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Long-term nitrate loss along an agricultural intensity gradient in the Upper Midwest USA

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ABSTRACT

Nitrate (NO_3^-) loss from intensively farmed cropland is a long-standing, recalcitrant environmental problem that contributes to surface and groundwater pollution and coastal zone hypoxia. Here nitrate leaching losses are reported from nine replicated cropped and unmanaged ecosystems in southwest Michigan, USA. Ecosystems include four annual corn–soybean–winter wheat rotations under conventional, no-till, reduced-input, and organic/biologically-based management, two perennial cropping systems that include alfalfa and hybrid poplar trees, and three unmanaged successional communities including an early successional community analogous to a cellulosic biofuel system as well as a mature deciduous forest. The organic, alfalfa, and unmanaged systems received no synthetic, manure, or compost nitrogen. Measured nitrate concentrations were combined with modeled soil water drainage to provide estimates of nitrate lost by leaching over 11 years. Among annual crops, average nitrate losses differed significantly ($p < 0.05$) and followed the order conventional (62.3 ± 9.5 kg N ha^{-1} yr^{-1}) > no-till (41.3 ± 3.0) > reduced-input (24.3 ± 0.7) > organic (19.0 ± 0.8) management. Among perennial and unmanaged ecosystems, nitrate loss followed the pattern alfalfa (12.8 ± 1.8 kg N ha^{-1} yr^{-1}) = deciduous forest (11.0 ± 4.2) ≫ early successional (1.1 ± 0.4) = mid-successional (0.9 ± 0.4) > poplar ($<0.01 \pm 0.007$ kg N ha^{-1} yr^{-1}) systems. Findings suggest that nitrate loss in annual row crops could be significantly mitigated by the adoption of no-till, cover crops, and greater reliance on biologically based inputs, and in biofuel systems by the production of cellulosic rather than grain-based feedstocks.

1. Introduction

Agriculture is the major contributor to reactive nitrogen levels in the biosphere, and reducing nitrogen export from agricultural ecosystems to ground and surface waters is a longstanding environmental priority (Robertson and Vitousek, 2009). Agricultural nitrogen is derived from a variety of sources, but primarily from inorganic fertilizer, manure, and biological nitrogen fixation. Most annual grain crops take up only about 50% of nitrogen applied (Robertson, 1997), leaving most of the remainder available for loss to the larger environment, including leaching loss to groundwater (e.g. 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 groundwater and groundwater-fed surface waters. Excessive nitrate can affect human health when ingested in drinking water; putative effects include infant methemoglobinemia (blue baby syndrome), cancer, and gastroenteritis (Gray, 2008). Nitrate can also cause eutrophication and associated algal blooms in some surface waters, which can kill fish and benthic organisms and promote the invasion of exotic species (Vitousek et al., 1997). Moreover, excess nitrate stimulates denitrification in soils, groundwater, and surface waters, resulting in emissions of nitrous oxide (Robertson et al., 2000; Burgin and Hamilton, 2007; Beaulieu et al., 2010), an important greenhouse gas. Once nitrate reaches coastal areas it can contribute to harmful algal blooms and marine hypoxia (Rabalais 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 et al., 2003).

Estimates of nitrate leaching loss from different row crops in the U.S. vary widely, with reported values ranging from 25 to

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

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Table 1
Soil profile characteristics the KBS LTER site. Soils of the Kalamazoo (fine-loamy, mixed, mesic Typic Hapludalfs) and Oshtemo (coarse-loamy, mixed, mesic Typic Hapludalfs) series are comingled on the site (from Crum and Collins, 1995).

Horizon	Depth (cm)	Texture			Bulk density (mg m^{-3})	pH
		Sand (%)	Silt (%)	Clay (%)		
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[a]	5.2
2E/Bt	88–152	93	0	7	nd[a]	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[a]	5.8
2E/Bt	97–152	92	0	8	nd[a]	6.0

[a] Not determined.

146 kg N ha^{-1} yr^{-1} in intensive grain and forage systems (Fox et al., 2001; Power et al., 2001; Basso and Ritchie, 2005). To date, apart from a well-documented positive relationship between the amount of N applied and the amount of N loss (e.g. Groffman et al., 1986; Andraski et al., 2000; Gehl et al., 2005), consistent management-related patterns in nitrate leaching losses have been hard to detect. For example, comparisons of organic and conventional systems have shown that organically managed systems can leach more (Pimentel et al., 2005; Basso and Ritchie, 2005), similar (Kirchmann and Bergstrom, 2001), or less (Drinkwater et al., 1998; Hansen et al., 2001) nitrate as compared to conventional systems. Likewise, comparisons of no-till and conventional tillage systems have shown no significant differences (e.g. Cabrera et al., 1999; Smith et al., 1990), or higher (Tyler and Thomas, 1977; Chichester, 1977) or lower (Rasse and Smucker, 1999; Ogden et al., 1999) losses of nitrate under no-till.

Some of this ambiguity may be related to experiment duration. Most 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 nitrogen loss differences if, for example, systems that do not 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).

This paper reports the results of an 11-year study of the effect of management on nitrate loss in large (1 ha), well-equilibrated, long-term field plots with well-defined and consistent management histories. To test the hypothesis that nitrate leaching is related to management intensity, nine different replicated ecosystems were compared that include annual grain crops (corn–soybean–winter wheat rotations under conventional, no-till, reduced-input, and organic/biologically-based management), perennial crops (alfalfa and hybrid poplar), and unmanaged communities in different stages of ecological succession (from recently abandoned crop fields to late successional deciduous forest).

2. Materials and methods

2.1. Site description

The experimental site is a series of replicated ecosystems that differ in management intensity at the W.K. Kellogg Biological Station (KBS) Long-term Ecological Research (LTER) site (www.lter.kbs.msu.edu). KBS is located in SW Michigan, within the northern boundary of the U.S. corn belt (85° 24′W, 42° 24′N).

The LTER site is underlain by comingled Kalamazoo (fine loamy) and Oshtemo (coarse loamy) soils, both mixed, mesic Typic Hapludalfs that mainly differ in the slightly thicker upper Bt horizon of the Kalamazoo series (Table 1; Crum and Collins, 1999; Mokma and Doolittle, 1993). Average depth to the high sand content Bt2/C horizon varies by ecosystem from 49 to 58 cm (Syswerda et al., 2011). The water holding capacity of plant available water in the soil is approximately 150 mm of water to 1.5 m depth. There is very little to no runoff at the site, due to the combination of well-drained soils and lack of slope.

Average annual temperature at KBS is 9.7 °C. Annual rainfall is 920 mm distributed evenly throughout the year, with about half of that falling as snow (Table 2). Potential evapotranspiration exceeds precipitation for about four months out of the year. Over the 11 years of this study, beginning in 1996, annual rainfall was 694, 776, 723, 608, 938, 1032, 732, 909, 959, 700, and 1156 mm yr^{-1}.

2.2. Experimental design

Nitrate leaching was measured in nine cropped and unmanaged ecosystems that are part of the Main Cropping System Experiment at KBS. Ecosystems include 4 annual cropping systems – conventional, no-till, reduced-input, and biologically based/organic (hereafter called organic); two perennial cropping systems – alfalfa and poplar; and three successional communities – an early successional community dominated by herbaceous vegetation, a mid-successional community in early stages of reforestation, and a late successional deciduous forest.

Differences in chemical inputs among ecosystems comprise a management intensity gradient that for most added chemicals (including fertilizer and pesticides) follows the order: conventional = no-till > reduced-input > organic among the annual cropping systems and for the ecosystems dominated by perennial vegetation alfalfa > poplar > unmanaged successional communities.

Seven of the nine ecosystems were established in 1989 as replicated 1 ha plots organized in a complete randomized block design (n = 6 replicate blocks). These include the four annual and two perennial cropping systems as well as the early successional community. Replicates for the mid-successional community and the deciduous forest, both established prior to 1989, were located within 2 km of the other ecosystems on the same soil series (n = 3 replicates each for 6 different locations in the surrounding landscape, Table 3).

Annual cropping systems include corn (*Zea mays*)–soybean (*Glycine max*)–winter wheat (*Triticum aestivum*) rotations. The

Table 2
Summary of weather conditions at Kellogg Biological Station during the study period (1996–2007), provided as means (standard errors in parentheses).

Month	January	February	March	April	May	June	July	August	September	October	November	December
Temperature (°C)												
Maximum	0.3 (0.7)	2.2 (0.7)	7.4 (0.7)	15.1 (0.6)	20.6 (0.7)	26.1 (0.5)	28.1 (0.5)	27.1 (0.7)	23.7 (0.7)	16.3 (0.5)	8.9 (0.9)	2.3 (0.8)
Minimum	−8.2 (0.9)	−7.0 (0.9)	−3.5 (0.7)	2.6 (0.4)	8.3 (0.7)	13.8 (0.3)	15.3 (0.4)	15.1 (0.4)	10.6 (0.2)	5.0 (0.5)	0.3 (0.5)	−5.1 (0.9)
Rainfall (mm)	50.4 (10.7)	43.0 (8.3)	54.7 (11.3)	69.4 (10.6)	111.3 (19.7)	74.6 (9.9)	66.1 (10.7)	96.7 (15.8)	78.0 (10.8)	78.6 (14.7)	74.2 (13.2)	47.1 (5.9)

conventional system was managed following best management practices typical of the region, including tillage as described below, weed control following integrated pest management (IPM) protocols for Michigan, and nitrogen and other fertilizer inputs based on university extension recommendations following soil tests. The no-till system was managed similarly to the conventional system but without tillage and with additional herbicide applications when called for by IPM scouting. The reduced-input system was managed similarly to the conventional system but with fewer chemical inputs: herbicides were banded within rows rather than broadcast, with additional weed control provided by mechanical cultivation as described below, nitrogen fertilizer was applied to corn and wheat at rates of about 20% and 50% of those applied to conventional corn and wheat, respectively (Table 4), and a leguminous winter cover crop was grown following the corn and winter wheat portions of the rotation (winter cover following soybean was provided by the fall-planted winter wheat crop). The organic was managed similarly to the reduced-input system but with no pesticides or nitrogen fertilizer additions (including neither manure nor compost). All cropping systems were planted and harvested during the same periods according to best management practices for each system.

Prior to the initiation of sampling, from 1989 to 1992 the conventional and no-till systems were in a corn–soybean rotation, and the reduced-input and organic systems were in a corn–soybean–winter wheat rotation. From 1993 all of the annual systems were in the same corn–soybean–winter wheat rotation.

The conventional, reduced-input, and organic systems underwent primary and secondary tillage in the spring prior to corn and soybean planting, followed by secondary tillage with a soil finisher and inter-row cultivation after planting. From 1989 to 1996 primary tillage was performed with a moldboard plow; from 1996 onward plots were chisel plowed to a depth of 20 cm. Soil was disked prior to fall wheat planting. The reduced-input and organic systems received additional inter-row cultivation and rotary hoeing as needed for weed control.

In the conventional and no-till systems, rates of N application ranged from 153 to 165 $kg\,N\,ha^{-1}\,yr^{-1}$ for corn, and from 56 to 90 $kg\,N\,ha^{-1}\,yr^{-1}$ for wheat. The reduced-input system received 28–31 $kg\,N\,ha^{-1}\,yr^{-1}$ for corn and 28–54 $kg\,N\,ha^{-1}\,yr^{-1}$ for wheat. No nitrogen was applied to crops in the organic system nor to soybean in any system (Table 4).

The two perennial management systems included a pure stand of alfalfa (*Medicago sativa*) and fast growing hybrid poplar trees (*Populus* × *canadensis* Moench 'Eugenei' [*Populus deltoides* × *Populas nigra*], also known as *Populus* × *euramericana* 'Eugenei'). The alfalfa was harvested 3–4 times per year and was reestablished once during the study period in 2000. Fertilizer (P, K, B, and lime) was applied according to MSU Extension recommendations (Table 4). Poplar trees were planted in 1989, and starter fertilizer (only) was added at that time at a rate of 60 $kg\,N\,ha^{-1}$. Creeping red fescue (*Festuca rubra*) was used as a cover crop to prevent soil erosion beginning in 1990. Trees were harvested in 1999, and allowed to coppice (regrow from cut stems).

The three unmanaged successional communities included (1) an early successional community that was abandoned from agriculture in 1989 and burned annually from 1996 to prevent tree colonization, (2) a mid-successional community that was released from agriculture in the 1950s, and (3) a late-successional native deciduous forest. The early successional community had been burned annually in the spring since 1997 to prevent tree colonization. None of the three deciduous forest replicates had ever been plowed; one was cut ca. 1900 and allowed to regrow and two have never been cleared. Additional site information is available at http://www.lter.kbs.msu.edu/about/experimental_design.php.

Table 3
Summary of agronomic management for cropping systems and unmanaged communities ($n = 3$ replicate plots per system).

System	Tillage	Nitrogen fertilizer[a]	Weed control
Annual cropping systems (corn–soybean–winter wheat rotation)			
Conventional	Disk plow prior to planting, cultivate	Conventional	Chemical and mechanical
No-Till	None	Conventional	Chemical
Reduced-input	Disk plow prior to planting, cultivate	1/3 Conventional with cover crop	1/3 Chemical and mechanical
Organic	Disk plow prior to planting, cultivate	Cover crop	Mechanical
Perennial cropping systems			
Alfalfa	None	None	None
Poplar	None	Starter	None
Unmanaged communities			
Early successional	None	None	None
Mid-successional	None	None	None
Deciduous forest	None	None	None

[a] N application rates and cover crops in annual cropping systems appear in Table 3; the Poplar System received 60 kg N ha^{-1} in 1989 only.

2.3. Sampling protocols

All systems were sampled for 11 years following an establishment period that exceeded 6 years. Soil water draining from all 9 ecosystems was sampled using quartz/PTFE tension samplers (Prenart, Fredriksburg, Denmark) installed in 1995. Three samplers were installed in each of three replicate blocks of each ecosystem for a total of 81 samplers (9 ecosystems × 3 blocks × 3 samplers). Expense prevented samplers from being installed in additional blocks. All samplers were installed at a depth of 1.2 m, approximately 20 cm into the unconsolidated sand of the 2Bt2 and 2E/Bt horizons (Table 1). Illuvial clay in these horizons provides for a higher water content than pure sand, minimizing preferential flow (Kung, 1990; DiCarlo et al., 1999) such that sampled water largely represents water which would otherwise freely leave the soil profile. Based on an irrigation well on-site, the depth to groundwater is estimated at approximately 5 m. The three soil water samplers per plot were installed with a hand auger at a 60° angle from the soil surface in locations 3 m apart and at least 10 m from the plot edge. In the poplar and deciduous forest sites where trees were present, samplers were not installed directly adjacent to the trees but instead placed in between trees.

Each soil water sampler was sampled by applying 50 kPa of vacuum for 24 h, during which water was collected in a clean flask. Samples were filtered through Pall Type A/E glass fiber filters (Pall Company, East Hills, New York) and then frozen until analysis. Samples were collected every two weeks April through October and monthly otherwise, except when freezing temperatures prevented sample collection due to sample line freezing. Stored samples were thawed and analyzed colorimetrically for nitrate on a continuous flow analyzer (OI Analytical, College Station, TX) with a detection limit of 0.02 mg N L^{-1} for nitrate. All samples that were found to be below detection limits were recorded as half the detection limit.

2.4. Modeling of water drainage

Nitrate concentrations were combined with modeled downward water drainage to provide estimates of nitrate leaching from the root zone. Water drainage was modeled using the Systems Approach for Land Use Sustainability (SALUS) model (Basso et al., 2006). SALUS is designed to simulate continuous crop growth and soil, water, and nutrient conditions under different management strategies for multiple years (Basso et al., 2007). SALUS is comprised of two plant growth modules, a simple module where growth and development are based on an input LAI curve and a thermal time calculation, and a complex module where crop growth and development are based on genetic characteristics of the species, radiation use efficiency, and thermal time. Both modules accommodate various crop rotations, planting dates, plant populations, irrigation, fertilizer applications, and tillage practices, and simulates plant growth and soil conditions every day during growing seasons and fallow periods. For each simulation, all major components of the crop–soil–water model were executed, including management practices, water balance, soil organic matter change, nitrogen and phosphorus dynamics, heat balance, plant growth, and plant development. SALUS simulated the systems evaluated in this study using the simple module for forest and successional communities and the complex module for the annual crops.

Table 4
Nitrogen fertilizer applications[a] and cover crops[b] in the annual grain cropping systems. RC = red clover (*Trifolium pratense*), CC = crimson clover (*T. incarnatum*), cover crops that are plowed under prior to planting corn or soybean in spring.

Cropping year	Cropping system			
	Conventional (kg N ha^{-1})	No-till (kg N ha^{-1})	Reduced-input	Organic
1995 - wheat	56	56	34 + RC	RC
1996 - corn	163	163	28 + CC	CC
1997 - soybean	0	0	0	0
1998 - wheat	56	56	28 + RC	RC
1999 - corn	163	163	28 + CC	CC
2000 - soybean	0	0	0	0
2001 - wheat	71	71	31 + RC	RC
2002 - corn	153	153	28 + RC	RC
2003 - soybean	0	0	0	0
2004 - wheat	90	90	54 + RC	RC
2005 - corn	155	155	31 + RC	RC
2006 - soybean	0	0	0	0

[a] N was applied as ammonium nitrate (N–P–K content: 34–0–0) in 1995, as a split application of 28% UAN (urea ammonium nitrate) and ammonium nitrate (34–0–0) in 1996, as ammonium nitrate (34–0–0) in 1998, as a split application of 28% UAN and ammonium nitrate (34–0–0) in 1999, as two split applications of 28% UAN in 2001, as UAN 28% in 2002, as 28% UAN in 2004, and as UAN 28% in 2005 plus P (19–17–0).
[b] Cover crop seeding rates were 13 kg ha^{-1} in 1995, 17 kg ha^{-1} in 1996, 13 kg ha^{-1} in 1998, 13 kg ha^{-1} in 1999, 13 kg ha^{-1} in 2001, 12 kg ha^{-1} in 2002, 13 kg ha^{-1} in 2004, and 10 kg ha^{-1} in 2005.

The SALUS water balance submodel considers surface runoff, infiltration, surface evaporation, saturated and unsaturated water flow, drainage, root water uptake, soil evaporation and transpiration (Ritchie, 1998). The soil water balance module is based on that used in the CERES models (Ritchie and Basso, 2008) but incorporates a major revision for calculating infiltration, soil water drainage (Suleiman and Ritchie, 2004), evaporation (Suleiman and Ritchie, 2003), and runoff. In this study runoff was negligible.

The simulation of soil water drainage rates produced by SALUS has been tested extensively at KBS using large monolith drainage lysimeters and field data records (Basso, 2000; Basso and Ritchie, 2005). The model accounts for snow melt and winter freeze. The snow melt is added as rainfall on the first day when air temperature warms to >5 °C. The first winter freeze stops development and growth of the plants based on the duration that they have experienced a temperature below their base temperature. Daily soil water balance is calculated as the difference between the input (precipitation) and the output (run-off, drainage, transpiration, soil evaporation). The model utilizes the lower limit (LL) and upper limit (DUL) of plant extractable water to redistribute water among different soil layers by a simple cascading approach. DUL is defined as the soil water content when drainage by gravity becomes negligible, and LL is defined as the soil water content when plant roots cease to extract water. The difference between DUL and LL is defined as the plant extractable soil water, although water held above DUL while draining is also available for plant use. DUL and LL were estimated from soil texture, bulk density and, where present, stone content using the procedure of Ritchie et al. (1999). Potential evapotranspiration (ETm) is partitioned between soil and plant surfaces using a leaf area index-based cover factor. Actual soil evaporation is estimated by the two-stage model (Ritchie, 1972). Root distribution and extractable water in soil layers with roots are used to adjust potential transpiration for actual water uptake or transpiration.

The N component of the model includes mineralization and immobilization associated with decomposition of organic matter, N transformation processes of nitrification, denitrification, and urea hydrolysis, downward movement through leaching of nitrate, and plant uptake of N. Nitrate and urea movement in the soil profile is dependent on water movement. The N uptake is controlled by crop demand for N and soil supply of N and the lesser of the two is used to compute the actual rate. Effects of water and N deficits on crop growth and development are taken into account by computing water and N stress factors, with the lesser of the two selected as the controlling factor.

2.5. Nitrate loss, leaching rates, and grain production impact

Measured nitrate concentration data was combined with each system's modeled water drainage to estimate total nitrate loss over the period November 1995–October 2006. Water drainage rates were modeled on a daily time step using daily nitrate concentrations interpolated between soil water sampling dates. Multiplying daily water drainage by interpolated nitrate–N concentrations provided daily nitrate–N loss in kg ha^{-1} at the 120 cm sampling depth.

The nitrate leaching rate for each system was calculated as the amount of nitrate–N lost per unit soil water drainage. Grain production impact was calculated as the amount of nitrate lost relative to grain yield produced. Yield was measured on each plot using a John Deere 9410 combine with a Greenstar yield monitor (John Deere International, York, NE), with grain moisture measured by a Burrows Digital Moisture Computer 700 (Burrow Equipment, Evanston, IL). Grain yield was measured at moisture contents of 15.5% for corn and 13% for wheat and soybean.

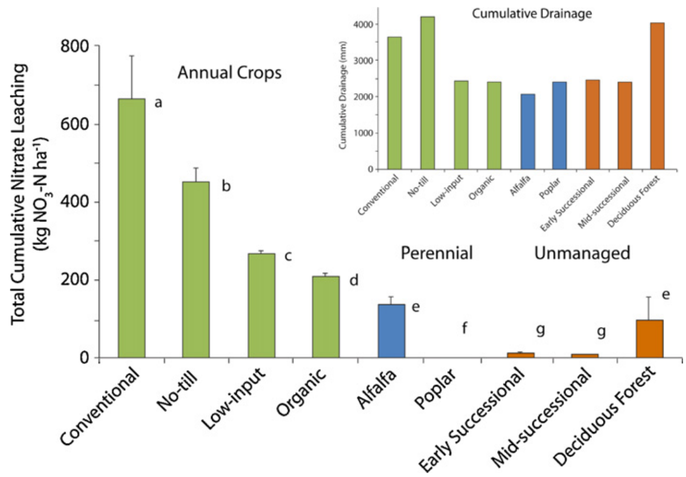

Fig. 1. Total cumulative nitrate leaching losses in studied ecosystems at the Kellogg Biological Station Long-Term Ecological Research (LTER) site over the 11 years of measurements (November 1995–October 2006). Error bars denote standard errors ($n = 3$ replicate locations). Inset: total cumulative drainage in millimeters is based on model estimates; precipitation for the period totaled 8985 mm.

2.6. Statistical analysis

The experiment was analyzed as a completely randomized design with 9 systems and three replicates of each system. The experiment could not be analyzed as a completely randomized block design since the nearby mid-successional and deciduous forest systems were included in the analysis. Further, although the model assumes random placement of the replicated mid-successional and deciduous forest systems, for historical reasons they were not randomly assigned at the onset of the experiment. Data were log-transformed to provide more normal distributions and more homogeneous variances. Systems were compared with analysis of variance (ANOVA) of the 11-year cumulative leaching values for the 3 replicate blocks per system. All comparisons were completed using the SAS proc mixed procedure (SAS Institute, 1999). Treatment means were compared for significance using the lsmeans (least significant difference) option in PROCMIXED.

Comparisons of seasonal differences were made separately in the annual crop systems and in the perennial and successional systems. The annual crops were first compared separately for corn, soybean, and wheat years, and differences were compared among the annual treatments. The perennial and successional systems were analyzed for total seasonal differences between off-season and in-season, and compared with the total off- and in-season leaching in the annual crops. In-season was defined as the growing period for the focal crop being considered. For the annual crops, this was the period from when the grain crop (corn, soybean, or wheat) was planted to when it was harvested. For the perennial and successional systems, this was the period 1 May–1 October. The off-season was defined as the period of fallow after the harvest for the annual systems, and the period from 2 October–30 April in the perennial and successional systems. All significance tests were performed using the lsmeans option of PROCMIXED.

3. Results

Total soil water drainage and associated nitrate leaching losses over 11 years are summarized in Fig. 1 and Tables 5 and 6. The eleven year period corresponded to three and a half full rotations of the annual cropping systems (conventional, no-till, reduced-input, and organic). Among these systems, the conventional lost the most nitrate over this period (685 kg NO_3^-–N ha^{-1}), while the organic

Table 5

Total nitrate loss, drainage, and leaching rates in the annual cropping systems, partitioned by crop year and season ("In season", while the primary crop (corn, soybean, or winter wheat) is on the field vs. "Off-season," outside of the growing season). Data averaged from 3 replicates over 11 years and values in parentheses are standard errors of the mean. Different superscripts within columns denote significant differences ($p \leq 0.05$) among only these cropping systems for corn, soybean and wheat year losses or (for remaining columns) among all ecosystems including the perennial cropping systems and unmanaged communities in Table 6.

Cropping system	Nitrate loss											Total drain-age (mm)	Nitrate leaching rate (g NO_3^-–N ha^{-1} mm^{-1})	Grain production impact (g NO_3^-–N kg^{-1} yield)
	Corn years			Soybean years			Wheat years							
	In-season (kg NO_3^-–N ha^{-1})	Off-season (kg NO_3^-–N ha^{-1})	Total (kg NO_3^-–N ha^{-1})	In-season (kg NO_3^-–N ha^{-1})	Off-season (kg NO_3^-–N ha^{-1})	Total (kg NO_3^-–N ha^{-1})	In-season (kg NO_3^-–N ha^{-1})	Off-season (kg NO_3^-–N ha^{-1})	Total (kg NO_3^-–N ha^{-1})	Total (kg NO_3^-–N ha^{-1})	Annual average (kg NO_3^-–N ha^{-1} yr^{-1})			
Conventional	32.2 (3.6)^a	339.0 (48.1)^a	371.2 (48.7)^a	56.2 (4.7)^a	8.3 (1.1)^a	64.5 (3.8)^a	180.7 (53.0)^a	65.1 (6.9)^a	245.9 (59.3)^a	685.4 (104.3)^a	62.3 (9.5)^a	3674	185.2 (28.4)^a	17.9 (3.4)^a
No-till	25.5 (3.5)^a	225.0 (30.5)^b	250.5 (32.8)^b	41.2 (8.2)^{ab}	2.1 (0.2)^b	43.2 (8.0)^b	90.6 (8.5)^b	70.1 (2.7)^a	160.7 (7.9)^b	458.7 (33.3)^b	41.7 (3.0)^b	4273	106.4 (7.8)^b	11.1 (0.7)^b
Reduced-input	27.5 (3.0)^a	124.4 (6.0)^c	152.0 (3.8)^c	39.7 (2.4)^b	0.2 (0.1)^c	39.9 (2.4)^b	63.2 (0.9)^c	11.3 (2.3)^b	74.6 (3.2)^c	267.0 (8.1)^c	24.3 (0.7)^c	2419	110.4 (3.3)^b	7.3 (0.4)^c
Organic	22.2 (4.8)^a	88.6 (1.8)^d	110.8 (6.5)^d	36.9 (2.5)^b	0.2 (0.1)^c	37.6 (2.6)^b	51.5 (2.1)^d	8.3 (1.8)^b	59.8 (1.2)^d	208.9 (8.5)^d	19.0 (0.8)^d	2415	86.5 (3.5)^c	7.2 (0.4)^c

lost the least (209 kg NO_3^-–N ha^{-1}). The no-till and reduced-input systems lost intermediate amounts of nitrate (458 and 267 kg NO_3^-–N ha^{-1}, respectively). Poplar and alfalfa lost less nitrate (0.8 kg NO_3^-–N ha^{-1} vs. 141.1 kg NO_3^-–N ha^{-1}, respectively) than any of the annual cropping systems. The successional communities and deciduous forest also lost less nitrate (12.3–121.1 kg NO_3^-–N ha^{-1}) than did any of the annual cropping systems.

Modeled drainage among annual cropping systems over the 11 year period followed the pattern: no-till (4273 mm) > conventional (3674 mm) > reduced-input (2419 mm) = organic (2415 mm). The perennial and unmanaged systems followed the pattern: deciduous forest (4137 mm) > early successional (2543 mm) > mid-successional (2507 mm) = poplar (2507 mm) > alfalfa (2174 mm).

Rates of nitrate leaching, defined as the mass of nitrate–N lost per unit of water moving through the soil (kg NO_3^-–N ha^{-1} mm^{-1}), were significantly different for each of the management systems. The highest rates of nitrate leaching were found in the conventional system (Table 5), where 185.2 g NO_3^-–N ha^{-1} were leached by each mm of soil water drainage. All of the other annual cropping systems had significantly lower rates of nitrate leaching, although rates were still much higher than in the unmanaged and perennial systems.

Grain yield impacts differed significantly among the annual cropping systems (Table 5). Impacts were greatest in the conventional system, with 17.9 g NO_3^-–N lost per kg yield. The no-till system had a significantly lower grain yield impact than the conventional system (11.1 g NO_3^-–N kg yield^{-1}), and the reduced-input and organic systems had grain yield impacts that were lower still (7.3 and 7.2 g NO_3^-–N kg yield^{-1}, respectively).

In the annual systems, the amount of time in each crop (i.e., the in-season) is not the same for each crop in the rotation. The corn portion of the rotation starts in May when corn is planted, and the in-season ends when the crop is harvested in late October or early November. The off-season for corn lasts from the fall harvest until

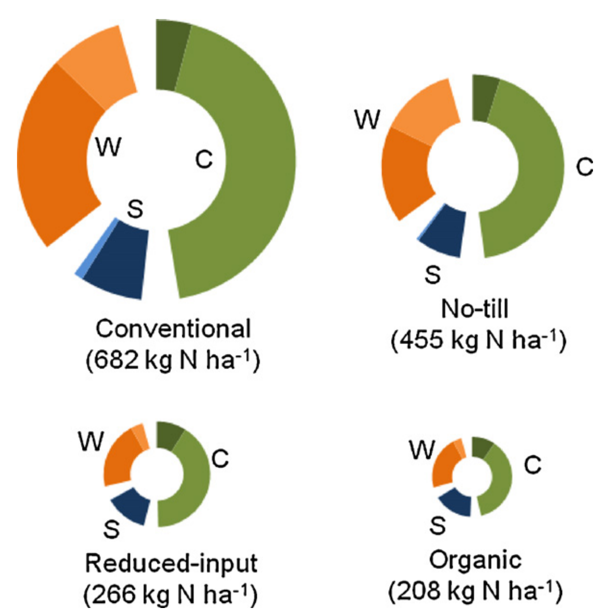

Fig. 2. Relative rates of nitrate loss from different phases of the conventional, no-till, reduced-input, and organic management systems. C = corn, S = soybean, and W = wheat phase of each corn–soybean–wheat rotation. The darker area of each crop segment represents nitrate loss during the time between planting and harvest of that crop; the lighter adjacent area (clockwise) represents off-season nitrate lost before the next crop is planted. The relative size of each circle represents the total amount of nitrate lost over the 11 year duration of the study (also in parentheses beneath each circle). See Table 5 for error terms.

Table 6
Total nitrate loss, drainage, and leaching rates in the perennial cropping systems and unmanaged communities partitioned into growing season ("In season", from May 1–October 1) and non-growing season ("Off season", October 2–April 30). Data are means from 3 replicate fields over 11 years and values in parentheses are standard errors of the mean. Superscripts within columns denote significant differences ($p \leq 0.05$) among these ecosystems only for In-season and Off-season losses or (for remaining columns) among all ecosystems including the annual cropping systems in Table 5.

Ecosystem	Nitrate loss				Total drainage (mm)	Nitrate leaching rate ($g\ NO_3{}^{-}–N\ ha^{-1}\ mm^{-1}$)
	In season ($kg\ NO_3{}^{-}–N\ ha^{-1}$)	Off season ($kg\ NO_3{}^{-}–N\ ha^{-1}$)	Total ($kg\ NO_3{}^{-}–N\ ha^{-1}$)	Annual average ($kg\ NO_3{}^{-}–N\ ha^{-1}\ yr^{-1}$)		
Alfalfa	72.0 (7.3)[a]	69.0 (12.8)[a]	141.1 (19.8)[e]	12.8 (1.8)[e]	2174	64.9 (9.1)[d]
Poplar	0.2 (0.1)[b]	0.7 (0.3)[b]	0.8 (0.4)[h]	0.1 (0.03)[g]	2507	0.3 (0.1)[g]
Early successional	4.1 (1.4)[c]	8.2 (3.3)[c]	12.3 (4.7)[f]	1.1 (0.4)[f]	2543	4.8 (1.8)[f]
Mid-successional	4.4 (0.4)[c]	4.9 (0.3)[c]	9.6 (0.7)[g]	0.9 (0.06)[f]	2507	3.8 (0.3)[f]
Deciduous forest	34.9 (12.4)[d]	85.0 (37.0)[a]	121.1 (46.7)[e]	11.0 (4.2)[e]	4137	28.9 (11.3)[e]

soybean is planted in June. The in-season for soybean lasts from planting in June until harvest in October. The off-season for soybean is normally very short, lasting from days to a few weeks, since wheat is planted in the fall following soybean. The in-season for wheat begins in the late fall when it is planted until it is harvested the following July, and the off-season for wheat lasts from July to the following May. Thus, in terms of time, each crop does not have an even third of the rotation, but instead corn has about one third, soybean has about one sixth, and wheat has about five sixths of the rotation.

In the annual crops, the largest nitrate leaching losses occurred during the corn phase of the corn–soybean–wheat rotation, which in all systems accounted for more than 50% of total nitrate loss (53–57%; Fig. 2). Wheat accounted for most of the rest – 35–36% of total losses in the conventional and no-till systems and 28–29% in the reduced-input and organic. The soybean phase accounted for less loss: 9.5% in the conventional and no-till systems and 15–18% of total loss in the reduced-input and organic systems.

In contrast to the soybean and wheat phases, almost all of the nitrate lost from the corn phase was lost during the winter "off season" following harvest prior to soybean planting: 90–91% of losses occurred during this period in the conventional and no-till systems and 80–82% in the reduced-input and organic systems. A substantially lower proportion of nitrate loss occurred in the wheat off-season: 27–44% in conventional and no-till systems and 14–15% in the reduced-input and organic. Soybean had even lower off-season proportional nitrate losses prior to fall wheat planting: 5–13% in the no-till and conventional systems, respectively, and <1% in the reduced-input and organic.

4. Discussion

Cropping systems receiving more intensive management – in particular more fertilizer inputs – lost more nitrate by leaching from the root zone than did those with less intensive management. More nitrate was lost from annual cropping systems (mean annualized loss rates ranged from 19 to 62 $kg\ NO_3{}^{-}–N\ ha^{-1}\ yr^{-1}$) than from perennial systems (0.01 to 13 $kg\ NO_3{}^{-}–N\ ha^{-1}\ yr^{-1}$), and in annual cropping systems more nitrate was lost from those with more N fertilizer inputs and longer periods without plant cover (conventional and no-till systems: 42–66 $kg\ NO_3{}^{-}–N\ ha^{-1}\ yr^{-1}$) than from those systems with less added nitrogen and winter cover (reduced-input and organic systems: 19–24 $kg\ N\ ha^{-1}\ yr^{-1}$).

The early successional, mid-successional, and poplar systems lost the least amount of nitrate (0.08–1.1 $kg\ NO_3{}^{-}–N\ ha^{-1}\ yr^{-1}$), mainly due to low concentrations of nitrate in drainage water. These systems had no (early and mid-successional) or very low (poplar) fertilizer inputs and very brief fallow periods. The alfalfa system lost the most nitrate of the perennial systems (12.8 $kg\ NO_3{}^{-}–N\ ha^{-1}\ yr^{-1}$, on average), about 10% more than was lost by the deciduous forest (11.0 $kg\ NO_3{}^{-}–N\ ha^{-1}\ yr^{-1}$), although the difference was not statistically significant. This range of loss rates is similar to those reported in previous shorter-term studies (Basso and Ritchie, 2005; Fox et al., 2001; Power et al., 2001).

Soil water drainage rates ranged from 198 to 422 $mm\ yr^{-1}$, representing 24–52% of precipitation. Previous studies in other KBS cropping systems had estimated that 31–36% of precipitation infiltrated the soils and percolated beyond the root zone (Basso and Ritchie, 2005; Smeenk, 2003, respectively). Watershed hydrologic balances yielded comparable estimates of groundwater recharge in this area (29% of precipitation: Rheaume, 1990). Nitrate leaching rates (nitrate–N lost per unit soil water drainage) varied substantially among systems, from a vanishingly low rate of 0.3 $g\ NO_3{}^{-}–N\ ha^{-1}\ mm^{-1}$ in poplar to 185.2 $g\ NO_3{}^{-}–N\ ha^{-1}\ mm^{-1}$ in the conventional system. Most differences are attributable to low nitrate concentrations in the low-leaching-rate systems combined with short or no periods without plant cover.

4.1. Effects of tillage

On average, nitrate loss from the no-till (41.6 $kg\ NO_3{}^{-}–N\ ha^{-1}\ y^{-1}$) was 35% lower than loss from the conventional system (62.3 $kg\ NO_3{}^{-}–N\ ha^{-1}\ y^{-1}$). These nitrate leaching losses represented 50 and 76%, respectively, of the total nitrogen applied to the no-till and conventional systems over the eleven year period. Less nitrate leached from the no-till system in spite of the higher soil water drainage, as has also been documented in other studies (Rasse and Smucker, 1999; Ogden et al., 1999). The corresponding leaching rates were 106 vs. 185 $g\ NO_3{}^{-}–N\ mm^{-1}$ in the no-till and conventional systems, respectively.

The grain production impact, measured as the amount of nitrate lost relative to grain yield, was also lower in the no-till than in the conventional system: 11.1 vs. 17.9 $g\ NO_3{}^{-}–N\ kg^{-1}$ yield, respectively (Table 5). These results differ from those reported in shorter term studies (Tyler and Thomas, 1977; Chichester, 1977), likely due to higher average yields in the no-till than in the conventional system (Grandy et al., 2006; Smith et al., 2007); the higher plant demand likely reduces the nitrate available for leaching in these soils. Higher average no-till yields are likely due to no-till gains in surface soil carbon (Syswerda et al., 2011), which helped to increase soil water holding capacity. The no-till system showed higher drainage compared to the conventional system, partially due to lower levels of hydraulic conductivity in the conventional system created by a tillage clay pan.

4.2. Conventional, organic, and reduced-input systems

Nitrate leaching losses in the conventional were higher than in the organic system: 62.3 vs. 19.0 $kg\ NO_3{}^{-}–N\ ha^{-1}\ y^{-1}$, respectively. The organic system had both lower soil water drainage as well as lower nitrate concentrations in the soil water throughout the study period. These differences were likely the result of the organic system's cover crops and higher weed pressure, which increase evapotranspiration and scavenge soil nitrogen, as well as large differences in applied nitrogen—the organic system did not receive manure or other fertilizer inputs. The nitrate leaching rate in the organic was less than half that of the conventional system (86.5 vs. 185.2 g NO_3^-–N ha^{-1} mm^{-1}, respectively).

The organic also had a lower grain production impact than did the conventional system, losing only 7.2 g NO_3^-–N kg $yield^{-1}$ compared to 17.9 g NO_3^-–N kg $yield^{-1}$ in the conventional system. These results are consistent with some (Hansen et al., 2001; Drinkwater et al., 1998) but not all (Pimentel et al., 2005) short-term comparisons of nitrate leaching in organic vs. conventionally managed row crops, though in contrast to other studies the organic system relied solely on nitrogen fixation by leguminous cover crops for exogenous N, rather than on organic fertilizers such as manure or compost. Levels of nitrogen fixation were not measured in this study, though it is likely nitrogen fixation by leguminous cover crops and soybeans did not meet the entire nitrogen demand of the organic system.

The reduced-input system lost more nitrate than did the organic system (24.2 vs. 19.0 kg NO_3^-–N ha^{-1} y^{-1}, respectively), but less than did the conventional system (62.3 kg NO_3^-–N ha^{-1} y^{-1}). Compared to the conventional system, the reduced-input system also had a reduced nitrate leaching rate (110 g NO_3^-–N ha^{-1} mm^{-1}) and a grain production impact (7.3 g NO_3^-–N kg $yield^{-1}$) similar to the organic system. The reduced-input had lower soil water drainage rates than the conventional system due to the use of cover crops and increased weed pressure, but compared to the organic system it had higher nitrogen applications and higher yields (Smith et al., 2007).

4.3. Perennial systems

The alfalfa system lost less nitrate (12.8 kg NO_3^-–N ha^{-1} yr^{-1}) than did the annual cropping systems but more than did the poplar, early successional, and mid-successional systems. The majority of alfalfa nitrate losses were in 2000 and 2001, during a period when the alfalfa stand was being re-established following disking in 2000. If 2000 and 2001 were excluded from the analysis, the total nitrate leaching would have been 46.0 ± 8.7 kg NO_3^-–N ha^{-1} for the period, or 5.1 ± 1.7 kg NO_3^-–N ha^{-1} yr^{-1} on average. Nonetheless, periodic re-establishment of alfalfa is typically required. Alfalfa had the lowest soil water drainage of all systems, 2174 mm, and had the highest nitrate leaching rate of the perennial and successional systems (64.9 g NO_3^-–N ha^{-1} mm^{-1}). The low soil water drainage is partially due to the fact that compared with all the other systems considered, alfalfa was continuously present on the field. Thus the alfalfa system was able to begin photosynthesis much earlier in the growing season than the poplar or deciduous forest systems, and unlike the annual cropping systems it lacked the fallow periods with no ground cover. Problems with increased nitrate leaching during the reestablishment period in alfalfa could be avoided by planting a nitrogen scavenging cover crop directly after killing the alfalfa. This can be difficult, but conserving the residual nitrogen in the soil is critical to maintain long term soil fertility and reducing groundwater contamination.

The poplar system lost the least nitrate (0.08 kg NO_3^-–N ha^{-1} yr^{-1}), with intermediate soil water drainage and often undetectable levels of nitrate in the soil water samples. The nitrate leaching rate of the poplar system was also the lowest among all of the systems, 0.3 g NO_3^-–N ha^{-1} mm^{-1}. Low nitrate leaching in poplar was likely due to a combination of high nitrate scavenging by roots plus little nitrogen input as these systems were fertilized only once at stand establishment in 1989. There are many environmental programs, both in the U.S. and abroad, that use poplar plantings to reduce nitrate concentrations in riparian areas, waste water treatment systems, or confined animal feeding operations (Ball et al., 2005).

4.4. Successional communities

The early and mid-successional communities lost very little nitrate (1.1 and 0.9 kg NO_3^-–N ha^{-1} yr^{-1} on average, respectively), while the mature deciduous forest lost an order of magnitude more (11.0 kg NO_3^-–N ha^{-1} yr^{-1}). The soil water drainage in the early and mid-successional communities was also lower than in the deciduous forest (2543 and 2507 vs. 4137 mm, respectively), implying greater evapotranspiration in these systems, perhaps due to a greater grass and forb cover that would be active in the spring and fall seasons as well as in the summer.

The deciduous forest also had the highest rates of nitrate leaching among the three successional communities, losing 28.9 compared to 4.8 and 3.8 g NO_3^-–N ha^{-1} mm^{-1} in the early and mid-successional systems, respectively. Low nitrate losses from the early and mid-successional ecosystems are consistent with their higher biomass accumulation rates (Vitousek and Reiners, 1975). Because the mature deciduous forest is likely close to equilibrium biomass, annual nitrate losses ought to be in approximate equilibrium with the amount of nitrogen that is deposited on the site annually by dry and wet deposition. KBS received on average 6.1 ± 0.4 kg N ha^{-1} yr^{-1} via wet precipitation during the study period (National Atmospheric Deposition Program, 2009), so the observed nitrate loss rate of 11 kg NO_3^-–N ha^{-1} yr^{-1} suggests near equilibrium depending on the balance between further losses from denitrification and dry deposition gains. This level of nitrate loss is well within the range of reported values for nitrate leaching in forest systems (Borken and Matzner, 2004), though higher than for some (Schleppi et al., 2004).

4.5. Seasonal and interannual variability

Nitrate leaching varies both seasonally and throughout the rotation cycle of cropping systems as a function of available nitrogen concentrations and soil water mobility (Martin et al., 1994; Rasse et al., 1999). Pimentel et al. (2005), for example, showed that in manure- and legume-based organic grain systems nitrate concentrations in leachate varied from 0 to 28 mg NO_3^-–N L^{-1} and were highest in June and July. Nitrate leaching should increase during months when soil moisture is highest, since water is needed to carry nitrate through the profile and soil hydraulic conductivity is higher. Leaching should also increase during the months when plants are absent or inactive, since roots will remove both water and nitrate from soil. Nitrate leaching should also be higher following fertilized or nitrogen fixing crops, since these periods are associated with high nitrate concentrations.

Annual precipitation varied significantly during the study period, ranging from 608 mm in 1999 to 1150 mm in 2006. Total precipitation from 1996 to 2006 was 9218 mm, which averages to an annual precipitation of 838 ± 51 mm. Years with higher amounts of precipitation had higher modeled soil water drainage in all of the systems. Despite precipitation variability, the annual crops differed consistently in nitrate leaching losses. Corn contributed disproportionally to total nitrate leaching losses over the corn–soybean–winter wheat rotation cycle. Over 50% of total losses in all four systems occurred during the corn phase, with most of this loss (90–91% in the conventional and no-till systems, 80–82% in the reduced-input and organic systems) occurring during the winter off-season after corn harvest and prior to soybean planting. The lower proportion in the reduced-input and organic systems is likely the result of winter cover crops in these systems.

The soybean phase accounted for the least overall proportion of nitrate loss: 9.5% for the conventional and no-till and 15–18% for the reduced-input and organic systems, respectively. Most of the lower proportional losses in soybean are likely due to a combination of no fertilizer inputs and subsequent winter wheat planting, which reduces the intercrop fallow period to a few weeks in the fall prior to November wheat planting: in soybean less than 15% of losses occurred during the off-season. Off-season losses for the reduced-input and organic systems were particularly low (0.5% vs. 5–13% for the no-till and conventional systems, respectively); reasons for this are not clear but could be related to nitrate immobilization in organic matter remaining from the prior cover crop in these systems, which also have a higher soil carbon content (Syswerda et al., 2011). The corn portion of the rotation had the majority of its losses during the off-season, with very little loss while the crop was growing. Wheat, on the other hand, had larger losses during the in-season period than the other crops. This is likely due to the fall planting of wheat, when the plants may not be efficient enough to take up available nitrogen during the early parts of their growth.

Proportional off-season nitrate loss was also relatively low during the wheat phase of the rotation, which accounted for about a third of total nitrate loss from each system (35–36% in conventional and no-till and 28–29% in the less fertilized reduced-input and organic systems; Fig. 2). The proportional off-season loss in wheat was highest in the conventional and no-till systems (27–44%, respectively) and substantially less in the organic and reduced-input (14–14%, respectively).

Cover crops are likely responsible for the lower proportional off-season nitrate losses in the reduced-input and organic systems for all crop rotation phases. As noted earlier, winter cover both reduces drainage as a result of more evapotranspiration during late fall and early spring, and removes inorganic N from the soil solution as a result of plant growth. Additionally, cover crops add organic matter to soil that can provide a substrate for N immobilization by microbes during its decomposition.

In the perennial cropping systems, poplar consistently lost very little nitrate, and nitrate leaching was not responsive to variation in precipitation as nitrate concentrations in the soil water drainage were consistently low. Alfalfa had greater nitrate leaching losses, which occurred mainly during stand re-establishment in 1999–2001. In the successional systems, interannual variation in precipitation and soil water drainage were less associated with temporal variation in nitrate leaching than in the annual management systems. This decoupling of nitrate loss from soil water drainage appears mainly due to the generally low concentrations of nitrate in water draining these systems.

The presence of nitrogen fixing crops (including soybean as well as cover crops) was not consistently related to higher nitrate leaching losses. The residual N from the cover crops used in the organic and reduced input systems was presumably assimilated during the subsequent period of crop growth without large impacts on nitrate leaching. The one exception was in the alfalfa system, in which a large flush of N leaching was observed after the stand was killed during reestablishment. This was partially due to the lack of plant uptake during this period, but also due to the large amount of fixed nitrogen that was immediately made available in this system. The cover crops used in the organic and reduced input systems were not nearly as productive or perennial as the alfalfa, and presumably they fixed less N on an annual basis.

5. Conclusions

This study found a wide range of nitrate leaching losses from the row crop systems, suggesting the potential for significant reductions by management. In particular these findings suggest that cover crops, reduced tillage, perennial crops, and reduced fertilizer inputs could all help to reduce nitrate leaching. In comparison to conventional management, implementing these practices at the site produced reductions in nitrate leaching losses that ranged from a low of 33% for no-till, 60% for reduced input, 70% for organic/biologically-based management (without manure), 80% for Alfalfa, and an almost 100% reduction for poplar. Additionally, management could be adjusted to target the loss of nitrate during particularly critical portions of the rotation in annual cropping systems, such as after corn harvest. Since the vast majority of the nitrate losses are during the fallow periods when crops are not actively growing, this period should be the focus for management to reduce nitrate leaching.

These results also have implications for the placement and management of different cropping systems within the landscape. In areas that are particularly vulnerable to nitrate leaching, systems that conserve nitrate loss could disproportionately reduce watershed nitrate loading. Management options that will mitigate nitrate loss from annual crops most strongly include (in order of magnitude): (1) the substitution of perennial for annual crops; (2) the use of winter cover crops, especially legumes such as clover that can reduce the need for N fertilizer; and (3) the adoption of permanent no-till management.

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