils with a change of 20% in the annual treatments and 30% in the perennial and successional systems (S. Kravchenko, personal communication).

Additionally, different management systems distributed their carbon differently within the profile, with some systems (such as conifers) storing the vast majority of their carbon in the surface, and others (such as the alfalfa and no-till systems) storing their carbon more evenly throughout the profile. Sampling only at the surface will bias the studies towards those systems that preferentially store their carbon at the surface. This issue merits further study at other research sites, particularly if soil carbon sequestration is to be used as a mitigation option for global climate change. However, the absence of detectable carbon change at depth does not discount the importance of change at the surface from the standpoint of CO_2 mitigation.

Future studies should include more extensive sampling at depth so that we might better understand the partitioning and variability of carbon in these soils. It stands to reason that the partitioning of soil carbon between different depths should vary depending on the ecosystem as well as the soil type, so documenting these relationships will be critical if soil carbon sequestration will be used as a carbon offset.

Conclusions

1) Eleven years post-establishment our no-till and organic systems had higher carbon concentrations and total carbon in the surface soil (A/Ap horizon) compared to the conventionally managed system, and showed a non-significant trend towards greater soil carbon in the total profile.
2) All of our perennial systems had higher surface soil carbon concentrations and total carbon than the conventionally managed system, and the alfalfa had higher carbon in the total profile. The poplar and conifers showed a non-significant trend of carbon accumulation in the total soil profile.
3) The early successional, never tilled mid-successional, and deciduous forest system had higher soil carbon concentrations and total carbon than the conventionally

managed system in surface soils, and the early successional and never tilled mid-successional system had higher total profile carbon.

4) In general, soil carbon concentrations were 340% more variable in the Bt2/C horizon than in the A/Ap horizon;
5) Different cropping systems distribute their carbon differently throughout the profile, with perennial cropping systems distributing more carbon at depth than either annual crops or successional systems;
6) Systems that have more carbon at the surface do not necessarily have more carbon at depth, and systems with less carbon at the surface do not necessarily have less total carbon; and
7) Future research should focus on defining the distribution and variability of carbon with depth and under differential management strategies in order to gauge the potential importance of deep soil carbon for storing carbon.

CHAPTER 4

TRADE-OFFS AND SYNERGIES IN ECOSYSTEM SERVICES ALONG A MANAGEMENT INTENSITY GRADIENT

ABSTRACT

Agricultural ecosystems are primarily managed for marketable yields, but they provide many other important ecosystem services as well. To assess tradeoffs and synergies among different services provided by major ecosystems in agricultural landscapes we measured agricultural yield, aboveground net primary productivity, greenhouse gas production, soil carbon, soil inorganic nitrogen, drainage, and nitrate leaching in eight 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 poplar trees), an early successional community, and an old-growth deciduous forest. The annual grain systems included conventionally tilled and no-till treatments, both of which included conventional chemical inputs. Annual grain systems also included a reduced-input system and a biologically-based organic system, both of which used tillage for weed control and cover crops for nitrogen. We constructed trade-off curves to illustrate relationships among the ecosystem services produced in these systems. Methane oxidation, nitrous oxide abatement, increased drainage, and carbon sequestration were positively correlated with one another, indicating that managing for one of these services will provide others and will synergistically lead to improved overall ecosystem functioning. We also found trade-offs, including a decrease in soil carbon and methane uptake associated with higher soil nitrate levels. Flower diagrams illustrate the suite of services provided by each system.

Opportunities to manage for multiple ecosystem services should allow farmers and policy makers to better balance trade-offs between productivity and environmental quality.

INTRODUCTION

Agriculture has many environmental costs, in part because agricultural systems tend to be managed for a single ecosystem service, marketable yield, with little attention paid to others. However, agricultural systems also provide other services that are valued by humans and important to the functioning of nearby ecosystems, including regulating services such as climate regulation and water purification, cultural services such as aesthetic attributes and recreation, and supporting services such as nutrient cycling, pollination, and soil formation (Robertson and Swinton 2005, Swinton et al. 2007, Millenium Ecosystem Assessment 2005).

The measurement of most of ecosystem services in agriculture has mostly been limited to only one or two services (e.g. Pradel et al. 2005, Guo et al. 2000, Kremen 2005). There have been few attempts to measure and understand multiple services and the interactions among them, with a small number of notable exceptions. In one of these, Pimentel et al. (2005) compared organic and conventional agricultural practices for energy usage, economic outcomes, and environmental benefits such as organic matter and retained soil moisture. In two others, Kling et al. (2006) and Feng et al. (2005) examined trade-offs among economic measures and environmental quality in the Upper Mississippi River Basin. These latter studies are novel in both their interdisciplinary nature and their comparisons of multiple economic and environmental indicators. They further demonstrate the potential value of understanding the mechanisms that produce services in order to develop management techniques that will favor their optimization.

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). Trade-off curves (Antle et al. 2006, Stoorvogel et al. 2001) describe relationships between pairs of sustainability indicators. The trade-off between yield and the production of nitrous oxide, a greenhouse gas produced in annual cropping system soils, for example, shows the degree to which one service (e.g. yield) can be affected by managing for the other (McSwiney and Robertson, 2005; Figure 4.1).

These sorts of analyses are needed for multiple services in order to quantify trade-offs and synergies. Without doing so it is difficult to know how ecosystem services interact and provide cumulative benefits, and therefore difficult to make informed management decisions. 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. The services we examined include grain yield, aboveground net primary productivity, water conservation (measured as drainage), water quality (measured as nitrate leaching), greenhouse gas flux abatement (measured as nitrous oxide conservation and methane oxidation), and soil quality (using soil carbon levels and soil inorganic nitrogen as indicators).

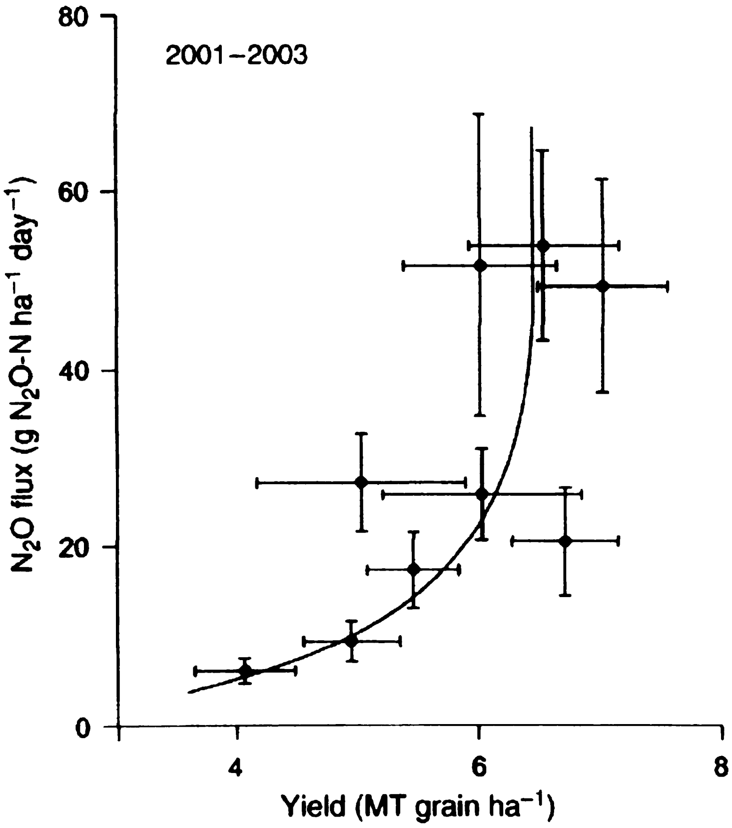

Figure 4.1: Relationship between maize grain yield and nitrous oxide flux for nine levels of N addition at the Kellogg Biological Station's Nitrogen Rate Study (McSwiney and Robertson 2005).

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. All of the services examined here are important in annual cropping systems for reducing the environmental impact of these systems, all are to at least some degree under management control, and all interact—and thus presumably can be optimized vis a vis production (Heal and Small 2002).

MATERIAL AND METHODS

Site Description

We compared ecosystem services from a field experiment that was established at the Kellogg Biological Station (KBS) in 1988. Multiple treatments at the KBS Long-Term Ecological Research (LTER) Site (www.lter.kbs.msu.edu) form a management intensity gradient that is well suited to ecosystem comparisons. KBS 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 Kalamazoo (fine loamy) and Oshtemo (coarse loamy) soils, both mixed, mesic Typic Hapludalfs that mainly differ in the thickness of the Bt horizon. The Kalamazoo has a thicker upper Bt horizon than the Oshtemo and therefore has a slightly greater water holding capacity. Annual rainfall at KBS is 920mm/yr, distributed evenly through the year. The water holding capacity of these soils is approximately 150 mm to 1.5 m depth (Crum and Collins, 1995).

Experimental Design

Seven experimental treatments were established in 1989 in replicated 1-ha plots organized in a complete block design (n=6). Additional offsite native deciduous forest sites were added in 1991 (n=3); for maps of the treatments and experimental design, see www.lter.kbs.msu.edu/. Cropping systems include four maize (*Zea mays*)-soybean (*Glycine max*)-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) organically with no chemical inputs and tillage. The latter two treatments include a leguminous winter cover crop grown following the maize and wheat portions of the rotation to provide 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.

From 1989 to 1992, the conventional tillage and no-tillage systems were in a maize-soybean rotation, and the reduced-input and organic systems were in a maize-soybean-wheat rotation. Since 1993, all four of the annual grain crops have been in a maize-soybean-wheat rotation. The conventional, reduced-input, and organic 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 and organic systems received additional inter-row cultivation and rotary hoeing as needed for weed control.

Table 4.1: Management summary for the KBS LTER treatments.

	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
Organic	Conventional	Cover crop	Mechanical
Perennial Crops			
Alfalfa	None	None	None
Poplar	None	Starter[1]	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.
[1] 60 kg N ha^{-1} in 1989 only.

The two perennial systems included alfalfa (*Medicago sativa*) and fast growing clonal poplar (*Populus* x *euramericana*) trees. The alfalfa was harvested 3-4 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. Poplar trees were planted in 1989, and starter fertilizer (only) was added at that time. Creeping red fescue was 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 two unmanaged systems included an early successional system that was abandoned from agriculture in 1989 and an old-growth oak-hickory forest that has never been cleared or plowed. The early successional system has been burned annually since 1997 to prevent tree colonization.

Sampling Protocols

The methodology for the drainage, nitrate leaching, soil carbon sequestration and total soil nitrogen measurements are described in detail in Chapters 2 (drainage, nitrate leaching) and 3 (carbon sequestration and total nitrogen). Soil carbon and nitrogen samples were taken in 2001, and drainage and nitrate leaching data were collected from 1996-2007. Methodology for greenhouse gas measurements, collected from 1991-2007, are described in Robertson et al. (2000).

All systems were sampled for Aboveground Net Primary Productivity (ANPP). Additionally, the annual cropping systems were sampled for grain yields from 1993 to 2007 in each of the agronomic plots. Yield was measured on each 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 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 clearcut in January 1999 and 2007, and the total woody biomass in each 1 ha plot chipped and weighed. 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 is estimated by changes in stem diameter for all trees within a 400 m^2 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 two 0.8 × 1.2 m litter traps placed on the forest floor prior to spring leafout. Traps were emptied, dried, and composited by plot over the season.

Trade-off curves were constructed 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 flower diagram. Flower diagrams have been used as a conceptual tool to compare trade-offs in ecosystem services with different land uses (Foley et al. 2005). We constructed a flower diagram for each of the management systems using information for each measured service as a way to compare systems. The relative size of each petal denotes the proportional delivery of the service it represents.

Statistical Analysis

The experiment was analyzed as a completely randomized design (CRBD) with 7 treatments and 6 replicates of each treatment. Comparisons were completed using SAS (SAS Version 8.2, SAS Institute 1999). Greenhouse gas fluxes, grain yield, total nitrate leaching, net primary productivity, soil nitrogen, and soil carbon levels were compared using proc mixed. Correlation analyses were performed using proc corr.

RESULTS

Individual Ecosystem Services

Nitrate leaching was tracked from 1996-2007. As reported in Chapter 3, highest leaching rates were found in the conventional row-crop system, which lost 680 ($\pm$ 104 s.e.) kg NO_3^--N ha^{-1} during the 11 year period. The no-till system leached about a third less nitrogen, losing 455 ($\pm$ 33) kg NO_3^--N ha^{-1}. The reduced input and organic systems lost significantly less nitrogen than either of the other annual systems, losing 267 ($\pm$ 8) and 209 ($\pm$ 9) kg NO_3^--N ha^{-1}, respectively. The alfalfa lost 141.1 ($\pm$ 19.8) kg NO_3^--N ha^{-1}, mainly during the period of replanting. Both the early successional and poplar systems lost very little nitrogen, 12.3 (± 4.7) and 0.8 (± 0.4) kg NO_3^--N ha^{-1}, respectively. The deciduous forest system lost 119.7 (± 46.7) kg NO_3^--N ha^{-1} over this period.

Drainage (as an indicator for groundwater replenishment) was highest in the no-till system and deciduous forest system, with 4.19 and 4.00 m, respectively, draining through the profile from 1996-2007. The conventional system had 3.62 m drainage. The reduced-input and organic systems, alfalfa, poplars, and early successional system drained about half that of the no-till drainage, draining 2.07 to 2.44 m.

As reported in Chapter 4, soil carbon levels to 1 meter depth ranged between 10.5 (± 1.7) kg C m^{-2} in the early successional community to 6.4 (± 0.7) kg C m^{-2} in the reduced-input annual system. The baseline conventional system contained 7.0 (± 0.6) kg C m^{-2}, suggesting that some systems gained as much as 3.5 kg C m^{-2} over the past two decades. Total soil nitrogen levels were similar in all the annual systems, though the alfalfa was significantly greater than the organic system, early successional, and deciduous forest systems.

The no-till system had the highest grain yields, with an average of 4.00 (± 0.68) Mg ha^{-1} from 1993-2007. The conventional and low-input systems had lower yields, averaging 3.66 (± 0.66) and 3.63 (± 0.64) Mg ha^{-1}, respectively, though these values were still higher than for the organic system, which averaged 2.79 (± 0.52) Mg ha^{-1}. These yields included 5 full rotations of maize-soybean-wheat.

Annual net primary productivity was highest in the reduced input system, averaging 10.4 (± 0.2) Mg $ha^{-1}y^{-1}$ over the period of 1993 to 2007. The other annual systems all showed lower production, with 9.2 (± 0.3) Mg $ha^{-1}y^{-1}$ in the organic system, 9.3 (± 0.4) Mg $ha^{-1}y^{-1}$ in the conventional system, and 9.7 (± 0.3) Mg $ha^{-1}y^{-1}$ in the no-till system. The alfalfa, deciduous forest, and early successional system produced 6.7 ($\pm$ 0.1), 6.5 ($\pm$ 0.7), and 6.2 ($\pm$ 0.3) Mg $ha^{-1}y^{-1}$ respectively, while the lowest production was in the poplar system with 4.5 ($\pm$ 0.2) Mg $ha^{-1}y^{-1}$.

Nitrous oxide production was highest in the annual systems and in the alfalfa, which emitted on average from 2.96 to 4.62 g ha^{-1} d^{-1} over the period 1991 to 2007. Nitrous oxide production was lowest in the poplar system, emitting 0.93 ($\pm$ 0.15) g N_2O-N ha^{-1} d^{-1}. Methane oxidation was highest in the deciduous forest system (-9.91 $\pm$ 0.96 g CH_4 ha^{-1} d^{-1} on average), and lowest in the conventional, no-till, and reduced-input system (range -1.32 to -1.56 g CH_4 ha^{-1} d^{-1})

Table 4.2 Ecosystem services in the KBS LTER Systems. Values are listed as mean (standard error). Statistical significance is indicated by different letters within the same column.

	Soil Quality		Water Quality		Climate Regulation		Productivity	
Treatment	Total Carbon to 1 meter[1] kg C m^{-2}	Soil Nitrogen[1] kg N m^{-2}	Nitrate Leaching[2] kg NO_3^--N ha^{-1}	Drain-age[3] mm	Nitrous Oxide Production[4] g ha^{-1} d^{-1}	Methane Oxidation[4] G ha^{-1} d^{-1}	Annual Net Primary Productivity[5] Mg $ha^{-1}y^{-1}$	Grain Yield[5] Mg $ha^{-1}y^{-1}$
Conventional	7.0 (0.6)bd	1.0 (0.11) ab	680.4(104.3)a	3617	3.49 (0.45) a	-1.3 (0.2) a	9.3 (0.4) b	3.7 (0.7)b
No-Till	8.5 (1.0) ab	1.0 (0.04) ab	454.7 (33.3) b	4190	3.74 (0.08) a	-1.6 (0.1)ab	9.7 (0.3) b	4.0 (0.7)a
Reduced-Input	6.4 (0.7)b	1.0 (0.09) ab	267.0 (8.1) c	2417	3.65 (0.23) a	-1.5 (0.1)ab	10.4 (0.2) a	3.6 (0.6)b
Organic	8.3 (0.7)ab	0.9 (0.06) a	208.9 (8.5) d	2413	3.77 (0.23) ab	-2.0 (0.2)c	9.2 (0.3) b	2.8(0.5)c
Alfalfa	10.5(1.7)ad	1.2 (0.08) b	141.1 (19.8) e	2070	4.23 (0.44) b	-1.9 (0.2)bc	6.7 (0.1) c	n/a
Poplar	9.1 (1.0)ad	1.0 (0.06) ab	0.8 (0.4) g	2402	0.92 (0.15) d	-1.8(0.2)bc	4.5 (0.2) e	n/a
Early Successional	8.6 (0.4)ac	1.0 (0.04) a	12.3 (4.7) f	2443	1.36 (0.12) c	-1.9 (0.3)bc	6.2 (0.3) d	n/a
Deciduous Forest	7.9 (1.4) abc	0.9 (0.08) a	119.7 (46.7) e	3999	1.74 (0.26)c	-9.9 (1.0) d	6.5 (0.7)cd	n/a

[1] Measured in 2001 to 1 meter depth (n=6 for all except the deciduous forest, where n=3)
[2] Measured from 1996-2007 (n=3 replicates for all treatments)
[3] Modeled values, from 1996-2007
[4] Measured from 1991-2007(n=4 except for deciduous forest, where n=3)

Table 4.3 Correlation matrix for all measures of ecosystem services. Values are listed as correlations and p-values.

	Nitrate Leach	Drain	Grain Yield	NPP	Nitrous Oxide	Methane	Soil N
Nitrate Leaching	1.0						
Drainage	0.54 p≤0.01	1.0					
Grain Yield	0.53 p=0.08	0.66 p≤0.01	1.0				
NPP	0.65 p≤0.01	0.34 p=0.02	0.49 p=0.02	1.0			
Nitrous Oxide	0.59 p≤0.01	-0.04 p=0.85	0.02 p=0.95	0.70 p≤0.01	1.0		
Methane	0.26 p=0.22	-0.39 p=0.03	0.37 p=0.16	0.24 p=0.19	0.31 p=0.09	1.0	
Soil Nitrogen	-0.03 p=0.91	-0.06 p=0.70	0.29 p=0.17	0.04 p=0.19	0.09 p=0.61	0.27 p=0.13	1.0
Soil Carbon	-0.19 p=0.37	-0.16 p=0.28	0.04 P=0.85	-0.26 p=0.09	-0.06 p=0.74	0.01 p=0.96	0.27 p=0.07

Trade-off Curves

Soil carbon levels were higher in systems with lower nitrous oxide emissions, more methane oxidation, and higher net primary productivity. Nitrate leaching was found in systems with higher drainage, and leaching levels greater than 200 kg NO_3^--N ha^{-1} during the 11 year period were only found in the annual cropping systems. Higher methane oxidation was associated with higher soil carbon, and lower nitrous oxide fluxes.

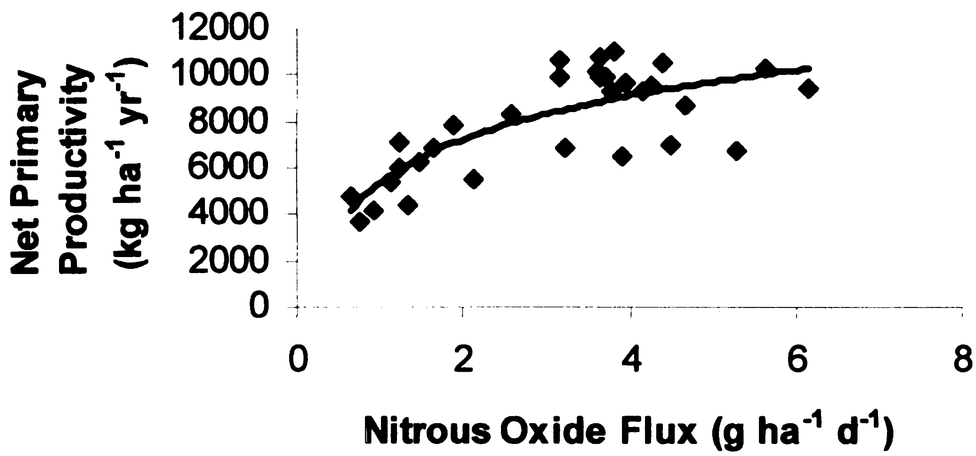

Figure 4.2 Relationship between net primary productivity and nitrous oxide fluxes on the Kellogg Biological Station Long Term Ecological Research Site. The curve represents a best-fit quadratic equation y=2729.9 Ln(x) + 5329.6 (r^2=0.603).

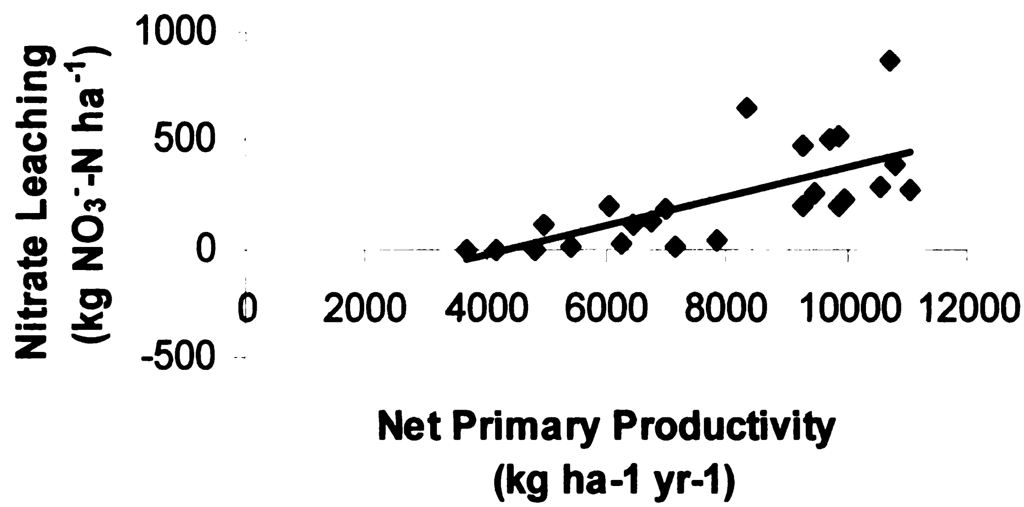

Figure 4.3 Relationship between nitrate leaching and net primary productivity at the KBS LTER Site. The line describes the regression equation $y = 0.0682x - 302.62$ ($r^2 = 0.469$).

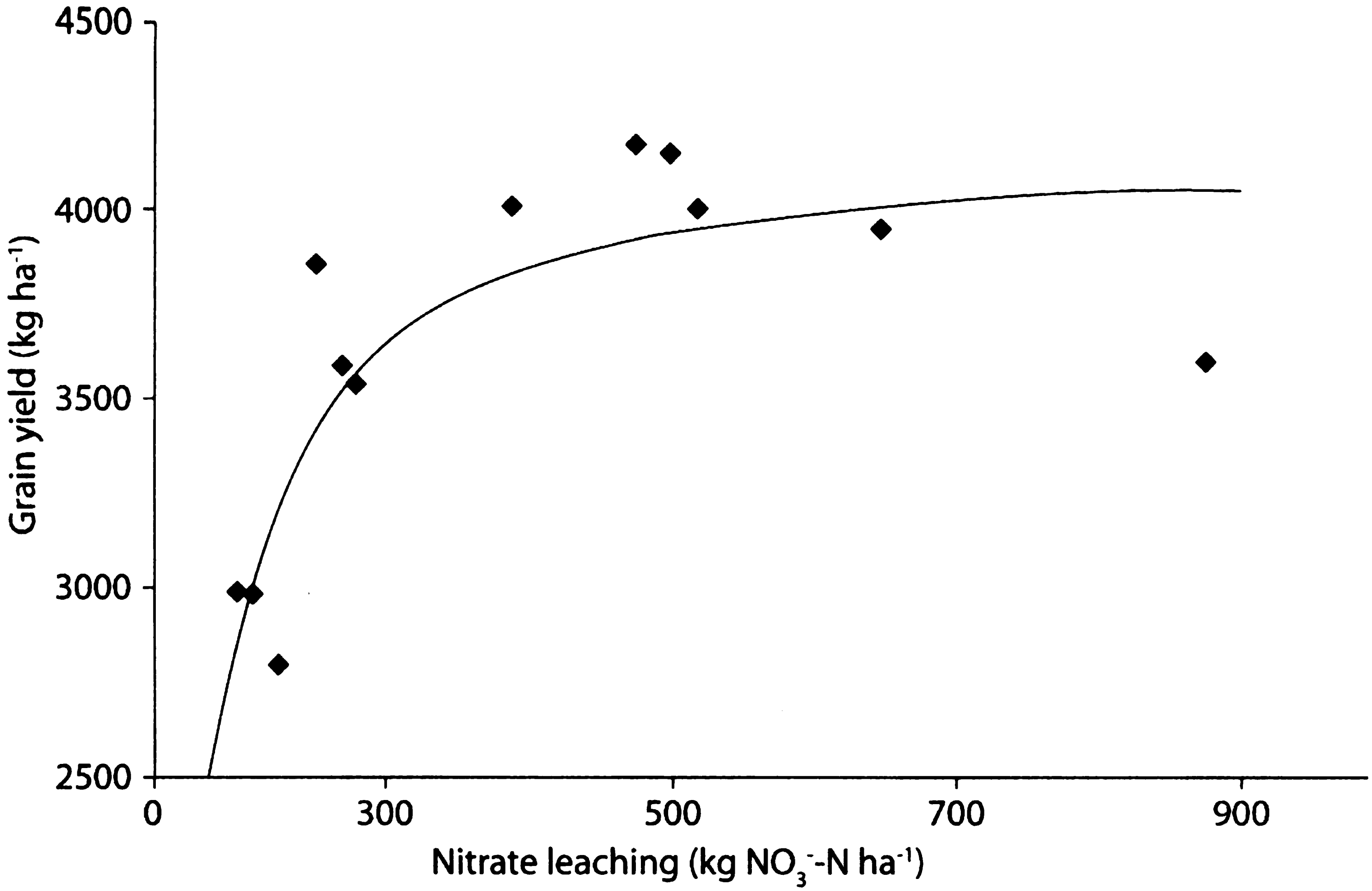

Figure 4.4 Relationship between grain yield and nitrate leaching at the KBS LTER Site. The best-fit curve is described by quadratic equation $y^2 = 16833657 + -3.29x^{-2}$ ($r^2 = 0.709$).

Flower Diagrams

Flower diagrams are represented in Figure 4.7 and 4.8. A complete petal represents the maximum ecosystem service provisioning possible at our site, while a smaller petal represents a decrease in ecosystem service provisioning relative to that service as delivered in another ecosystem.

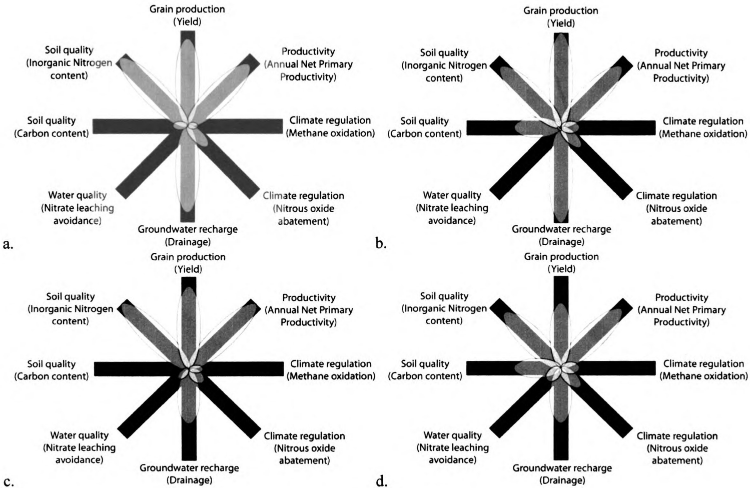

Figure 4.5 a. Conventional, b. No-till, c Reduced Input, and d. Organic Systems. Each flower represents the bundle of ecosystem services provided by each system relative to the maximum capacity for each service at the KBS LTER site.

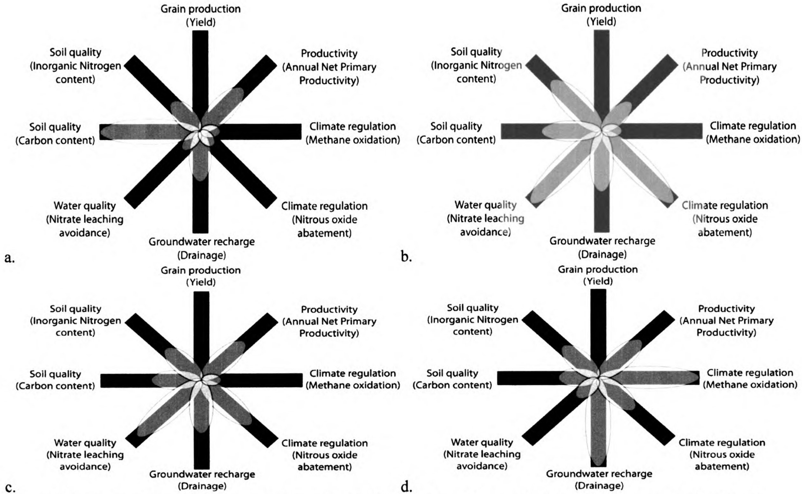

Figure 4.6 a. Alfalfa, b. Poplar, c. Early Successional, and d. Deciduous Forest System. Each flower represents the bundle of ecosystem services provided by each system relative to the maximum capacity for each service at the KBS LTER site.

DISCUSSION

Ecosystems in this agricultural landscape vary 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 leads to big differences in the capacity of each system to deliver enhanced soil quality, climate regulation, groundwater recharge, and primary production even with similar levels of crop productivity.

Under conventional management, the maize-soybean-wheat grain-based system delivered moderate to high levels of groundwater recharge, net primary productivity, and grain yield, and little water quality protection or climate protection. Grain production was high, as was annual net primary productivity and soil quality as indicated by soil inorganic nitrogen, but soil carbon and methane oxidation were low and nitrous oxide production was high.

Under no-till management, the grain-based system delivered moderate to high levels of groundwater recharge, annual net primary productivity, and grain yield, with more water quality protection than the conventional system. Grain production was high, as was annual net primary productivity and soil quality as indicated by soil nitrogen, but soil carbon and methane oxidation were low and nitrous oxide production was high.

In contrast, the reduced-input system delivered high grain yields, annual net primary productivity, and soil quality as measured by soil nitrogen, but had less groundwater recharge than the conventional and no-till systems. The reduced-input system also provided greater water quality protection than either the conventional or no-till systems. The organic system had lower grain yields than the other annual crops, however, although annual net primary productivity and soil quality as measured by soil nitrogen were both still quite high. The organic system delivered greater water quality protection and methane oxidation than did any of the other annual cropping systems. The organic system also provided less groundwater recharge than the conventional or no-till systems.

The perennial crops excelled at the delivery of water quality protection and soil quality as measured as carbon content, though they did not produce any grain and had lower annual net primary productivity and soil nitrogen than the annual systems. The alfalfa had the highest soil carbon contents of any of the systems, and had lower nitrate leaching than any of the annual systems. The poplar also had high soil carbon levels, and had lower leaching levels than any other system. The poplars also showed a reduction in nitrous oxide emissions compared to the annual crops.

The successional systems delivered improved climate protection and water quality protection, although productivity and soil quality as indicated by soil inorganic nitrogen levels decreased. The early successional system showed reduced net primary productivity. However the early successional system did show improved climate and water quality protection through reductions in both nitrous oxide emissions and nitrate leaching. Soil quality was lower than in the annual systems in terms of soil nitrogen, but soil carbon levels were higher than in the conventional and reduced input annual systems. The deciduous forest had high levels of water quality protection, groundwater recharge, and climate protection. The deciduous forest also had higher methane oxidation than any other system, and only produced about half as much nitrous oxide as the annual systems. The forest had lower productivity and soil nitrogen levels compared to the annual crops.

These ecosystem service differences among systems provide a basis for describing trade-offs among particular services. Trade-off curves provide insights into how management can optimize the delivery of multiple services. For some services (e.g. methane oxidation and nitrate leaching) there is a direct trade-off with food production, while the delivery of other services synergistically increase as food production increases (e.g. water use conservation). Even within the annual cropping systems, the particular management of each system drives the production of ecosystem services. This is particularly true for the use of nitrogen fertilizer, cover crops, and tillage, which seem to play a dominant role in determining the state of ecosystem services in these systems.

Many of these trade-offs are what one would expect based on current knowledge of ecosystem functioning. However, some of these relationships, while obvious, do not appear to be linear. In the deciduous forest system, for example, methane oxidation is very high. However in all other systems methane oxidation is less than one fifth of rates in the deciduous forest. This may be due to shifts in microbial populations that occurred when these systems were tilled and fertilized. Yet even in the early successional system, which was last tilled twenty years ago, this service has shown little recovery. When changing from one type of management to another, managers must be aware that it is possible to encounter these large shifts in ecosystem service provisioning which do not appear to be reversible in fairly long period of time. Other services can also take years to develop or recover – soil carbon and its associated services, for example, may take decades after the cessation of tillage to recover to levels that provide significant fertility benefits. Conversely, carbon sequestration (climate mitigation) benefits will be provided immediately but eventually will diminish as soil carbon saturates 50-100 years post-tillage.

When increasing management intensity, there is a trade-off between the yield in the systems and some of the other ecosystem services provided. By changing crops and management, microbial and plant communities change, and thus the functioning of these systems change. Similar trade-offs were noted at our site by McSwiney and Robertson (2005), who found that additional nitrogen fertilization improved yields but at a cost to climate regulation in the form of increased nitrous oxide production.

Knowing that trade-offs exist and understanding the relationship between land-use types and the services they offer presents an opportunity for implementing land use strategies that balance the ecosystem services that are provided across the landscape. Because no one land use is optimal for all ecosystem services, having a multifunctional landscape will help to balance ecosystem service provisioning. However, implementing such a mixed landscape will be difficult and probably require legislation, particularly in those portions of the world dominated by millions of hectares of monoculture crops. Diversifying the landscape may help offset the imbalances these types of landscapes create.

Management Implications

There are many trade-offs among competing goals in agriculture, in particular between the economic goals of farmers and the food and environmental goals of society. A better understanding of the key biological, biogeochemical, and ecological processes that function in agricultural systems should lead to a scenario in which food production can increase without an increase in environmental degradation (Tilman et al. 2002). Managing for multiple ecosystem services (Robertson and Harwood 2001) is an idea that is entirely foreign to almost all commercial agricultural producers today, and it is a process that will take further research to support informed management decisions (Robertson and Swinton 2005).

There is a growing body of research on changing the suite of ecosystem services produced by ecosystems (Antle and Capalbo 2002, Maier and Shobayashi 2001) and on using a systems approach to analyze the complex mechanisms driving the ecosystem services (Robertson et al. 2004). Particularly in agricultural systems, soil biological, chemical, and physical processes are driving the production of many of the ecosystem services that are important in these systems. A systems approach is necessary to understand the complex interactions between all the components of the system. This sort of approach lends itself well to modeling, and sites like KBS are ideal for this sort of research where many of the individual components of the system have been well studied and 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. 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 ecosystem services. Further research will be needed on the valuation of ecosystem services to give common currency to the multitude of services provisioned, in order for decision makers to compare the relative suites of ecosystem services produced in different systems.

Conclusions

In conclusion we found that

1. Differences in the provision of services are marked in ecosystems typical of agricultural landscapes.
2. The management of each system, and in particular the use of nitrogen fertilizer, cover crops, and tillage, seems to play a dominant role in determining the state of ecosystem services in these systems.
3. In our ecosystems differences including greater production of provisioning services (food production and fresh water replenishment) in the conventional and no-till systems, great production of regulating services (climate protection and water quality) in the poplar successional systems, and increased supporting services (soil quality) in the annual systems (soil inorganic nitrogen) and perennial systems (soil carbon).
4. Tradeoff curves showed both linear and nonlinear relationships among alternative services, with some services such as methane oxidation and nitrous oxide abatement being synergistic, and others such as yield vs. nitrate leaching being antagonistic.
5. Management for services should include the suite of services available from specific systems in a landscape, and diversification of landscapes could be used to diversify and enrich the variety of services provided.

6. Future research is needed to both identify the full suite of services available from alternative management and cropping systems and to value services in order to provide a means to compare services in the same currency.

CHAPTER 5

SUMMARY AND FUTURE DIRECTIONS

Summary

Ecosystem services at Kellogg Biological Station's Long Term Ecological Research (KBS LTER) Site were responsive to changes along a management intensity gradient. As systems were managed more intensely, methane oxidation decreased, while nitrate leaching, net primary productivity, and nitrous oxide production all increased. These sorts of analyses, involving multiple ecosystem services, are a first step towards better understanding the large scale trade-offs of land management decisions.

Future Directions

Research is needed in the area of the impact of individual crops, and particularly cover crops, on the rates of nitrate leaching and drainage from particular soil types. This, in addition to research on the impacts of tillage and nitrogen fertilization levels in particular soils, would be useful in order to provide information necessary to design models that land managers and agricultural producers could use to make decisions about the crops they would grow, rates of fertilizer application, and the type of tillage they would use on their particular farms, considering their particular soil type and climate. This would also allow modelers to integrate at a landscape scale the effects of land-use changes (such as deforestation, afforestation, etc.) on water resources. Water quality and quantity is an emerging issue that will inevitably necessitate the conservation of water resources. Improved crop management is necessary to protect the ground water that nourishes vast portions of the global population.

Further research on carbon sequestration should focus on determining the distribution of carbon through out the soil, and the patterns of variability with depth. This is particularly important for crops with seep rooting depths, such as trees, alfalfa, grasses, and corn. Assessing this change in carbon distribution with depth in different soil types, crops, and climates is necessary for the accurate prediction of the potential for agricultural soils to be used as a mitigation strategy to deal with the current climate crisis.

Future research in multiple ecosystem service trade-offs should focus on using the data we have gathered at the KBS LTER to help with the development and improvement of ecological models to enable them to better predict multiple outcomes of management decisions. The SALUS model is one such model that is already in use at the KBS LTER that has the potential to include many of the parameters that were discussed in this work. I am particularly interested in modeling nitrous oxide and methane fluxes so that policy makers have better information and tools to use when trying to make decisions about global climate change policies and their impacts. Other avenues of research will include looking at the impact of biodiversity in agricultural systems, particularly on the impact of greater taxonomic and genetic diversity in a system on the provisioning of ecosystem services.

APPENDIX

CHAPTER 2 SUPPLEMENTARY MATERIALS

SAS Output on nitrate leaching values using the proc mixed procedure.

Covariance Parameter Estimates

Cov Parm	Estimate
Residual	4.1693

Fit Statistics

-2 Res Log Likelihood	96.3
AIC (smaller is better)	98.3
AICC (smaller is better)	98.5
BIC (smaller is better)	99.3

The Mixed Procedure

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Trt	9	20	47.15	<.0001

APPENDIX

CHAPTER 3 SUPPLEMENTARY MATERIALS

Table A.1 Coefficients of Variation for bulk density and profile layer thickness in KBS LTER Treatments

	A/Ap		B/Bt		Bt2/C	
	Thickness CV	BD CV	Thickness CV	BD CV	Thickness CV	BD CV
Conventional	0.28	0.08	0.26	0.07	0.13	0.05
No-till	0.12	0.08	0.14	0.05	0.11	0.05
Reduced Input	0.16	0.03	0.22	0.05	0.17	0.04
Organic	0.18	0.07	0.23	0.06	0.14	0.06
Alfalfa	0.23	0.07	0.17	0.07	0.20	0.08
Poplar	0.30	0.09	0.18	0.04	0.21	0.04
Conifers	0.08	0.06	0.23	0.03	0.24	0.04
Early Successional	0.18	0.05	0.23	0.06	0.13	0.05
Mid-Succesional (HT)	0.18	0.05	0.20	0.09	0.29	0.01
Mid-Successional (NT)	0.03	0.05	0.06	0.03	0.12	0.03
Deciduous Forest	0.13	0.03	0.18	0.08	0.18	0.02
Average	0.17	0.06	0.19	0.06	0.17	0.04

Table A.2 Coefficients of Variation for carbon concentrations and total carbon in KBS LTER Treatments.

	A/Ap		B/Bt		Bt2/C		Total
	Conc. CV	Total CV	Conc. CV	Total CV	Conc. CV	Total CV	Total CV
Conventional	0.07	0.08	0.41	0.41	0.27	0.41	0.21
No-till	0.09	0.07	0.28	0.29	0.98	0.92	0.26
Reduced Input	0.26	0.28	0.35	0.37	0.49	0.49	0.30
Organic	0.08	0.06	0.27	0.27	0.82	0.77	0.24
Alfalfa	0.02	0.20	0.38	0.38	0.90	0.96	0.35
Poplar	0.40	0.41	0.57	0.53	1.08	1.02	0.22
Conifers	0.24	0.22	0.67	0.67	0.69	0.43	0.30
Early Successional	0.09	0.05	0.15	0.17	0.26	0.38	0.09
Mid-Successional (HT)	0.40	0.40	0.40	0.46	0.19	0.29	0.37
Mid-Successional (NT)	0.07	0.07	0.19	0.23	0.47	0.50	0.15
Deciduous Forest	0.25	0.26	0.43	0.42	0.53	0.58	0.32
Average	0.18	0.19	0.37	0.38	0.61	0.61	0.25

APPENDIX

CHAPTER 4 SUPPLEMENTARY MATERIALS

Statistical Output for Nitrous Oxide using the mixed procedure in SAS.

The Mixed Procedure

Covariance Parameter Estimates

Cov Parm	Subject	Estimate
Rep		0.004888
CS	Trt*Rep	0.007611
Residual		1.7664

Fit Statistics

-2 Res Log Likelihood	19584.8
AIC (smaller is better)	19590.8
AICC (smaller is better)	19590.8
BIC (smaller is better)	19588.9

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Trt	6	20.5	51.22	<.0001
Year	15	5596	90.81	<.0001
Trt*Year	90	5596	2.92	<.0001

Statistical Output for Methane using the mixed procedure in SAS.

The Mixed Procedure

Covariance Parameter Estimates

Cov Parm	Subject	Estimate
Rep		0.03324
CS	Trt*Rep	0.02828
Residual		9.2719

Fit Statistics

-2 Res Log Likelihood	26443.2
AIC (smaller is better)	26449.2
AICC (smaller is better)	26449.2
BIC (smaller is better)	26447.3

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Trt	6	20.6	3.33	0.0188
Year	14	5119	20.87	<.0001
Trt*Year	84	5119	1.71	<.0001

Statistical Output for Soil Inorganic Nitrogen using the mixed procedure in SAS.

The Mixed Procedure

Covariance Parameter Estimates

Cov Parm	Estimate
rep	0
Residual	0.4131

Fit Statistics

-2 Res Log Likelihood	85.9
AIC (smaller is better)	87.9
AICC (smaller is better)	88.0
BIC (smaller is better)	87.7

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
trt	7	32	67.03	<.0001

Statistical Output for Grain Yields using the mixed procedure in SAS.

The Mixed Procedure

Covariance Parameter Estimates

Cov Parm	Estimate
rep	1.4963
CS	10.6025
Residual	0.8278

Fit Statistics

-2 Res Log Likelihood	1667.8
AIC (smaller is better)	1667.8
AICC (smaller is better)	1667.8
BIC (smaller is better)	1667.8

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
trt	3	288	142.06	<.0001
date	14	288	282.92	<.0001
date*trt	42	288	13.69	<.0001

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