Original Research

Core Ideas

- Corn–soybean and continuous corn had similar soil water dynamics and N leaching.
- Urea and anhydrous ammonia resulted in similar leachate nitrate concentrations.
- The kura clover cropping system reduced drainage, N leaching, and fall soil N.

Soil Water Dynamics and Nitrate Leaching Under Corn–Soybean Rotation, Continuous Corn, and Kura Clover

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Improving water quantity and quality impacts of corn (*Zea mays* L.)- and soybean [*Glycine max* (L.) Merr.]-based cropping systems is a key challenge for agriculture in the US Midwest. Long-term field experiments are important for documenting those effects and exploring possible solutions. This study examines differences in soil water dynamics and nitrate-nitrogen (N) leaching among cropping systems and N fertilizer sources in a long-term experiment in southeastern Minnesota. Drainage and leachate concentrations were measured for 4 yr using automated equilibrium tension lysimeters installed below the root zone in replicated, large plots on a well-drained silt loam soil. Soil water storage was monitored using water content reflectometers. Corn–soybean and continuous corn cropping systems exhibited similar soil water dynamics, drainage rates (145–202 mm yr^{-1}), leachate nitrate N concentrations (21.3–25.6 mg L^{-1}), and nitrate N leaching loads (30–75 kg ha^{-1} yr^{-1}). Nitrate-N concentrations in the leachate were similar whether N was added as urea (21.2 mg L^{-1}) or anhydrous ammonia (25.7 mg L^{-1}). A perennial kura clover (*Trifolium ambiguum* M. Bieb)-based cropping system with no N fertilizer significantly altered soil water dynamics and resulted in lower ($p < 0.10$) drainage rates (53 mm yr^{-1}), nitrate N concentrations (7.1 mg L^{-1}), and nitrate N leaching loads (2–5 kg ha^{-1} yr^{-1}) compared with corn–soybean or continuous corn, but also reduced corn grain yields. These impacts are generally consistent with a growing body of literature showing substantial environmental benefits of a kura clover living mulch system for corn production, but the economic viability of such a system is not yet proven.

Abbreviations: ANCOVA, analysis of covariance; GHG, greenhouse gas.

Long-term experiments are invaluable for advancing scientific understanding of the agronomic and environmental performance of cropping systems (Rasmussen et al., 1998). One such experiment established at Rosemount, MN, in 1990, has been used to document the long-term responses of continuous corn (*Zea mays* L.) and corn–soybean [*Glycine max* (L.) Merr.] cropping systems to different tillage and fertilizer practices. These two cropping systems are widespread in the Upper Mississippi River Basin, the larger geographic region in which the experiment is located. The research in this long-term experiment to date has provided new insights into greenhouse gas (GHG) emissions and soil organic carbon storage as affected by tillage and fertilizer management.

Venterea et al. (2005) reported that emissions of non-CO_2 GHGs (i.e., N_2O and CH_4) were two to four times greater when nitrogen (N) was supplied by anhydrous ammonia compared with urea ammonium nitrate or broadcast urea. That study also revealed an interaction between tillage and N source. No tillage had greater non-CO_2 GHG emissions than conventional tillage when N was applied as broadcast urea, but lower emissions when N was applied as anhydrous ammonia. In addition to the no tillage and conventional tillage treatments, the corn–soybean rotation in this experiment contained a unique biennial tillage treatment (i.e., no tillage from soybean planting until after corn harvest). This

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biennial tillage treatment resulted in greater soil organic carbon storage than either no tillage or conventional tillage (Venterea et al., 2006). Soil moisture and temperature differences were key factors in explaining the differences in soil organic carbon storage and CO_2 flux between the tillage systems.

Subsequent studies in this long-term cropping system experiment at Rosemount have shown that GHG emissions are influenced by N source interactions, not only with tillage, but also with cropping system. Shifting from corn–soybean to continuous corn would increase annual N_2O emissions by 0.78 kg N ha^{-1} (57%) with anhydrous ammonia, but only 0.21 kg N ha^{-1} (26%) with incorporated urea (Venterea et al., 2010). This result is significant given the trend toward increasing reliance on urea and other N sources besides anhydrous ammonia. The amount of anhydrous ammonia used annually in the United States was 16% lower during the 10 yr from 2001 to 2010 than during the prior 10 yr, whereas urea use increased 33% for the same period (USDA-ERS, 2016). The experiment at Rosemount has shown clear in-field advantages of lower GHG emissions with urea compared with anhydrous ammonia, but it is unclear whether these advantages are offset, or perhaps enhanced, by differences in N leaching between anhydrous ammonia and urea.

Nitrous oxide emissions were greater, as expected, for continuous corn than for corn–soybean, but the difference was not large. Furthermore, soil inorganic N concentrations during the corn phase were unaffected by whether the preceding crop was corn or soybean (Venterea et al., 2010). These findings suggest that N leaching may not differ significantly between continuous corn and corn–soybean, even though continuous corn in the experiment receives exactly twice as much N fertilizer per each 2-yr rotation; however, N leaching has not been previously studied in this experiment. There is a clear need for measurements of N source and cropping system effects on soil water dynamics and N leaching in the long-term cropping system experiment at Rosemount to complement the existing data on GHG emissions and soil organic carbon storage.

Recent increases in the frequency of continuous corn in the Upper Mississippi River Basin are the latest expression of the long decline of cropping system diversity in the region. Perhaps the most significant component in the decline has been the loss of perennial crops. Land cover change from perennials to annual crops has been associated with negative environmental impacts including increased soil erosion, decreased water quality (Huggins et al., 2001), and increased baseflow in streams and rivers (Zhang and Schilling, 2006). Studies in the Upper Mississippi River Basin have clearly shown that perennial cropping systems offer some distinct environmental and hydrological advantages. For example, alfalfa (*Medicago sativa* L.), Conservation Reserve Program land, and native prairie have shown lower drainage volumes, nitrate concentrations, and nitrate loads than corn–soybean and continuous corn (Randall et al., 1997; Brye et al., 2000, 2001). Additionally, climate modeling has predicted that reestablishment of perennials on agricultural land could produce significant regional-scale cooling through changes in albedo (Georgescu et al., 2011). However, widespread perennial reestablishment appears unlikely in the near future given strong market conditions for annual grain crops like corn and soybean.

An intriguing "hybrid" cropping system is corn production in kura clover (*Trifolium ambiguum* M. Bieb) living mulch. Kura clover is a perennial, rhizomatous legume that can be managed as a living mulch in corn with little or no yield reduction (Zemenchik et al., 2000). Effective management of this cropping system can be challenging but is made more feasible with herbicide-resistant corn (Affeldt et al., 2004). Kura clover living mulch in corn has been shown to reduce leachate nitrate concentrations and nitrate leaching load by 31 to 74% relative to corn following killed kura clover (Ochsner et al., 2010). Kura clover living mulch in corn has not previously been shown to reduce drainage volume but can reduce soil water storage during the spring and early summer (Ochsner et al., 2010; Qi et al., 2011b). Inadequate suppression of the living mulch can lead to significant corn yield loss (Ochsner et al., 2010; Sawyer et al., 2010; Qi et al., 2011b), and the reductions in spring soil water storage may be a key contributing factor.

The previous studies with kura clover living mulch have focused on mature stands of kura clover. However, kura clover is slow to establish. The first year after planting typically results in no harvestable yield. In the second year, the kura clover can be harvested as high-quality forage (Baker, 2012). Corn is not typically planted in the system until the third growing season after kura clover establishment. To date, there are no studies examining how drainage and N leaching are affected during the 2-yr transition from annual crops to the kura clover living mulch system. Thus, there is a need to quantify the water balance and N leaching dynamics across the land cover transition from annual cropping to the kura clover living mulch.

The objectives of this study were: (i) to complement existing research on GHG emissions and soil organic carbon storage in a long-term cropping system experiment by quantifying soil water and N leaching differences between cropping systems and N sources, and (ii) to monitor changes in soil water and N leaching associated with land cover change from annual crops to perennial kura clover living mulch. We hypothesized that nitrate leaching would be similar for the continuous corn and corn–soybean cropping systems but that nitrate leaching losses would be greater with urea compared with anhydrous ammonia because anhydrous ammonia has been shown to reduce rates of nitrification in soil. We also hypothesized that the kura clover-based cropping system would exhibit different soil water dynamics and reduced nitrate leaching relative to the continuous corn and corn–soybean cropping systems.

Materials and Methods

Experimental Site and Design

The research was conducted at the University of Minnesota Research and Outreach Center located near Rosemount (44.715° N 93.100° W). Soil at the site is a Waukegan silt loam (fine-silty over sandy or sandy-skeletal mixed, superactive mesic Typic Hapludoll). The loess-derived silt loam is underlain by outwash sands starting at depths ranging from 0.6 to 1.2 m. The mean sand content increases from 25.8% at the surface to 56.2% at the 90- to 105-cm depth, and the soil bulk density increases from 1.34 to 1.60 g cm^{-3} over the same interval (Table 1). There is a marked increase in the soil heterogeneity with depth as well, with the standard deviation of sand content increasing from 5.0% at the surface to 17.9% at the 90- to 105-cm depth and the standard deviation of bulk density increasing from 0.07 to 0.22 g cm^{-3} over the same interval. The study site was nearly level, with a slope of <1%. The site was planted to alfalfa prior to 1987 and corn from 1987 to 1989. In 1990, a 7-ha section of the site was divided into 36 total plots (each 27.4 m × 61 m) arranged in a randomized complete block design with 12 plots in each of three blocks. Twelve plots were assigned to corn every year, and 12 plots to each of corn and soybean in rotation, so that each phase of the corn–soybean rotation was present each year. Three additional adjacent plots with a similar management history were not included in the 1990 experimental design but were used in the current study.

Agronomic Management

The plots in corn–soybean rotation were maintained under a biennial tillage regime consisting of fall chisel plowing or disk ripping starting in 2000 with spring cultivation after each corn crop, and no fall plowing or spring cultivation after each soybean crop. Corn stalks were chopped prior to fall tillage. Prior to 2004, all corn plots were fertilized with broadcast urea as a sidedress at 130 to 150 kg N ha^{-1}. In spring 2005, the study plots with corn were subdivided into three subplots each 12 rows wide. One of the subplots, which received the long-term fertilizer practice, was not examined in this study. The other two subplots received 146 kg N ha^{-1} applied 1 to 2 wk prior to planting during the corn phase either as (i) anhydrous ammonia, which was knife injected 0.15 to 0.20 m below the surface, or (ii) urea, which was surface broadcast and then incorporated by disking the same day. The fertilizer subplot treatments were maintained in the same 12-row sections for 2005 to 2008. Starter fertilizer consisting of 135 kg ha^{-1} of 9–23–30 (N–P–K percentages) was applied to corn plots on 17 May 2006.

Corn and soybean were harvested after plants were physiologically mature using a combine (John Deere 4400). Plant residue was returned to the plots through the combine using normal machine and harvesting practices. For each subplot, the middle eight rows of corn were harvested using a four-row combine head, whereas all 12 rows of soybeans were harvested using a six-row head. After each plot area was harvested, grain was transferred from the combine to a grain wagon (Brent Yield Cart, Unverferth Manufacturing) equipped with tared, calibrated load cells for obtaining grain weight. Grain yield weights were corrected for water content in subsamples obtained from harvested grain. Each year, corn harvest occurred between 26 October and 1 November, and soybeans were harvested between 10 and 24 October.

Three plots were selected for establishment of kura clover (cultivar 'Endura') in spring 2006. Prior to establishment, these plots were disked, 34 kg N ha^{-1} and 112 kg K ha^{-1} fertilizers were broadcast, trifluralin herbicide was applied at 0.84 kg a.i. ha^{-1}, and light tillage was performed to incorporate the chemicals and produce a smooth seedbed. Kura clover was seeded on 22 May 2006 at a target rate of 9.4 kg ha^{-1} pure live seed with a Brillion seeder set to a depth of 7 to 10 mm. Kura clover plots were mowed as needed in 2006 for weed control. Kura clover forage was harvested on 29 May and 12 July 2007 using a mower-conditioner and removed from the plots. In 2008, corn was grown in the plots with kura clover as a herbicide-suppressed living mulch with no added N fertilizer. Thus, the kura clover plots were in a state of transition throughout the experiment: from annual crops, to establishment year perennial, to harvested second-year perennial, and finally to the end goal, the living mulch system.

Weather Data

Daily weather data were recorded by Research Station staff following National Weather Service Cooperative Observer protocols. The archived data (Cooperative Station no. 217107) were retrieved from the Minnesota State Climatology Office website (Minnesota State Climatology Office, 2008). Daily weather data included precipitation totals, maximum and minimum temperatures,

Table 1. Depth distribution of the means and standard deviations of soil bulk density and the sand, silt, and clay percentages for the plots used in this study.

	Bulk density		Sand		Silt		Clay	
Depth	Mean	SD	Mean	SD	Mean	SD	Mean	SD
cm	g cm^{-3}		%					
0–15	1.34	0.07	25.8	5.0	50.7	5.0	23.5	2.0
15–30	1.48	0.10	24.5	3.1	52.4	3.5	23.0	1.9
30–45	1.39	0.09	25.8	6.5	52.4	5.9	21.8	2.7
45–60	1.46	0.09	34.6	10.3	44.2	7.2	21.3	4.2
60–75	1.46	0.09	38.6	12.6	40.9	9.6	20.5	5.7
75–90	1.56	0.12	44.4	17.1	38.9	11.0	16.7	6.7
90–105	1.60	0.22	56.2	17.9	32.2	12.5	11.6	5.8

snowfall depth, and depth of snowpack. The liquid water equivalent was determined for each snowfall and included in the daily precipitation total. Thirty-year mean annual precipitation and air temperature (1975–2004) for the site are 887 mm and 7.4°C, respectively. Soil temperatures were recorded hourly at depths of 6, 24, 48, 72, and 96 cm in each of the plots used in this study from December 2005 onward.

Drainage Measurements

Drainage was measured at a depth of 105 cm beneath undisturbed soil using automated equilibrium tension lysimeters (Brye et al., 1999; Masarik et al., 2004), in which the suction was adjusted automatically and continuously to match the matric potential in the adjacent soil, as described below. This type of lysimeter is not filled with soil but rather inserted horizontally beneath an intact profile of undisturbed soil. A pit was excavated to facilitate installation of each lysimeter, and a cavity that protruded laterally beneath the adjacent undisturbed soil was created near the base of each pit. The 76-cm-long × 25-cm-wide lysimeters were installed in these cavities such that the long sides were perpendicular to the crop rows, which were at a 76-cm spacing. Full details of the installation process are provided by Brye et al. (1999). Drainage measurements began in May 2005 with eight lysimeters. Three additional lysimeters were installed in November 2006. One of the original lysimeters was also moved from its original location and installed in a new location at that time. The groundwater table in the region of the field site is typically far below the lysimeter depth, at a depth of 15 to 30 m (Barr Engineering Company, 2008).

An automated vacuum system provided continuous suction to the 0.2-μm, porous stainless steel plate, which formed the top of each lysimeter (Masarik et al., 2004). Heat dissipation sensors (CS-229, Campbell Scientific) were located above the porous plate of each lysimeter and in the surrounding bulk soil. These sensors were used to measure the soil matric potential every 10 min. Suction in the lysimeter was then automatically adjusted to a value 0.2 kPa lower than the matric potential in the surrounding bulk soil. These adjustments were to prevent flow divergence at the lysimeter.

Leachate volumes were monitored with dielectric sensors (ECHO EC20, Decagon Devices) mounted diagonally inside the lysimeters (Masarik et al., 2004). The failure rate for these sensors inside the lysimeters proved to be high, perhaps due to water intrusion. Leachate samples were collected approximately monthly, but sampling frequency was adjusted seasonally with more frequent sampling in spring and fall and less frequent sampling in winter and summer. In total, there were 48 sampling dates during the 48-mo period covered in this study. Leachate was collected from a designated drain tube with the aid of pressurized air. Drainage volumes were recorded to the nearest 10 mL using a graduated cylinder, and subsamples were saved for chemical analysis.

Water samples were collected in the field into labeled 250-mL high-density polyethylene bottles at an aboveground spigot. Water samples were placed into a cooler and frozen after returning to the laboratory. The day before analysis, samples were moved into a refrigerator to begin thawing. Samples were completely thawed and poured into 9-mL glass culture tubes the day of analysis. Nitrite + nitrate N was analyzed on a Lachat QuikChem 8500 (Hach) using a cadmium reduction method (12-107-04-1-B) with deionized water as a carrier.

Soil Water Content Measurements

Soil volumetric water content was recorded hourly at depths of 6, 24, 48, 72, and 96 cm in each of the plots used in this study from December 2005 onward using water content reflectometers (CS-616, Campbell Scientific). A linear, soil-specific calibration for the reflectometers was developed using repacked soil columns in the laboratory ($r^2 = 0.99$). Before applying the calibration, raw data were first corrected for soil temperature at the time of measurement, following the manufacturer's instructions. Soil water content values >0.60 $m^3 m^{-3}$ or <0.05 $m^3 m^{-3}$ were considered out of range and ignored in subsequent analyses. Given these criteria, ~0.03% of the 1.18 million soil water content values were over range and 7.3% were under range. The under-range values were essentially missing data because they occurred primarily when sensors at the 6- and 24-cm depths had to be removed for several days in the spring and fall to facilitate field operations like tillage and planting. A daily soil water content time series was generated by sampling the 24-h running average value for each sensor every midnight. Missing daily water content values for individual sensors were filled in using linear interpolation.

Absolute values of soil water content varied from plot to plot because of inherent spatial variability in soil properties (e.g., soil texture), which often constitute the largest cause of spatial variability in soil water content (Brocca et al., 2014). To reduce the variance due to spatial variability of soil properties and to enhance the ability to detect treatment effects, daily soil water content data were normalized by subtracting the temporal mean soil water content of each sensor from every soil water content measurement from that sensor. These incremental soil water surpluses or deficits were then converted to a depth of water by multiplying by the thickness of the soil layer represented by each sensor. For simplicity, these values will be referred to as surpluses hereafter, with negative values indicating deficits. Profile soil water surplus to a depth of 108 cm was determined by summing the results from the five layers. Analyses focused on the growing seasons (1 April–30 September) to avoid measurement errors due to frozen soil.

Soil Sampling

Soil samples from 0- to 105-cm depth were collected in fall 2007 and 2008 after harvest but before fall tillage by a truck-mounted hydraulic probe (Giddings Machine Company) and were cut into 15-cm depth intervals. Each soil segment was placed into a labeled plastic slider-seal bag, and the bag was sealed. Soil samples were brought back to the laboratory and stored overnight in a cooler at 4°C. The next day, the samples were placed into a ventilated chamber at 30°C to dry for ~48 h. After drying, the soil samples were ground using a hammermill-style soil grinder. Fifteen grams of dried and ground soil were weighed and placed into a 250-mL high-density polyethylene bottle for extraction, followed by 30 mL of 2 M KCl solution. The bottles were shaken for 30 min at ~130 oscillations min^{-1} on an Eberbach reciprocal shaker. Samples were poured through Whatman no. 1 filter paper into a 9-mL glass culture tube. Tubes were placed into a labeled autosampler rack, sealed, and stored in a refrigerator at 4°C overnight. Samples were removed from the refrigerator the next morning and analyzed for nitrite + nitrate N on a Lachat QuikChem 8500 using cadmium reduction method 12-107-04-1-B.

Study Design and Statistical Analyses

For this study, lysimeters were installed under eight plots in spring 2005. Four of those lysimeters were under corn–soybean rotation, two were under continuous corn, and two were installed under plots that were designated to convert to the kura clover cropping system. The corn–soybean plots included both phases each year: two plots with soybean and two plots with corn. The corn–soybean plots included two under the anhydrous ammonia treatment and two under the urea treatment. The two continuous corn plots both received anhydrous ammonia. The locations of the lysimeters were constrained by the need to have the lysimeters in pairs so that one suction control and data acquisition system could support two lysimeters. The control systems were placed on the boundaries between two plots with one lysimeter in the plot on either side. This resulted in a completely randomized design for this study.

During the 2006 crop year, changes were made to the study design in an effort to increase representativeness of the lysimeter data and bolster statistical power. One of the lysimeters under continuous corn was excavated and relocated because the original installation location had a relatively high sand content at and above the lysimeter depth, which was perhaps not representative of the bulk of the field. Three additional lysimeters were constructed and installed to increase replication in the continuous corn and kura clover cropping systems, bringing the total number of lysimeters to 11. These changes were completed in fall 2006. As a result of these changes, only seven lysimeters had data for the full 2006 crop year. After the relocation of one lysimeter and the installation of three others, there were four lysimeters under corn–soybean rotation as described above, four under continuous corn, and three under kura clover. Two of the continuous corn lysimeters received anhydrous ammonia and two received urea. Corn and soybean grain yields were averaged across years for each plot, and ANOVA was used to test for effects of cropping system or N fertilizer form on corn yield. A separate ANOVA was performed for corn yields in 2008, when corn was harvested from all three cropping systems.

Crop year drainage totals were calculated for each lysimeter, and one outlier was evident in the annual drainage totals. One lysimeter under continuous corn reported a drainage total of 705 mm for the 2007 crop year, which indicates substantial flow convergence to the lysimeter given that the crop year precipitation was 815 mm. All other measured crop year drainage totals were <450 mm, and the value of 705 mm was much greater than 1.5 times the interquartile range above the 75th percentile of measured crop year drainage totals, a common criteria for identifying outliers. Therefore, this outlier was removed from the dataset. Cropping system effects on the relationship between annual precipitation and drainage totals were evaluated by analysis of covariance (ANCOVA). Statistical significance for this and all subsequent tests was assessed using a threshold of $\alpha = 0.10$ to protect against false negatives because of the limited number of replicates and the relatively high spatial variability of soil properties, especially at the lysimeter depth (Table 1). All data analysis was completed in Matlab (Mathworks, 2016).

Cropping system and N source effects on flow-weighted nitrate N concentrations in the leachate and on nitrate leaching loads for the corn–soybean and continuous corn cropping systems were evaluated by fitting linear mixed-effects models to the data, using the Matlab function *fitlme*. Year was treated as a random effect grouped by lysimeter to account for repeated measures, whereas cropping system and N source were treated as fixed effects. The kura clover cropping system was not included in these models because it was not part of the N source comparison. Jarque–Bera tests indicated that residuals for nitrate leaching loads were not normally distributed ($p < 0.05$). Therefore, a natural log transformation was applied to the nitrate leaching load data, and the linear mixed-effect model was fit to the transformed data, resulting in normally distributed residuals. After fitting the models, ANOVA was used to perform F-tests on the null hypothesis that the coefficients representing the fixed-effects term were zero. Separate linear mixed-effects models were used to evaluate the effects of cropping system on flow-weighted nitrate N concentrations and nitrate leaching loads across all three cropping systems for the 2006 to 2008 crop years, the years when kura clover was present. As before, a natural log transformation was applied to the nitrate leaching loads prior to fitting the model. Follow-up ANOVAs were used to test the significance of the cropping system effects. Linear mixed-effects models were chosen for these analyses because they are more effective than repeated measures ANOVA for handling unbalanced designs and missing data.

Cropping system effects on soil water surplus were evaluated with separate ANOVAs for every available growing season day in the 2006 to 2008 crop years. Cropping system effects on fall soil nitrate N concentrations were analyzed by ANOVA, separately by soil depth, with the corn and soybean phases of the corn–soybean rotation analyzed as separate treatments.

Results

Precipitation and Growing Degree Days

Precipitation during the study period was generally below the 30-yr average, with 2006 and 2008 having precipitation >35% below average (Table 2). Among the years in this study, the 2005 cropping year had the greatest precipitation amount, which was 96% of the 30-yr average. In contrast, air temperature during the study period was generally above the 30-yr average as reflected by the growing degree day totals (Table 2). The 2008 cropping season was the only one with below average growing degree day accumulation.

Grain Yields

Corn grain yields averaged 8.9 Mg ha^{-1} and were 3% lower in the continuous corn rotation than in the corn–soybean rotation and 5% lower in the plots receiving anhydrous ammonia than in the plot receiving urea, but these differences were not statistically significant (Table 3). Corn grain yield in kura clover living mulch in 2008 averaged 6.1 Mg ha^{-1}, which was 32% lower ($p < 0.008$) than the average corn yields in the corn–soybean and continuous corn cropping systems that year. Soybean yields averaged 2.3 Mg ha^{-1} and were not different between plots receiving anhydrous ammonia during the corn phase and those receiving urea.

Drainage

Crop year drainage totals ranged from 40 to 297 mm (Table 4). Drainage totals were positively and linearly related to precipitation ($p < 0.001$, Fig. 1), and the drainage versus precipitation relationships differed between cropping systems ($p = 0.0063$) based on ANCOVA. The population marginal mean drainage rate was 145 mm yr^{-1} under the corn–soybean rotation and 202 mm yr^{-1} under continuous corn, and these drainage rates were not significantly different ($p > 0.10$). However, both of these drainage rates were significantly greater than the 53 mm yr^{-1} under the kura clover cropping system (Table 4). These drainage rates represent 21% of the annual precipitation during the study period for the corn–soybean rotation, 29% for continuous corn, and 7.6% for the kura clover cropping system. Crop year drainage totals varied substantially between lysimeters under a given cropping system (Fig. 1); thus, only relatively large differences in drainage between treatments could be detected with confidence.

Table 2. Precipitation and growing degree day (GDD) summary for four crop years (1 May–30 April) at Rosemount, MN. Climate norm were calculated using 30-yr averages. A base of 10°C was used to calculate GDD. Crop years are named for the year in which they begin.

	Year			
	2005	2006	2007	2008
Precipitation (mm)	851	539	815	565
% of normal	96	61	92	64
GDD (°C d^{-1})	1586	1525	1630	1362
% of normal	107	103	110	92

Table 3. Average grain yields (dry weight) by cropping system and N fertilizer form. Cropping systems are corn–soybean (C/S), continuous corn (C/C), and kura clover (KC). Fertilizer forms are anhydrous ammonia (AA) and incorporated urea (U). Yields were averaged over 2005–2008 for the C/S and C/C cropping systems. Corn yield for the KC cropping system is for 2008 only.

	Corn yields			Soybean yields	
Cropping system	AA	U	None	AA	U
	kg ha^{-1}				
C/S	8781	9333		2373	2337
C/C	8605	9034			
KC			6102		

Table 4. Mean drainage totals by crop year (1 May–30 April) under the corn–soybean (C/S), continuous corn (C/C), and kura clover (KC) cropping treatments, along with the population marginal mean (PMM) for each estimated by analysis of covariance (ANCOVA) for drainage versus precipitation. Drainage under KC < C/S and C/C at $p < 0.10$. The kura clover cropping system was not initiated until 2006.

	Year				ANCOVA
Cropping system	2005	2006	2007	2008	PMM
	mm				mm yr^{-1}
C/S	211	83	209	80	145
C/C	297	138	284	113	202
KC	–	40†	61‡	45§	53

† Kura clover seeding year.
‡ Kura clover harvested as second-year perennial.
§ Corn planted into established kura clover perennial.

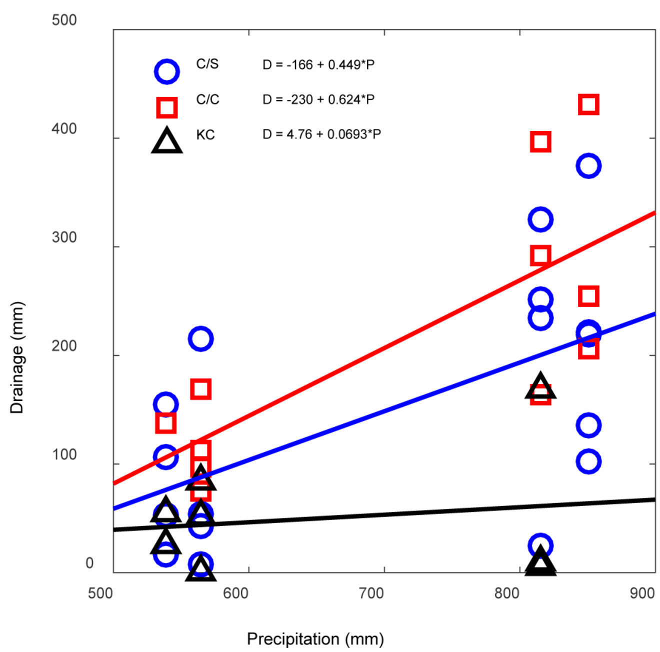

Fig. 1. Crop year drainage total versus precipitation for corn–soybean (C/S), continuous corn (C/C), and kura clover (KC) cropping systems for the 2005 to 2008 crop years. Each symbol represents the crop year drainage total from one lysimeter and plot. The solid lines are the least squares regression lines, the equations for which are given in the legend.

Soil Water Surplus

The profile soil water surplus ranged from near 100 mm in the spring to near −100 mm in the summer (i.e., deficits); thus, the soil profile provided ~200 mm of active storage capacity (Fig. 2). Soil water surplus was greater under the kura clover cropping system than under the other two cropping systems during the 2006 growing season, the establishment year for the kura clover. However, the largest cropping system impacts on profile soil water surplus occurred during the 2007 growing season when the kura clover was managed for forage production in its second growing season after establishment (Fig. 2). Soil water surplus in the top 108 cm was reduced significantly by the perennial kura clover relative to the corn–soybean and continuous corn treatments. The kura clover treatment reduced the soil water levels from mid-May into late June and again in the month of September. During these periods, soil water surplus under kura clover averaged 26.7 mm less than under the continuous corn treatment and 26.8 mm less than under the corn–soybean treatment. During 2008, when kura clover was managed as a living mulch for corn, soil water surplus under kura clover averaged 21.5 mm greater than under the continuous corn treatment and 24.3 mm greater than under the corn–soybean treatment (Fig. 2).

Nitrate Concentrations

Average crop year flow-weighted nitrate N concentrations in the leachate ranged from 7.1 to 26.7 mg L^{-1} (Table 5). For the 2005 to 2008 crop years, there were no significant differences in the leachate

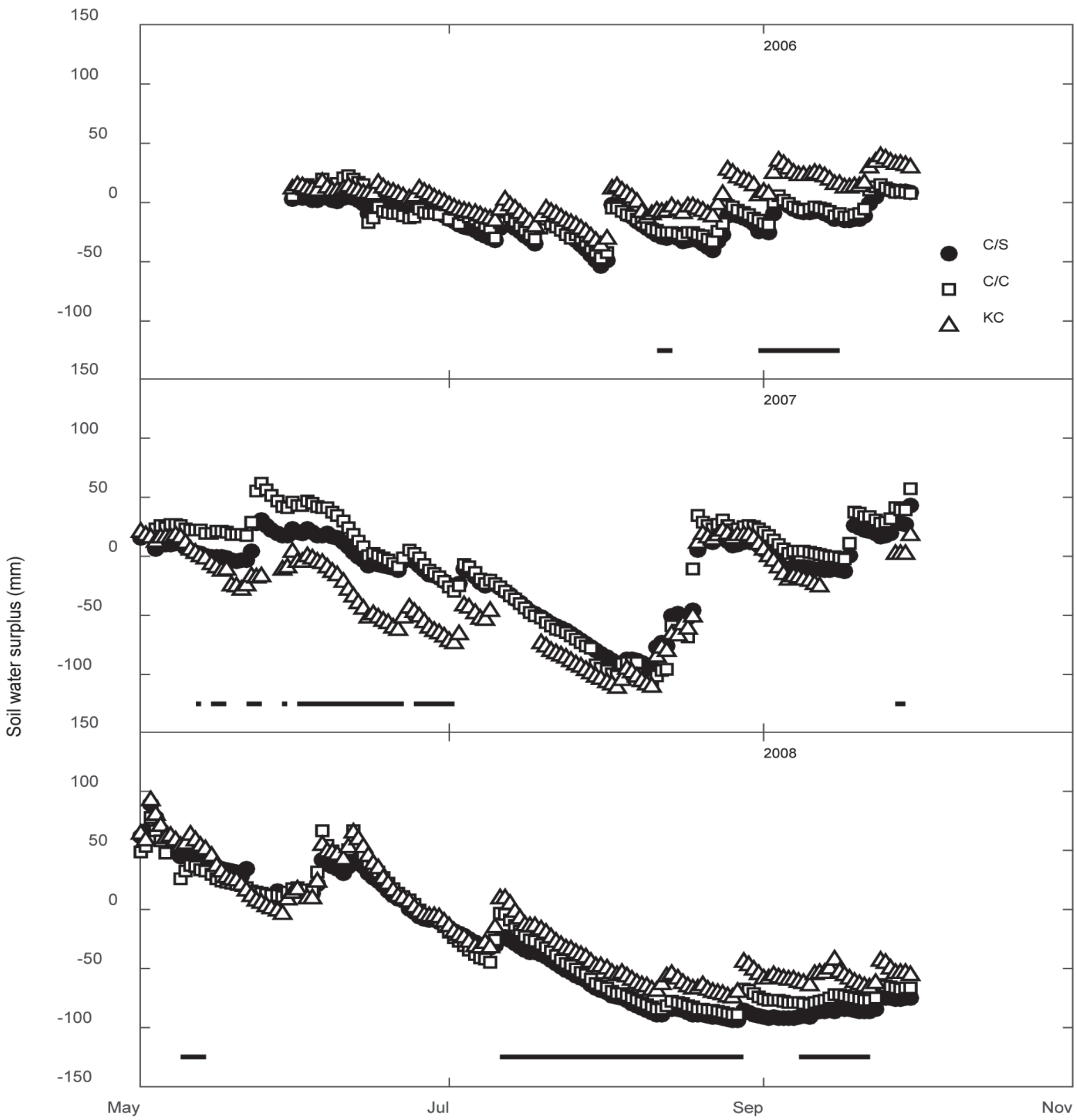

Fig. 2. Average daily growing season soil water surplus to a depth of 108 cm under corn–soybean rotation (C/S), continuous corn (C/C), and kura clover (KC) cropping systems for the 2006 to 2008 growing seasons. Kura clover was planted in 2006, harvested as a perennial in 2007, and used as a living mulch for a corn crop in 2008. Horizontal lines indicate days with statistically significant differences among cropping systems ($p < 0.10$).

Table 5. Average annual flow-weighted nitrate N concentrations in leachate as affected by cropping system and N fertilizer form. Cropping systems are corn–soybean (C/S), continuous corn (C/C), and kura clover (KC). Fertilizer forms are anhydrous ammonia (AA) and incorporated urea (U). Data for C/S and C/C cropping systems span 2005–2008, and data for KC cropping system span 2006–2008. KC < C/S and C/C at $p < 0.10$.

	N form			
Cropping system	AA	U	None	Mean
	mg L^{-1}			
C/S	26.7	24.6		25.6
C/C	24.6	17.9		21.3
KC			7.1	
Mean	25.7	21.2		

nitrate concentrations between the corn–soybean and continuous corn cropping systems, nor between the plots receiving anhydrous ammonia and the plots receiving urea ($p > 0.10$). For the 2006 to 2008 crop years, data across all three cropping systems indicated a significant effect of cropping system on leachate nitrate concentrations ($p = 0.046$). For those years, leachate nitrate concentrations under the kura clover cropping system were ~74% less than those under either corn–soybean or continuous corn, which did not differ.

Nitrate Leaching

Crop year nitrate N leaching loads ranged from 2.2 to 77 kg ha^{-1} (Fig. 3). For the 2005 to 2008 crop years, there were no significant differences in the nitrate leaching loads between the corn–soybean and continuous corn cropping systems, nor between the plots receiving anhydrous ammonia and the plots receiving urea ($p > 0.10$). For the 2006 to 2008 crop years, data across all three cropping systems indicated a significant effect of cropping system on nitrate leaching loads ($p = 0.014$). For those years, nitrate leaching loads under the kura clover cropping system were ~91% less than those under either corn–soybean or continuous corn, which did not differ. The variability of nitrate leaching within a cropping system was large, as indicated by the error bars in Fig. 3. The greatest measured crop year nitrate leaching total for a single lysimeter was 129 kg ha^{-1} recorded, surprisingly, by a lysimeter under soybean during 2007. The flow-weighted nitrate N concentration for that lysimeter and year was 51.4 mg L^{-1}, and the crop year drainage total was 252 mm. This instance of high nitrate leaching occurred in a near-normal rainfall year after a relatively dry year and could have been due, in part, to soil N accumulation during the preceding corn year.

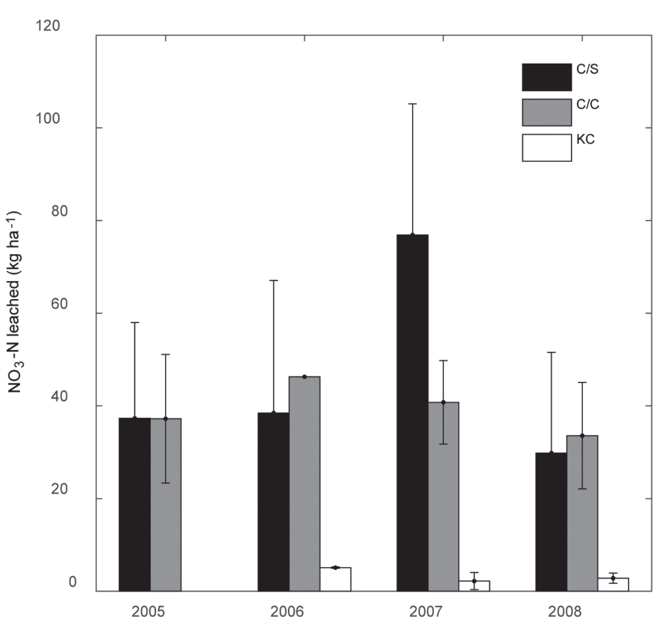

Fig. 3. Crop year nitrate N (NO_3–N) leaching totals for corn–soybean (C/S), continuous corn (C/C), and kura clover (KC) cropping systems. Error bars represent the standard error of the mean. Kura clover was planted in 2006, harvested as a perennial in 2007, and used as a living mulch for a corn crop in 2008.

Fall Soil Nitrate

Residual soil nitrate N concentrations in the 0- to 1.05-m profile after harvest were uniformly low (<5 mg kg^{-1}) throughout the profile under kura clover in both 2007 and 2008 (Fig. 4). Soil nitrate concentrations in the 0- to 0.3-m layer under corn and soybean were <5 mg kg^{-1} in 2007, but >10 mg kg^{-1} in 2008. This pattern likely resulted from late-season leaching occurring during 2007, a relatively wet year, but not during 2008, a relatively dry year (Tables 2 and 3). There were no differences either year between residual nitrate concentrations under continuous corn and those under corn after soybean. In 2007, residual nitrate was less under soybean than corn in the 0.45- to 1.05-m layer, but in 2008, that pattern was reversed (Fig. 4). In general, differences in residual soil nitrate between the annual cropping systems were small, and only the kura clover resulted in substantially reduced fall soil nitrate levels.

Discussion

Grain yields in the corn–soybean and continuous corn cropping systems in this study were comparable with those previously reported for this site (Venterea et al., 2010, 2011; Venterea and Coulter, 2015). For a different subset of the plots in this experiment, the corn grain yields for 2005 to 2007 were 10% higher in plots receiving urea than in plots receiving anhydrous ammonia (Venterea et al., 2010). Corn yields were numerically greater with urea than anhydrous ammonia in this study as well, but the difference was not statistically significant. Twenty-six out of 28 studies reviewed by Erickson (2008) showed corn yield reductions in continuous corn compared with corn–soybean rotation, with reductions ranging from 2 to 19%. Corn yields were 3% lower in continuous corn compared with corn–soybean rotation in this study, but again the difference was not statistically significant.

The 32% reduction in corn yield with kura clover living mulch and no added N fertilizer is in close agreement with a 30% reduction previously observed in a study in Wisconsin (Ochsner et al., 2010). In that study, the yield reduction was decreased to 14% when

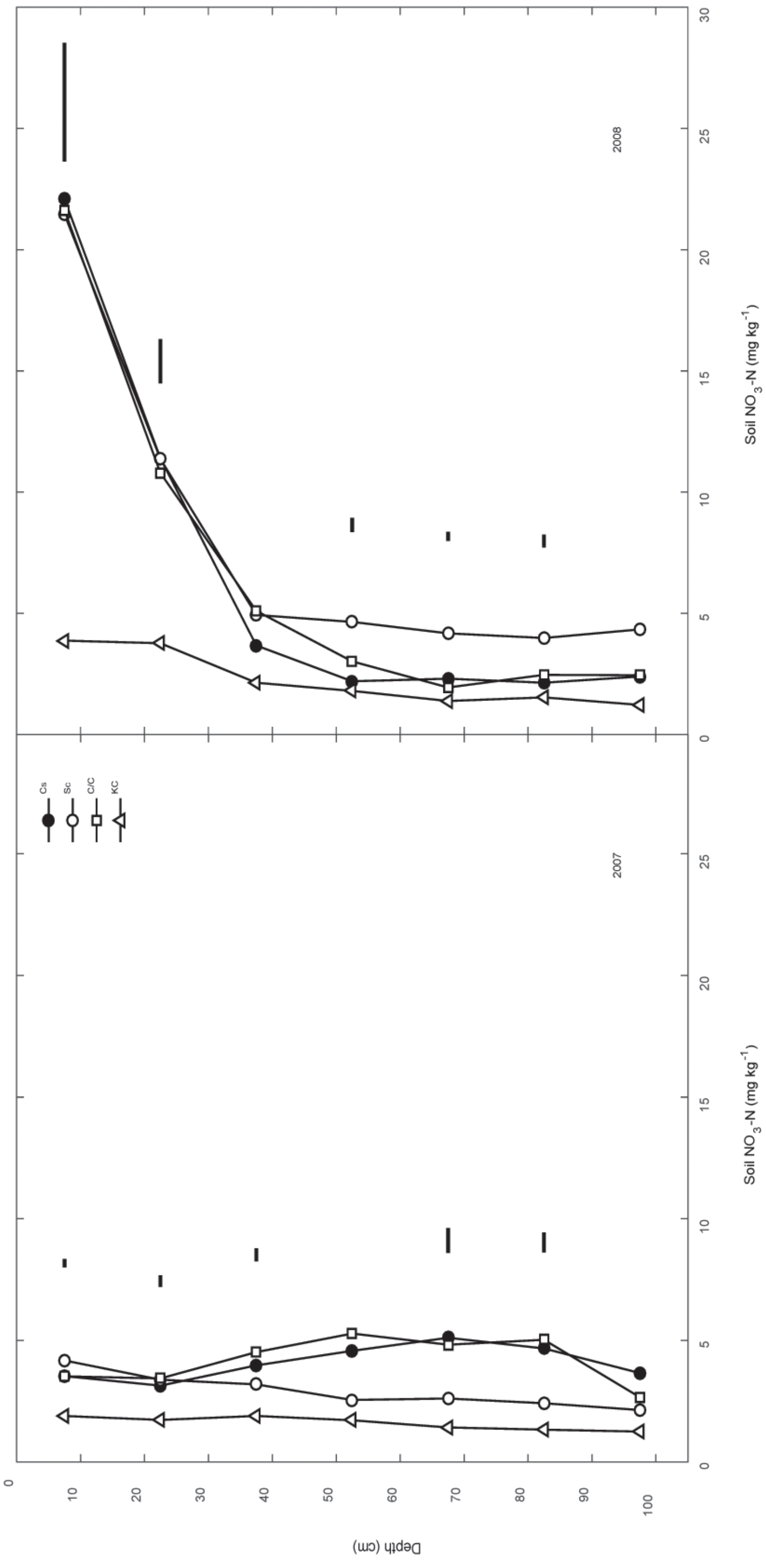

Fig. 4. Fall soil nitrate N (NO_3–N) concentration profiles for the 2007 and 2008 cropping seasons under the corn phase of the corn–soybean rotation (Cs), the soybean phase of the corn–soybean rotation (Sc), continuous corn (C/C), and kura clover (KC). Horizontal lines indicate the least significant differences for a given soil depth ($p < 0.10$).

the corn was supplied with 90 kg N ha^{-1}. In another recent study at Rosemount, irrigated corn yields were 13% lower for corn grown in kura clover living mulch than for irrigated corn grown in corn–soybean rotation, although the difference was not statistically significant (Turner et al., 2016). Thus, increased water and N supply would likely have led to a smaller corn grain yield reduction under living mulch in this study. Yield impacts of kura clover living mulch are also influenced by the degree of kura clover suppression during the corn growing season (Zemenchik et al., 2000; Affeldt et al., 2004), the soil texture (Sawyer et al., 2010), and the degree of drought susceptibility of the corn hybrid used (Ziyomo et al., 2013). In some circumstances, with appropriate management, corn yields in kura clover living mulch are equal to (Zemenchik et al., 2000; Affeldt et al., 2004; Ziyomo et al., 2013; Turner et al., 2016) or greater than those without living mulch (Sawyer et al., 2010).

The drainage rates measured with the automated equilibrium tension lysimeters in this study were generally consistent with drainage rates previously reported under cropping systems in the Midwest region of the United States (Randall et al., 1997; Daigh et al., 2014; Jaynes, 2015). For example, drainage under continuous corn averaged 280 mm yr^{-1} for conventional tillage and 315 mm yr^{-1} for no tillage during an 11-yr study of tile-drained plots at Waseca, MN, ~100 km south of the experiment reported here (Randall and Iragavarapu, 1995). The drainage rates under continuous corn measured by the lysimeters in the current study fall within this range for the 2005 and 2007 cropping seasons, when precipitation was within 8% of the 30-yr mean. Since precipitation was below the 30-yr mean in each year of the current study, the mean drainage rates (Table 4) are likely to be less than the long-term mean annual drainage rates for these cropping systems at this location. The linear regression equations in Fig. 1 provide a simple means to estimate expected drainage rates at other precipitation levels for these cropping systems at this location, albeit with relatively large uncertainty.

Conversion of cropland from annual crops to perennial kura clover reduced drainage by 63 to 74% in this study. This substantial reduction in drainage under kura clover is in contrast with results of prior studies in Wisconsin (Ochsner et al., 2010) and Iowa (Qi et al., 2011b). In those studies, kura clover did not reduce drainage either when managed as a living mulch for corn production (Ochsner et al., 2010) or during a 3-yr period spanning from the second year after planting through 2 yr of living mulch management (Qi et al., 2011b). One hypothesis to explain the contrast between this study and that of Qi et al. (2011b) is that the effect of kura clover on drainage depends, in part, on the vigor of the stand. In the study of Qi et al. (2011b), the kura clover stand had numerous bare spots during the second year after establishment. Low stand vigor may explain why a significant reduction in drainage during the second year after establishment was not measured by Qi et al. (2011b), as it was in this study. An alternative hypothesis to explain the contrast between this study and that of Qi et al. (2011b) is that the reduced drainage under kura clover in this study is actually a chance effect of the specific plots or lysimeters to which the kura clover treatment was assigned.

Previous studies in the region have shown large reductions in drainage under other types of perennial cropping systems, although not quite as large as the reduction due to kura clover in the present study. Alfalfa reduced drainage ~50% compared with continuous corn and corn–soybean cropping systems in Minnesota (Randall et al., 1997). Prairie land use reduced drainage ~35% compared with corn–soybean cropping systems in Iowa (Daigh et al., 2014), and drainage was reduced ~65% under a restored prairie compared with continuous corn in Wisconsin (Masarik et al., 2014). The spatial variability in drainage rates was too large and the number of replicates ($n = 4$) was too low to confidently detect any differences in drainage between corn–soybean and continuous corn cropping systems in this study.

The measurements of soil water storage dynamics in this and two related studies indicate that kura clover can both reduce soil water storage early in the growing season and increase soil water storage late in the growing season. Perennial kura clover has the potential for greater water use early in the season than corn or soybean, as evidenced by the reduced soil water storage under kura clover in May to June 2007 (Fig. 2), a pattern also observed by Ochsner et al. (2010) and Qi et al. (2011b). However, kura clover living mulch can also lead to increased soil water storage in July to September, as seen in this study in 2008 (Fig. 2) and in the work of Ochsner et al. (2010). This increased late-season soil water storage is likely not beneficial. It may indicate that early-season competition from the living mulch has reduced root water uptake and growth of the intercropped corn, leaving untapped soil water in the profile during the summer. This hypothesis is consistent with the reduced corn yields in the living mulch compared with the other cropping systems in 2008.

The perennial kura clover cropping system reduced nitrate N concentrations in the leachate to below the USEPA drinking water limit of 10 mg L^{-1}, with a mean flow-weighted concentration of 7.1 mg L^{-1}. This is similar to the previously reported values of 6 mg L^{-1} for kura clover living mulch with no fertilizer N (Ochsner et al., 2010) and 6.8 mg L^{-1} for kura clover living mulch with 140 kg ha^{-1} of N fertilizer (Qi et al., 2011a). However, Ochsner et al. (2010) observed a substantially greater nitrate N concentration (17 mg L^{-1}) for kura clover living mulch with 90 kg ha^{-1} of N fertilizer. Leachate concentrations under kura clover, although low relative to annual cropping systems, were not as low as reported for other perennial cropping systems such as alfalfa (1.3–4.1 mg L^{-1}) or prairie (<1 mg L^{-1}) (Randall et al., 1997; Daigh et al., 2014). One hypothesis for this observation is that the rooting system of kura clover may not take up soil N as aggressively as alfalfa or prairie grasses, particularly when the kura clover is suppressed by herbicides for management as a living mulch.

The corn–soybean and continuous corn cropping systems both resulted in nitrate N concentrations in the leachate that exceeded the USEPA drinking water limit. The concentrations measured in this study are comparable with the 23 to 26 mg L^{-1} for corn–soybean and 32 mg L^{-1} for continuous corn previously reported in the long-term study at Waseca (Randall et al., 1997). The fact that we measured no significant difference in leachate nitrate N concentrations between corn–soybean and continuous corn rotations may seem counter intuitive, since the continuous corn rotation receives twice as much N fertilizer as the corn–soybean rotation over a 2-yr period. However, others have shown that leaching potential is similar for the corn and soybean phases of a corn–soybean rotation (Zhu and Fox, 2003) and that leachate nitrate N concentrations do not necessarily differ between corn–soybean and continuous corn rotations when recommended N fertilizer rates are applied (Daigh et al., 2015). The corn–soybean rotation in this study received exactly half of the total fertilizer N received by the continuous corn, but the leachate N concentrations were not reduced. One possible explanation is that N fixation by soybean contributes to soil N concentrations in the corn–soybean rotation that are comparable with those in the continuous corn rotation during the fall and spring, when the majority of the leaching occurs.

No significant differences in nitrate N concentration in the leachate for urea versus anhydrous ammonia were observed. We are not aware of any prior studies comparing nitrate N concentrations in the leachate for these two N sources. Nitrate-N concentrations in the soil solution under corn were lower for anhydrous ammonia than for urea-ammonium-nitrate (UAN) in one study in Ontario, Canada (Ball-Coelho and Roy, 1999). The authors hypothesized that anhydrous ammonia resulted in more of the applied N persisting in the soil as ammonium, rather than nitrate, for a longer period of time than did UAN. The anhydrous ammonia in the current study was also injected in a narrow band, which can slow conversion of ammonium to nitrate and reduce leaching (Malhi et al., 2001). Therefore, we expected to observe lower nitrate N concentrations in the leachate under anhydrous ammonia than urea based on prior studies. As mentioned earlier, the amount of anhydrous ammonia used annually in the United States has been declining, whereas urea use has been increasing. That trend does not appear to pose any increased risks to water quality but may offer substantial benefits of reduced GHG emissions for urea compared with anhydrous ammonia (Venterea et al., 2005, 2010). Conversely, greater gaseous losses of nitric oxide (NO), a reactive gas that can affect atmospheric ozone and contribute to acid rain, have been observed with urea compared with anhydrous ammonia (Fujinuma et al., 2011).

The reduced fall soil nitrate concentrations under kura clover relative to continuous corn and corn–soybean is counter to the results of a study conducted in northeast Iowa (Sawyer et al., 2010). In that study, fall soil nitrate concentrations were greater after corn in kura clover living mulch than in plots without living mulch (controls) for two out of six sites and were not different for the other four sites. However, the observed soil nitrate concentrations after corn in kura clover living mulch with no added N were $\leq$5 mg kg^{-1} in that study, just as in this study. The main difference is in the controls which, in that study, also had fall soil nitrate values <5 mg kg^{-1} and often had undetectable levels. The fall soil nitrate levels measured in this study are generally consistent with those of Randall et al. (1997), who observed concentrations reaching up to 19 mg kg^{-1} under continuous corn and corn after soybean and significantly lower levels under a perennial legume (alfalfa) compared with continuous corn or corn–soybean rotation.

Sumamry and Conclusions

The long-term cropping system experiment near Rosemount has provided valuable insights regarding the effects of cropping system, tillage, and N management on soil carbon sequestration and GHG emissions. The findings presented here add to that existing knowledge base with new information regarding leachate water quality impacts. As hypothesized, corn–soybean and continuous corn cropping systems exhibited similar soil water dynamics, drainage rates, leachate nitrate N concentrations, and nitrate N leaching loads. Both cropping systems resulted in leachate nitrate N concentrations that exceeded the USEPA drinking water standard. Contrary to our hypothesis, nitrate N concentrations in the leachate and nitrate leaching loads were not different when urea, rather than anhydrous ammonia, was used as the N source. Any delays in nitrification for anhydrous ammonia relative to urea apparently were not persistent enough to significantly reduce nitrate leaching during this 4-yr experiment. Finally, as hypothesized, implementation of a perennial kura clover-based cropping system significantly altered soil water dynamics and reduced leachate nitrate concentrations, nitrate leaching loads, and fall soil nitrate concentrations relative to continuous corn and corn–soybean cropping systems. The kura clover also reduced drainage rates relative to continuous corn and corn–soybean rotation, a reduction that has not been observed in prior experiments with kura clover. The impacts of kura clover were generally consistent with a growing body of literature showing substantial environmental benefits of a kura clover living mulch system for corn production, but the economic viability of such a system has not yet been proven.

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