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Nitrate Leaching from Continuous Corn, Perennial Grasses, and Poplar in the US Midwest

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Abstract

Leaching from annual corn (*Zea mays* L.) crops is a primary source of nitrate (NO_3^-) pollution of ground and surface waters. Here, we compare NO_3^- losses from no-till corn with losses from various alternative perennial cropping systems (switchgrass [*Panicum virgatum* L.], miscanthus [*Miscanthus* ×*giganteus* J.M. Greef & Deuter ex Hodkinson & Renvoiz], a native grass mixture, and restored prairie), as well as hybrid poplar (*Populus nigra* L. × *P. maximowiczii* A. Henry 'NM6'), all grown on a well-drained soil in Michigan. Soil water was sampled from below the root zone using suction cup samplers during nonfrozen periods (March–November) between 2009 and 2016. Leaching was estimated from NO_3^- concentrations in soil water and modeled drainage (percolation) rates. Drainage rates were not significantly different among crops, constituting ~30% of total annual precipitation. Aboveground net primary production (Mg ha^{-1} yr^{-1}) averaged across the 7 yr was highest in poplar (30.8 ± 1.9 [SE]) followed by miscanthus (23.9 ± 2.4) and corn (20.4 ± 0.9). Volume-weighted mean NO_3^- concentrations (mg N L^{-1}) and NO_3^- leaching (kg ha^{-1} yr^{-1}) averaged across the 7 yr were 9.2 and 34.1, 2.3 and 5.9, and 3.0 and 7.2, respectively, for corn, perennial grasses and poplar. Approximately 10 to 32% of applied N was lost as NO_3^- from these crops, with the highest percent losses from poplar (32%) followed by corn (20%). Perennial cropping systems leached considerably more NO_3^- in first few years after planting, but over 7 yr they lost much less NO_3^- than corn. Perennial crops may therefore help ameliorate NO_3^- pollution in agricultural landscapes even if they receive modest N fertilization.

Core Ideas

- Over 7 yr, perennial grasses and poplar trees leached much less nitrate than corn
- Nitrate leaching from grasses and poplar was comparable with corn for 1–2 yr after planting.
- Perennial crops can ameliorate nitrate pollution in agricultural landscapes.

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Nitrate (NO_3^-) is a highly water-soluble form of nitrogen (N) that moves readily with water percolating through the soil profile, potentially contaminating groundwater and eventually moving into surface waters (Basso and Ritchie, 2005; Cameron et al., 2013; Robertson and Saad, 2011). Mitigation of NO_3^- leaching from agricultural soils is desirable because excess NO_3^- originating from agricultural land uses is a major concern for drinking water quality and a driver of eutrophication of surface waters including marine coastal zones (Baron et al., 2013). In landscapes with intensive row crop agriculture, inorganic N fertilizers added to annual crops are the primary source of NO_3^- pollution, as has been shown by numerous studies (Padilla et al., 2018; Wang et al., 2019). Corn (*Zea mays* L., also referred to as maize) in particular receives high rates of applied N—from 100 to >200 kg N ha^{-1} yr^{-1} in the US Midwest, and often two to three times more than this in China (Vitousek et al., 2009). Even at optimal application rates, about 15 to 65% of the N applied is typically lost as NO_3^- leached out of the rooting zone (Basso et al., 2016; Randall and Mulla, 2001). Corn production in the US has increased in recent years in response to increasing demand for grain-based ethanol production (Lark et al., 2015), potentially exacerbating the problem of NO_3^- pollution (Donner and Kucharik, 2008).

Strategically located perennial plantings including riparian buffers and filter strips have shown the potential to reduce NO_3^- export in overland flow from agricultural landscapes (Sahu and Gu 2009; Schulte et al., 2017). An emerging option that could also mitigate NO_3^- leaching from agricultural landscapes is to grow cellulosic bioenergy crops rather than corn for biofuel production (Robertson et al., 2017). Perennial grasses such as switchgrass have been identified as promising feedstocks for bioenergy production and are more suitable for marginal lands that may be particularly vulnerable to NO_3^- leaching under intensive agriculture. Because of their low N fertilization requirements,

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Abbreviations: ANPP, aboveground net primary production; BCSE, Biofuel Cropping System Experiment; KBS, Kellogg Biological Station; SALUS, Systems Approach for Land Use Sustainability model.

perenniality, and longer growing seasons, some studies have shown that perennial grass crops can reduce NO_3^- leaching compared with annual corn (David et al., 2010; McIsaac et al., 2010; Smith et al., 2013; Schulte et al., 2017) while offering other desirable ecosystem services (Robertson et al., 2017; Schulte et al., 2017). Growing poplar (*Populus* spp.) or other short-rotation woody crops for bioenergy production is another option, increasingly popular in Europe, because of their efficient nutrient cycling, low fertilizer requirements, and high economic yields (Diaz-Pines et al., 2016; Djomo et al., 2015).

Here we combine NO_3^- concentration measurements in soil water beneath the root zone with modeled drainage rates to estimate NO_3^- leaching losses from corn, four perennial grass cropping systems (miscanthus [*Miscanthus* ×*giganteus* J.M. Greef & Deuter ex Hodkinson & Renvoiz], switchgrass [*Panicum virgatum* L.], a mixture of five native grasses, and restored prairie), and poplar, all grown in close proximity on a well-drained sandy loam soil in the humid temperate climate of southwestern Michigan. Our study is designed to determine how NO_3^- losses compare among these annual and perennial crops over the 7-yr period spanning the establishment and stabilization of the perennial crops and a wide range of climate variability. Although several studies of specific perennial cropping systems have suggested that they leach less NO_3^- than traditional corn, NO_3^- leaching likely varies by plant type, N fertilization rate, water table, and soil texture, and thus comparative studies of NO_3^- leaching from different environmental settings are needed. The well-drained soil and deep unsaturated zone at our study site contrasts with similar comparative NO_3^- leaching studies conducted elsewhere in the US Midwest on sites with more fine textured soil, poorer drainage, and high water tables (e.g., McIsaac et al., 2010; Smith et al., 2013), and thus our study represents another widespread soil type in the region.

Materials and Methods

Experimental Details

The Biofuel Cropping System Experiment (BCSE) is located at the W.K. Kellogg Biological Station (KBS) (42.3956° N, 85.3749° W; elevation 288 m asl) in southwestern Michigan. This site is a part of the Great Lakes Bioenergy Research Center (www.glbrc.org) and Long-term Ecological Research Site (www.lter.kbs.msu.edu). Soils are mesic Typic Hapludalfs developed on glacial outwash (Crum and Collins, 1995) with high sand content (~76% in the upper 150 cm) intermixed with more silt in the upper 50 cm. The water table lies approximately 12 to 14 m below the surface. The climate is humid temperate with a mean annual air temperature of 10.1°C and annual precipitation of 1005 mm, 511 mm of which falls between May and September (1981– 2010) (NCDC, 2013; Robertson and Hamilton, 2015).

The BCSE was established as a randomized complete block experiment in 2008 on a field previously used for grain crop agriculture for many decades and mostly for alfalfa (*Medicago sativa* L.) since 2001, and it consists of five randomized blocks each containing 10 treatment (cropping system) plots of 28 × 40 m (Supplemental Fig. S1; Sanford et al., 2016). Experimental treatment details are at https://lter.kbs.msu.edu/research/long-term-experiments/glbrc-intensive-experiment/. For this study, six cropping systems were selected: (i) continuous no-till corn, (ii) switchgrass, (iii) miscanthus, (iv) a mixture of five species of native grasses [*Andropogon gerardii* Vitman, *Elymus canadensis* L., *Panicum virgatum* L., *Schizachyrium scoparium* (Michx.) Nash, and *Sorghastrum nutans* (L.) Nash] that will hereafter be referred as the "native grasses" treatment, (v) an 18-species restored native prairie, and (vi) hybrid poplar (*Populus nigra* L. × *P. maximowiczii* A. Henry 'NM6'). Initial species composition in the restored prairie cropping system is provided in Supplemental Table S1.

Agronomic Practices and Nitrogen Fertilizer Application

Corn was planted each year in the first week of May, whereas all perennial crops including poplar were planted between May and June 2008. The crops were grown without irrigation or tillage. Due to washout of seeds by intense rainfall, the switchgrass, native grasses, and restored prairie treatments were replanted in July 2009. Annual emergence of the perennial crops occurred between mid-April and mid-May, depending on year, and was determined from daily phenological images taken by permanently mounted cameras. Aboveground net primary production (ANPP) was estimated from samples collected at maximum biomass. All of the cropping systems were harvested; the timing of harvest depended on weather, varying between October and November for corn and between November and December for the perennial herbaceous crops. The poplar was harvested only once in the winter of 2013–2014, as the culmination of a 6-yr rotation. Leaf emergence and senescence based on the phenological images indicated the beginning and end of the poplar growing season, respectively, in each year.

Application of N fertilizer to the different crops followed typical management approaches for the region. Corn was fertilized with 150 to 170 kg N ha^{-1} yr^{-1} as ammonium sulfate in three splits (a first split either prior to planting or at the time of planting depending on the year, a second split a week later, and a third split in mid-June). All perennial grasses (except restored prairie) were provided 56 kg N ha^{-1} yr^{-1} of N fertilizer between 2010 and 2016; an additional 77 kg N ha^{-1} was applied to miscanthus in 2009. Poplar was fertilized once in 2010 with 157 kg N ha^{-1}. The restored prairie remained unfertilized throughout the study period (Table 1). Each cropping system was managed using typical agronomic practices for crop protection and production (Sanford et al., 2016).

Field Soil Water Sampling and Laboratory Analysis

Prenart soil water samplers (http://www.prenart.dk/soil-water-samplers/) were installed in Blocks 1 and 2 of the experimental site, and ceramic soil water samplers (Eijkelkamp; http://www.eijkelkamp.com) were installed in Blocks 3 and 4 (there were no soil water samplers in Block 5) (Supplemental Fig S1). All samplers were installed at a depth of 1.2 m at a 45° angle from the soil surface, ~20 cm into the unconsolidated sand of the 2Bt2 and 2E/Bt horizons (soils are described in Crum and Collins 1995). Beginning in 2009, soil water was sampled at weekly to biweekly intervals during nonfrozen periods (April–November) by applying 50 kPa of vacuum for 24 h, during which water was collected in glass bottles. Depending on the volume of leachate collected, the samples were filtered using different filters: 0.45-µm pore size, 33-mm-diam. cellulose acetate membrane filters when volumes were <50 mL, and 0.45-µm pore size, 47-mm-diam. Supor 450 membrane filters for larger volumes.

Table 1. Nitrogen fertilizer applications to the cropping systems.

Crop-year†	Nitrogen applied					
	Corn	Switchgrass	Miscanthus	Native grasses	Poplar	Restored prairie
	kg ha^{-1}					
2009	158	0	77	0	0	0
2010	176	56	56	56	0	0
2011	172	56	76	56	157	0
2012	174	56	0	20	0	0
2013	173	57	57	57	0	0
2014	168	57	57	57	0	0
2015	172	57	57	57	0	0
Total	1193	339	380	303	157	0

† Crop-years refer to the period from planting or emergence of the crop in the indicated year through the ensuing year until the next year's planting or emergence.

Samples were analyzed for NO_3^- concentration (expressed here as mg N L^{-1}) using a Dionex ICS1000 ion chromatograph system with membrane suppression and conductivity detection; the detection limit of the system was ~0.010 mg NO_3^--N L^{-1}.

Nitrate Leaching Estimates

Drainage and NO_3^- leaching were estimated on a crop-year basis, defined from the date of planting or emergence in a given year to the day prior to planting or emergence in the following year. For each sampling point, the NO_3^- concentration was linearly interpolated between the sampling dates during nonfreezing periods (April–November). Nitrate concentrations during any modeled drainage occurring in the nonsampling winter period (December–March) were also linearly interpolated based on the preceding November and subsequent April samples.

Nitrate leaching (kg N ha^{-1}) in soil water below the root zone (1.2-m depth) was calculated by multiplying the NO_3^-–N concentrations by drainage rates (m^3 ha^{-1}), which were estimated using the Systems Approach for Land Use Sustainability (SALUS) model. The SALUS model is a crop growth model that is well calibrated for KBS soil and environmental conditions. It simulates yield and environmental outcomes in response to weather, soil, management (planting dates, plant population, irrigation, N fertilizer application, and tillage), and genetics (Basso and Ritchie, 2015). The SALUS water balance submodel simulates surface runoff, saturated and unsaturated water flow, drainage, root water uptake, and evapotranspiration during growing and nongrowing seasons (Basso and Ritchie, 2015). The SALUS model has been used in studies of evapotranspiration (Hamilton et al., 2015, 2018; Hussain et al., 2019) and nutrient leaching (Syswerda et al., 2012; Ruan et al., 2016) on KBS soils, and its predictions of growing-season evapotranspiration are consistent with independent measurements based on soil water drawdown (Hamilton et al., 2015) and water vapor fluxes measured by eddy covariance (Abraha et al., 2015). Nitrate leaching was assumed insignificant on days when SALUS predicted no drainage. The volume-weighted mean NO_3^-–N concentration (mg L^{-1}) of the leachate for the entire crop-year and for the 7 yr combined was calculated as the sum of daily NO_3^-–N leaching (kg ha^{-1}) divided by the sum of daily drainage rates (m^3 ha^{-1}).

Statistical Analysis

One-way ANOVA was conducted to compare total annual drainage rates, NO_3^- leaching rates, and volume-weighted mean NO_3^- concentrations, as well as maximum aboveground biomass, among the crop treatments, including all seven crop-years. When a significant ($\alpha = 0.05$) difference was detected among the groups, we used the Tukey honest significant difference post-hoc test to make pairwise comparisons among the groups. For maximum aboveground biomass in poplar, we lacked data for 2014 and 2015, and because of the resultant unequal sample sizes, we used the Tukey–Kramer method to make pairwise comparisons among the groups.

Results

Climate and Drainage

Air temperature recorded from a nearby weather station averaged 9.3°C (mean for 2009–2016), which was 0.2°C warmer than the long-term average (1988–2016, 9.1°C). Precipitation differed among years: 2009–2010 was 200 mm below the long-term average (1988–2016, 915 mm), whereas other years were either 200 mm above or close to the long-term average (Fig. 1).

Drainage rates (mm) simulated by SALUS over the seven crop-years were not significantly different ($p = 0.85$) among cropping treatments, with mean annual rates ranging from 315 (poplar) and 330 (perennial grasses) to 360 mm (corn) (Fig. 1). Among all treatments, the amount of water drained from miscanthus in the 2015 crop-year was the highest as a result of its relatively higher percolation during summer 2015, when there were particularly heavy rain events. Years with lower precipitation had lower drainage; the overall mean annual drainage across treatments was 173 mm in the 2009 crop-year versus 360 mm over crop-years 2010 to 2016. Overall, modeled drainage rates for all cropping systems across years averaged 331 mm yr^{-1}, which is ~34% of the mean annual precipitation of 970 mm (Fig. 1, Supplemental Table S2).

Growing Season Length and Primary Production

Depending on the year, the growing period for corn varied between 160 and 190 d, whereas growing periods for perennials including poplar were often a few weeks longer (Supplemental Fig. S2). Aboveground net primary production (Mg ha^{-1} yr^{-1}) averaged across the 7 yr (including the four replicate plots) significantly differed ($p < 0.05$) among cropping treatments. Poplar, miscanthus, and corn were the most productive systems, whereas switchgrass, native grasses, and restored prairie were less productive. The ANPP was lower in corn (grain + stover, 20.4 ± 0.9 [SE] Mg ha^{-1} yr^{-1}) than poplar (30.8 ± 1.9 Mg ha^{-1} yr^{-1}) and

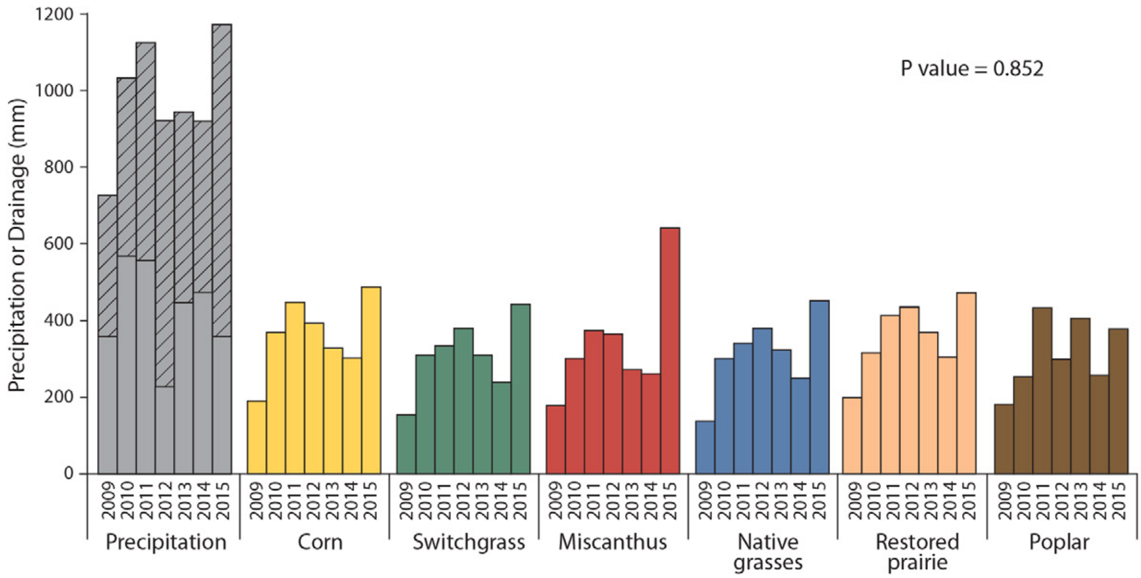

Fig. 1. Precipitation during crop-years (May–April, gray bars) and total crop-year drainage (colored bars) of the different cropping systems. Precipitation for each crop-year is divided into the growing season (May–September, solid bar) and nongrowing season (October–April, hatched bar). There were no significant differences in the drainage rates among treatments grouped across years (ANOVA). Years refer to crop-years that extend from the period from planting or emergence of the crop in the indicated year through the ensuing year until the next year's planting or emergence.

miscanthus (23.9 ± 2.4 Mg ha^{-1} yr^{-1}), but higher than the other perennial systems (switchgrass: 7.7 ± 0.9 Mg ha^{-1} yr^{-1}; native grasses: 8.1 ± 0.9 Mg ha^{-1} yr^{-1}; restored prairie: 6.8 ± 0.8 Mg ha^{-1} yr^{-1}). Interannual variability in maximum biomass of the perennial crops was high, with a general trend of increasing biomass over time, except for lower production in the rainfall-deficit years 2009 and 2012 (Table 2, Supplemental Fig. S3).

Nitrate Concentration and Leaching Rates

Volume-weighted mean NO_3^- concentrations (mg L^{-1}) and leaching rates (kg ha^{-1} yr^{-1}) across the seven crop-years (averaging the four replicate plots) varied significantly ($p < 0.05$) among cropping treatments depending on N fertilization and the stage of cropping system establishment (Fig. 2). Corn, which received the highest rate of N fertilization (170 kg ha^{-1} yr^{-1}), had higher NO_3^- leaching rates over the seven crop-years (34.1 ± 10.4 [SE] kg ha^{-1} yr^{-1}) compared with perennial grassland systems (switchgrass: 9.2 ± 1.4 kg ha^{-1} yr^{-1}; miscanthus: 7.7 ± 4.2 kg ha^{-1} yr^{-1}; native grasses: 4.4 ± 1.9 kg ha^{-1} yr^{-1}; restored prairie: 2.4 ± 1.8 kg ha^{-1} yr^{-1}) and poplar (7.2 ± 1.5 kg ha^{-1} yr^{-1}). The volume-weighted mean NO_3^-–N concentration averaged across the seven crop-years in corn (9.2 ± 2.7 [SE] mg L^{-1}) was higher than in perennial grasses and poplar, where average concentrations were no higher than 3.2 mg L^{-1}, although the 7-yr mean for corn was not statistically distinguishable from means for switchgrass and miscanthus, which had relatively high concentrations during their establishment phases (Table 2, Fig. 2).

Rates of NO_3^- leaching were also influenced by the stage of cropping system establishment (Fig. 2). The perennial crops leached NO_3^- at higher rates during initial establishment years (means for the first two crop-years; switchgrass: 22.2 ± 0.0 [SE] kg N ha^{-1} yr^{-1}; miscanthus: 17.4 ± 12.2 kg N ha^{-1} yr^{-1}; native grasses: 8.0 ± 4.1 kg N ha^{-1} yr^{-1}; restored prairie: 1.1 ± 0.0 kg N ha^{-1} yr^{-1}; poplar: 14.6 ± 0.0 kg N ha^{-1} yr^{-1}) than in following five crop-years (switchgrass: 4.0 ± 1.4 [SE] kg N ha^{-1} yr^{-1}; miscanthus: 3.8 ± 1.0 kg N ha^{-1} yr^{-1}; native grasses: 3.0 ± 1.1 kg N ha^{-1} yr^{-1}; restored prairie: 2.9 ± 1.8 kg N ha^{-1} yr^{-1}; poplar: 4.2 ± 2.1 kg N ha^{-1} yr^{-1}). Average NO_3^-–N concentrations in establishing perennials varied from 5.5 ± 2.8 (grassland systems) to 8.3 ± 5.7 (miscanthus) and 7.7 mg L^{-1} (poplar), although concentrations during the later years were considerably lower. Overall, compared with the sustained high rate of NO_3^- leaching in corn, the perennial grass and poplar systems had significantly decreased NO_3^- leaching after the first couple of years of establishment (Fig. 2). Those initial years included, in the case of miscanthus and poplar, N fertilizer additions in 2009–2011 and 2011, respectively.

The total NO_3^- leached over the seven crop-years in the various cropping systems represented 10 to 32% of each system's total N fertilizer input, with poplar showing the highest leaching relative to inputs (32%) and native grasses showed least leaching (10%), compared with 20% leaching relative to inputs in corn (Fig. 3).

Table 2. Maximum aboveground biomass (ANPP), nitrate leaching rates, and volume-weighted mean nitrate concentration (means ± SE) over seven crop-years (2009–2016) in each cropping system. Pairwise comparisons of these means are shown in Supplemental Fig. S3 (ANPP) and Fig. 2 (nitrate).

Cropping system	ANPP	NO_3^- leached	Mean NO_3^- concentration
	Mg ha^{-1} yr^{-1}	kg N ha^{-1} yr^{-1}	mg N L^{-1}
Corn	20.4 ± 0.9	34 ± 10.4	9.2 ± 2.7
Switchgrass	7.7 ± 0.9	9.2 ± 1.3	3.2 ± 0.4
Miscanthus	23.9 ± 2.4	7.6 ± 4.2	3.1 ± 1.8
Native grasses	8.1 ± 0.9	4.4 ± 1.9	2.3 ± 1.1
Poplar	30.8 ± 1.9	7.2 ± 2.1	3.0 ± 0.6
Restored prairie	6.8 ± 0.8	2.4 ± 1.7	0.6 ± 0.4

Discussion

This study measured NO_3^- leaching rates from corn, perennial grassland cropping systems (switchgrass, miscanthus, and native grasses), restored prairie, and poplar, all rainfed cropping systems grown in close proximity on a well-

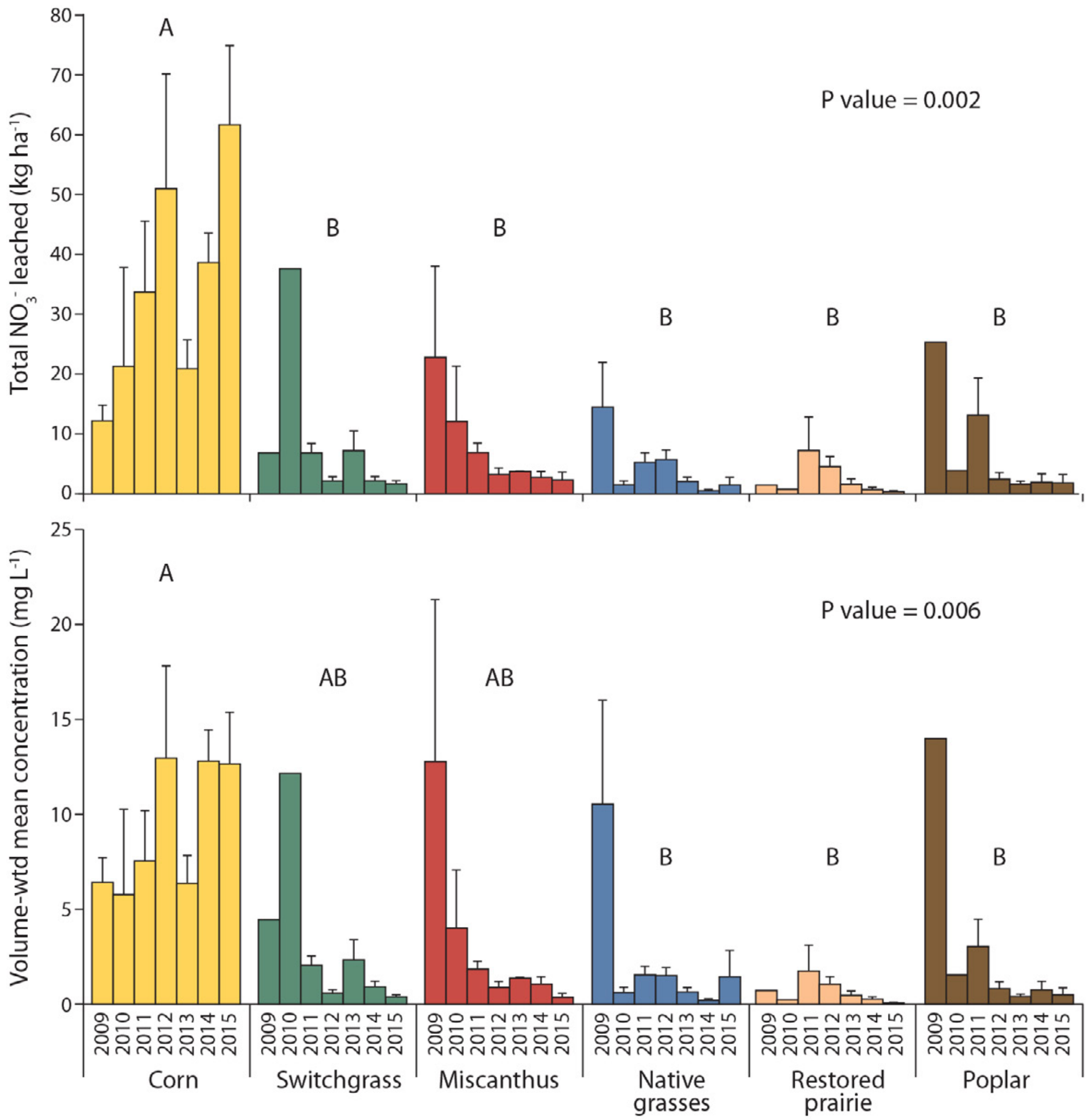

Fig. 2. Top panel: Total nitrate leached (kg N ha^{-1} yr^{-1}); bottom panel: annual volume-weighted mean nitrate concentrations (mg N L^{-1}) in leachate from the different cropping systems. Each bar shows the standard error of the means of four replicate plots. Water samples were not available from all replicates, resulting in no error bars in some years. The *p* values refer to the overall ANOVA. Where cropping combinations share a similar letter, the means grouped across years are not significantly different as determined by the Tukey honest significant difference post-hoc test ($\alpha = 0.05$). Years refer to crop-years that extend from the period from planting or emergence of the crop in the indicated year through the ensuing year until the next year's planting or emergence.

drained sandy loam soil. Our results clearly show that over the seven crop-years, the perennial grassland systems and poplar leached less NO_3^- than corn even when fertilized at modest rates, and that NO_3^- leaching rates from the perennial cropping systems decreased markedly within a few years of initial crop establishment.

Nitrate Leaching

Nitrate leaching rates differed significantly among cropping systems, depending on N fertilization and the time since establishment of the cropping system (Fig. 2). During the initial establishment phase (2009–2011), NO_3^- leaching rates from the perennial cropping system were highest and similar to leaching rates in corn. During this phase, the ANPP of perennial cropping systems had not yet reached maximum levels (Sanford et al., 2016), and thus the systems may not have been able to fully utilize the N that was available from fertilizer and mineralization of soil

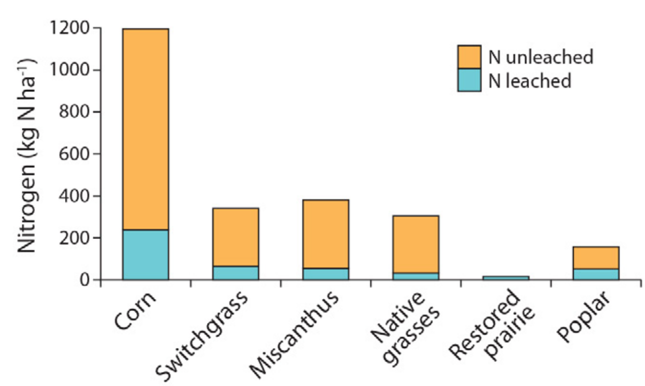

Fig. 3. Summary of total amount of nitrogen fertilizer applied (entire bar) and nitrate leached (green bar) in the different cropping systems over the seven crop-years. The fate of unleached N (orange bar) includes removal in harvest, accumulation in root biomass and soil organic matter, and nitrogen losses via gaseous nitrogen emissions.

organic N. Organic N mineralization may have been especially high at this site due to tillage and cultivation of alfalfa for the 5 yr prior to establishment of the BCSE, although the unfertilized restored prairie system leached less NO_3^- in its establishment phase, suggesting that legacy N from the alfalfa may not explain higher initial NO_3^- leaching rates in the other perennial cropping systems.

Nitrate leaching rates from the perennial cropping systems substantially decreased 3 to 4 yr after planting, when the crops reached their maximum ANPP. The lower NO_3^- leaching rates could be explained by increasing crop N demand with time after establishment as roots became distributed throughout the soil profile (Sprunger et al., 2017). However, previous studies of the relation between NO_3^- leaching rates and N fertilization in perennial crops after establishment have reported contrasting results. Decreased NO_3^- leaching from miscanthus has been reported within 4 yr of establishment without fertilization, and from switchgrass even with fertilization (Smith et al., 2013). In contrast, other studies have found increased NO_3^- leaching rates with N fertilization 4 to 5 yr after establishment of miscanthus and switchgrass (Davis et al., 2015; Ruan et al., 2016). In poplar, Diaz-Pines et al. (2016) showed that N losses diminished by 80% within 4 yr without annual fertilization and by 40% with fertilization. Although the unfertilized restored prairie had lower ANPP than the other perennial crops, that system also showed a decrease in NO_3^- leaching over time, as previously reported for similar cropping systems (Hernandez-Ramirez et al., 2011; Smith et al., 2013). Overall, our study shows that with moderate rates of N fertilization (56 kg N ha^{-1} yr^{-1}) or even without fertilization, perennial cropping systems can reduce NO_3^- leaching by up to 60 to 80% once they develop their maximum ANPP; the reductions were greatest in switchgrass and miscanthus, followed by poplar, grasses, and prairie.

Corn was similar in ANPP to miscanthus, but leached much more NO_3^- (34.1 ± 10.4 kg N ha^{-1} yr^{-1}) than miscanthus (7.7 ± 4.2 kg N ha^{-1} yr^{-1}). Nitrate leaching rates in corn also exceeded rates in the less productive perennial cropping systems (switchgrass: 9.2 ± 1.4 kg N ha^{-1} yr^{-1}; native grasses: 4.4 ± 1.9 kg N ha^{-1} yr^{-1}; restored prairie: 2.4 ± 1.8 kg N ha^{-1} yr^{-1}). Our finding of higher NO_3^- leaching in corn than in perennial systems agrees with previous studies conducted at KBS (Syswerda et al., 2012). Based on 11 yr of observations using similar methodology to our study, Syswerda et al. (2012) reported NO_3^- leaching at the nearby Long-term Ecological Research site of 42 kg N ha^{-1} yr^{-1} for no-till corn, a rate that is somewhat higher than our results, but found lower rates of 1.1 kg N ha^{-1} $yr^{-}$for an unharvested and unfertilized successional grassland treatment, and near-zero rates for poplar. Nitrous oxide emissions from the same experimental treatments analyzed in the present study showed patterns generally similar to those reported here for NO_3^- leaching (Oates et al., 2016).

Elsewhere, McIsaac et al. (2010) and Smith et al. (2013) reported much-reduced NO_3^- leaching rates from perennial cropping systems. That our absolute rates of NO_3^- leaching are higher than reported in those studies probably reflects the more permeable soils at our site that promote rapid percolation. The soils studied in Illinois by McIsaac et al. (2010) and Smith et al. (2013), in contrast, are poorly drained loess Argiudolls that require tile drainage for crop production. A study in France by Ferchaud and Mary (2016), conducted on deep loam soils where roots did not reach the water table, found that switchgrass and miscanthus leached less NO_3^- than annual sorghum [*Sorghum bicolor* (L.) Moench] and triticale (×*Triticosecale* Wittm. ex A. Camus) crops, except during the first year of miscanthus when N fertilizer was applied. Modeling suggested that miscanthus may have later recovered that leached N as its roots grew deeper into the subsoil.

Drainage Rates

The overall mean annual drainage rates predicted for these crops by the SALUS model over the seven crop-years (303–360 mm yr^{-1}, or 31 to 37% of mean annual precipitation; Supplemental Table S2) agree with previous studies of annual and perennial crop evapotranspiration estimated by soil water monitoring at the same site (Hamilton et al., 2015), and from eddy covariance analyses of water vapor fluxes for nearby plantings of corn, switchgrass, and prairie (Abraha et al., 2015). These conclusions are also supported by the observation that watershed water balances in the vicinity have not changed in spite of historical land cover changes (Hamilton et al., 2018).

Conclusion

Our results show that over the seven crop-years, the perennial cropping systems, including switchgrass, miscanthus, native grasses, and poplar, leached much less NO_3^- than corn, even when fertilized at modest rates (Table 2, Fig. 2 and 3). However, those crops that were fertilized leached NO_3^- at rates comparable to corn during the first 1 to 2 yr after planting despite N fertilizer rates that were much lower than for corn. Once established, however, perennial crops leached little NO_3^- and thus could mitigate NO_3^- losses from agricultural lands if planted strategically (e.g., on those lands most vulnerable to NO_3^- loss, which often include less productive farmland with coarse-textured soils and rapid infiltration and percolation rates) (Feng et al., 2006; Robertson et al., 2007).

Supplemental Material

The supplemental material includes the plant species composition of the prairie treatment, mean annual drainage (percolation from the root zone) for each cropping system treatment, a map of the experimental layout, and growing season lengths and ANPP for each treatment in each year.

Conflict of Interest

The authors declare no conflict of interest.

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Supplemental Material

Nitrate Leaching from Continuous Corn, Perennial Grasses, and Poplar in the US Midwest

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Supplemental Tables

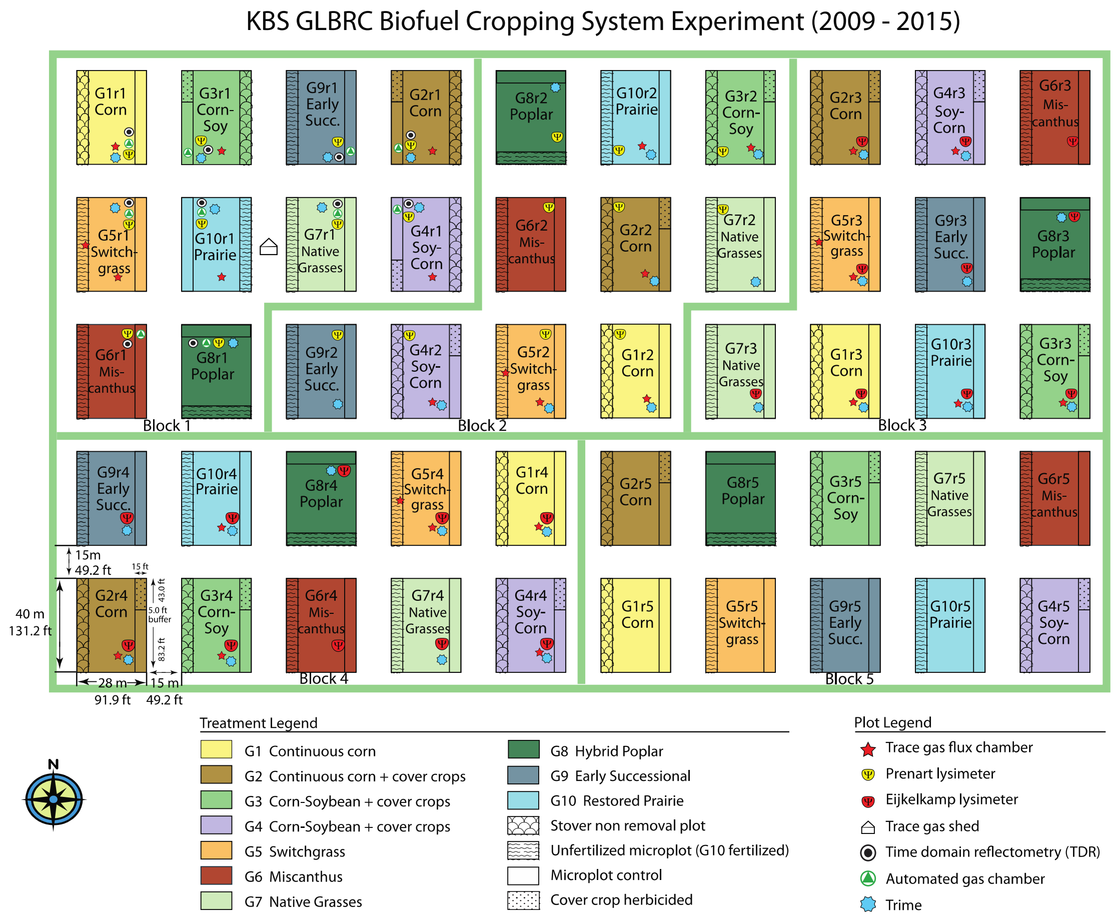
Supplemental Table S1. Plant species composition in the restored prairie cropping system

	Species	Type
1	*Elymus canadensis*	Grass
2	*Sorghastrum nutans* (L.) Nash ex Small	Grass
3	*Schizacyrium scoparium* (Michx.) Nash	Grass
4	*Andropogon gerardii*	Grass
5	*Desmodium canadense*	Forb
6	*Lespedeza capitate*	Forb
7	*Baptisia lacteal* var. lacteal	Forb
8	*Rudbeckia hirta* L.	Forb
9	*Anemone canadensis* L.	Forb
10	*Asclepias tuberosa* L.	Forb
11	*Monarda fistulosa* L.	Forb
12	*Silphium perfoliatum* L.	Forb
13	*Ratibida pinnata* (Vent.) Barnh.	Forb
14	*Solidago rigida* L.	Forb
15	*Solidago speciose* L.	Forb
16	*Aster novae-angliae* L.	Forb
17	*Koeleria cristata*	Grass
18	*Panicum virgatum* var. Southlow	Grass

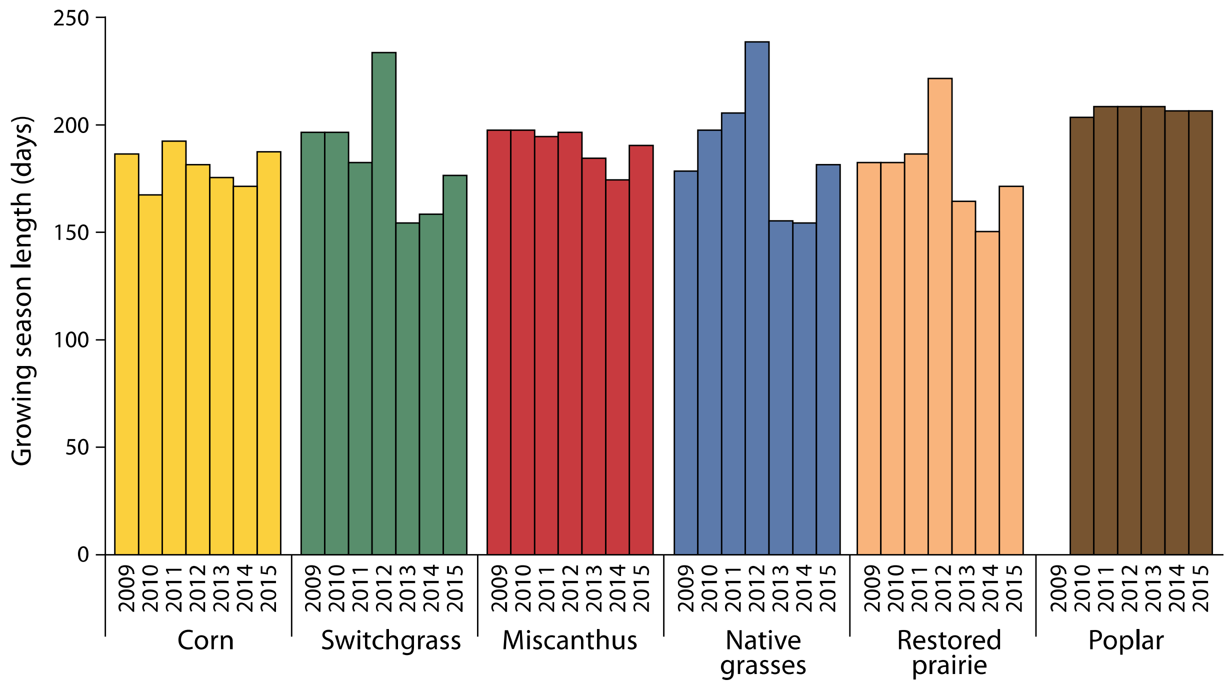
Supplemental Table S2. Mean annual drainage (percolation from the root zone) and % of mean annual precipitation (970 mm) in each cropping system across the seven crop-years (2009-2016). There were no significant differences in annual drainage estimates among cropping treatments (p=0.85; Fig. 1).

Cropping system	Drainage (mm)	% of total precipitation
Corn	360	37
Switchgrass	310	32
Miscanthus	342	35
Native grasses	303	31
Poplar	315	32
Restored prairie	358	37
Means	331	34

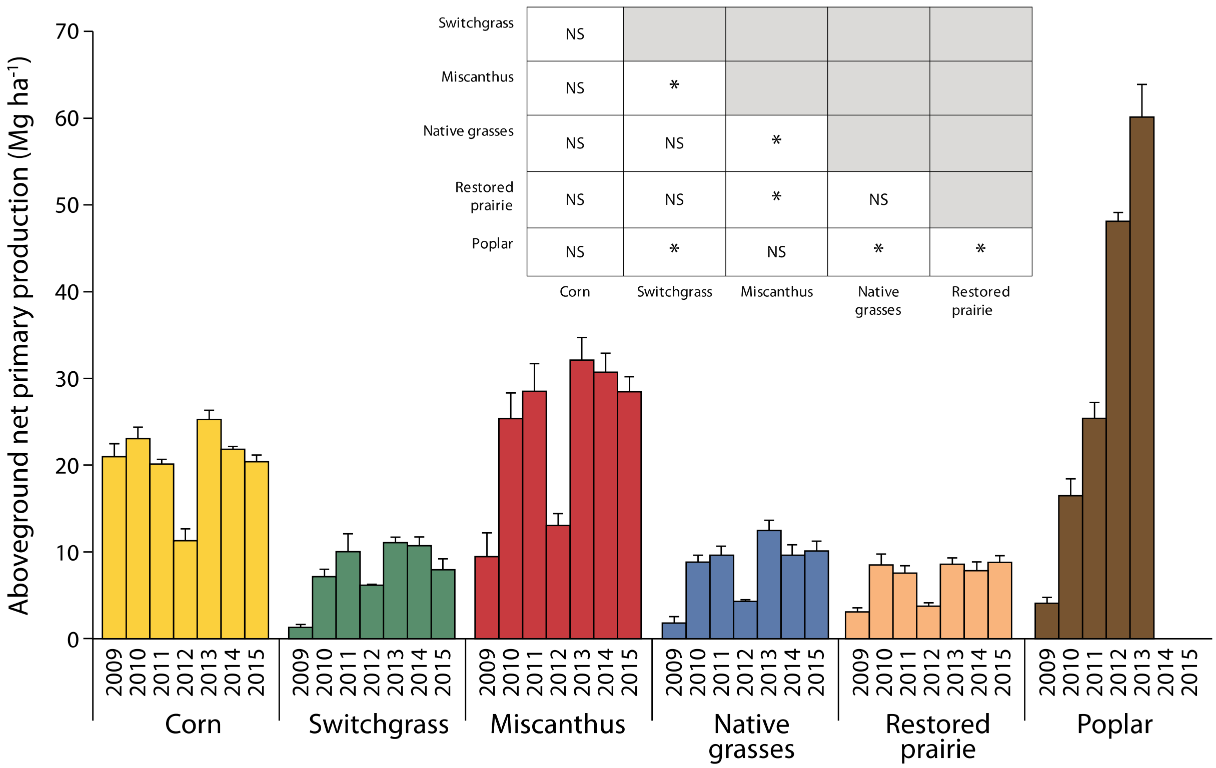
Supplemental Figures



Supplemental Fig S1: Experimental layout of GLBRC Biofuel Cropping System Experiment (BCSE) showing the distribution of treatments, and locations of suction-cup water samplers (denoted as either Prenart or Eijkelkamp lysimeters).



Supplemental Fig. S2. Growing season lengths for corn and the perennial cropping systems over the seven years. Growing season is defined as date of planting or emergence to the date of harvest (or leaf emergence and senescence in case of poplar).



Supplemental Fig. S3. Aboveground Net Primary Production (ANPP) of the different cropping systems over the seven growing seasons. Corn biomass includes grain and aboveground stover. Poplar biomass was estimated from growth curves and the poplar was harvested once in the winter of 2013-14 (2014, 2015 data not available). Error bars indicate the standard error for the four replicated blocks in each year. The inset shows which treatment means grouped across years are significantly different (*) in pairwise comparisons as determined by the Tukey-Kramer method (α = 0.05; NS = not significantly different).