Published online June 27, 2007

Influence of Alternative and Conventional Farming Practices on Subsurface Drainage and Water Quality

K. A. Oquist, J. S. Strock,* and D. J. Mulla

ABSTRACT

Agricultural runoff contributes nutrients to nonpoint-source pollution of surface waters. This study was conducted to investigate the potential use of alternative farming practices to improve water quality. The study examined the effects of both alternative and conventional farming practices on subsurface drainage and nitrogen and phosphorus loss through subsurface drainage from glacial till soils (i.e., Calciaquolls, Endoaquolls, Eutrudepts, Hapludolls) in southwest Minnesota. Alternative farming practices included organic management practices, species biodiversity, and/or practices that include reduced inputs of synthetic fertilizer and pesticides. Conventional farming practices include corn–soybean (*Zea mays* L.–*Glycine max* L., respectively) rotations and their associated recommended fertilizer rates as well as pesticide usage. Precipitation was highly variable during the 3-yr study period including a below-average year (2003), an average year (2002), and an above-average year (2004). Results indicate that alternative farming practices reduced subsurface drainage discharge by 41% compared with conventional practices. Flow-weighted mean nitrate-nitrogen (nitrate N) concentrations during tile flow were 8.2 and 17.2 mg L^{-1} under alternative and conventional farming practices, respectively. Alternative farming practices reduced nitrate N losses by between 59 and 62% in 2002 and 2004 compared with conventional practices. Ammonium-nitrogen (ammonium N), orthophosphorus, and total phosphorus losses in subsurface drainage were very low and did not pose a substantial risk of pollution. Results suggest that alternative farming practices have the potential to reduce agricultural impacts on water quality.

Recent attention has been focused on reducing agricultural pollution from the Upper Midwest, where large portions of agricultural lands contain subsurface drainage (Zucker and Brown, 1998; Goolsby et al., 1999; Magner et al., 2004). Subsurface drainage enhances crop growth and yield through earlier planting in spring, reduced waterlogging of the soil, increased oxygen supply to plant roots, and increased soil temperature in early spring, allowing for earlier plant emergence and a longer growing season (Wesseling, 1974). Subsurface drainage has also been shown to decrease surface runoff, thereby reducing sediment and phosphorus losses to receiving waters (Zucker and Brown, 1998). Excess nutrients such as nitrate are susceptible to leaching from artificially drained fields (Baker and Johnson, 1981; Randall et al., 1997; Sims et al., 1998; Zhao et al., 2001; Dinnes et al., 2002). As a result, agriculturally polluted surface waters may be unsuitable for drinking water supplies and recreation, contribute to hypoxia and eutrophication of downstream waters, and induce stress to aquatic fauna (Goolsby et al., 2001; Randall and Goss, 2001).

In an effort to mitigate nonpoint-source pollution originating from agriculture and other sources, Section 303(d) of the Clean Water Act requires states to develop total maximum daily loads (TMDLs) for all surface waters that frequently violate water quality standards. While subsurface drainage is important for agriculture production in the Upper Midwest, changes to current agricultural practices will be necessary to meet emerging nitrogen-based TMDLs. In a recent review of management strategies to reduce nitrate leaching from tile-drained soils, Dinnes et al. (2002) identified numerous methods for reducing nitrate losses from subsurface drainage water. One potential strategy for improving water quality by reducing nitrate losses not considered but potentially beneficial is the adoption of alternative farming practices. Alternative farming practices include organic management practices, species biodiversity, and/or practices that include reduced inputs of synthetic fertilizer and pesticides.

A study comparing water quality from alternative versus conventional farming practices in the United States showed nitrate-nitrogen (nitrate N) concentrations above regulatory levels occurred more frequently from conventional than alternative farming practices (Rodale Institute, 2004). A simulation study of two Minnesota watersheds comparing conventional with alternative cropping systems that included perennial crops concluded that adding perennials to the crop rotation reduced nitrogen and phosphorus loads (Boody et al., 2005). In contrast, European comparisons of nutrient losses from alternative versus conventional farming practices have not been consistent. While some studies indicated a greater loss of nutrients with conventional agriculture, others found greater pollution with alternative practices, mainly those involving plow-down of leguminous crops (Armstrong Brown, 1993; Nguyen et al., 1995). Research conducted in Norway on loamy and silty sand soils showed that 42% more nitrogen was lost in subsurface drainage from conventionally farmed land than from organically farmed land (Korsaeth and Eltun, 2000). In view of the conflicting results, further study of the differences in nutrient losses resulting from alternative and conventional management practices is necessary to evaluate the potential for alternative systems to improve water quality.

K.A. Oquist, Mississippi Watershed Management Organization, 2520 Larpenteur Ave. W., Lauderdale, MN 55113. J.S. Strock, Southwest Research and Outreach Center, Univ. of Minnesota, 23669 130th St., Lamberton, MN 56152. D.J. Mulla, Dep. of Soil, Water, and Climate, Univ. of Minnesota, 1991 Upper Buford Circle, St. Paul, MN 55108.
Received 14 July 2006. *Corresponding author (jstrock@umn.edu).

Published in J. Environ. Qual. 36:1194–1204 (2007).
Technical Reports: Surface Water Quality
doi:10.2134/jeq2006.0274

677 S. Segoe Rd., Madison, WI 53711 USA

Abbreviations: AL, alternative; ammonium N, ammonium-nitrogen; CN, conventional; NH_4, ammonium-nitrogen; nitrate N, nitrate-nitrogen; NO_3, nitrate-nitrogen; OP, orthophosphorus; TP, total phosphorus.

Nutrient and sediment loss through subsurface drainage is dependent on precipitation frequency, intensity, and timing, and farming practices such as fertilizer rate and timing, crop type, and tillage practices (Fenelon and Moore, 1998). Periods of below average annual precipitation can lead to buildup of residual soil nitrogen that may be leached from the soil in wet years (Lucey and Goolsby, 1993; Randall and Iragavarapu, 1995; David et al., 1997; Randall and Mulla, 2001). Timing of precipitation also affects nutrient losses. Intense rainfall in early spring before crop uptake of fertilizer begins may result in subsurface losses of nitrogen and phosphorus (David et al., 1997).

Farming practices also influence nutrient and sediment losses via subsurface drainage. Studies have shown that as nitrogen application rates increase above crop needs, nitrate N loss increases (Gast et al., 1978; Baker and Johnson, 1981). Timing of fertilizer application also controls nitrate N loss. Nitrification and mineralization of fall applied nitrogen increases the amount of nitrate N available for leaching in the spring before crop uptake occurs (Keeney and DeLuca, 1993; Dinnes et al., 2002). Fertilizer type also affects the amount of nitrate N lost from the soil. Inorganic fertilizers are available for crop uptake and leaching more rapidly than manure since mineralization of organic N occurs later in the growing season (Randall et al., 2000; Thoma et al., 2005). Nitrogen source does not affect nutrient loss when applied at rates required to meet crop N demands. Studies conducted in Minnesota on glacial till soils similar to those in this study showed no difference between nitrate N losses from urea and manure when both were applied at the same overall rate of N (Randall et al., 2000; Zhao et al., 2001).

Cropping practices also affect nutrient losses from soils. Row crops, including corn (*Zea mays* L.) and soybean (*Glycine max* L.), have exhibited greater loss of nitrate N and sediment-bound phosphorus and lesser loss of dissolved phosphorus when compared with perennial species (Culley et al., 1983; Drury et al., 1993; Randall et al., 1997). The increased losses of nitrate N with row crops are attributed to larger applications of N fertilizer combined with lower evapotranspiration rates that result in more drainage flow. Nitrate N losses may be reduced by the inclusion of cover crops or legumes in the crop rotation, as they decrease drainage volume through increased uptake and evapotranspiration, thereby decreasing soil nitrate N so there is less available for leaching (Power, 1987; Huggins et al., 2001; Dinnes et al., 2002; Strock et al., 2004).

The objective of this study was to examine the differences between drainage volume and nitrogen and phosphorus losses through subsurface drainage from alternative and conventional farming practices to determine if alternative farming practices are a potential management system to reduce nutrient losses to surface water. The impact of individual farming practices, including crop rotation and fertilizer management, on water quality was not measured, instead measurements focused on the impact of the farming practices combined as a system.

MATERIALS AND METHODS

Study Area

The study was conducted between 2002 and 2004 at the University of Minnesota Southwest Research and Outreach Center near Lamberton, MN (44°14′15.936″ N, 95°16′26.2056″ W), within the Cottonwood River watershed (Fig. 1). Average annual precipitation at the site is 670 mm with over 74% occurring during a period extending from April until September. The average annual temperature is 7°C with monthly extremes ranging from 21°C in July to −9°C in January. Soils at the site were formed in glacial till and included Webster (Typic Endoaquolls) and Revere (Typic Calciaquolls) clay loams, Okoboji (Cumulic Vertic Endoaquolls) silty clay loam, Ves (Calcic Hapludolls), Storden (Typic Eutrudepts), Linder (Aquic Hapludolls), and Normania (Aquic Hapludolls) loams, and Estherville (Typic Hapludolls) sandy loam. The areas of soil map units identified at the alternative and conventional farming system sites are listed in Table 1. Detailed soils information can be found in Oquist et al. (2006).

The research was conducted on adjacent 65-ha areas containing non-replicated, long-term alternative and conventional farming practices. The conventional farming practices have consisted of mainly corn and soybean cropping systems, inorganic fertilizer inputs, and pesticide inputs since 1959. Management practices for both the conventional and alternative

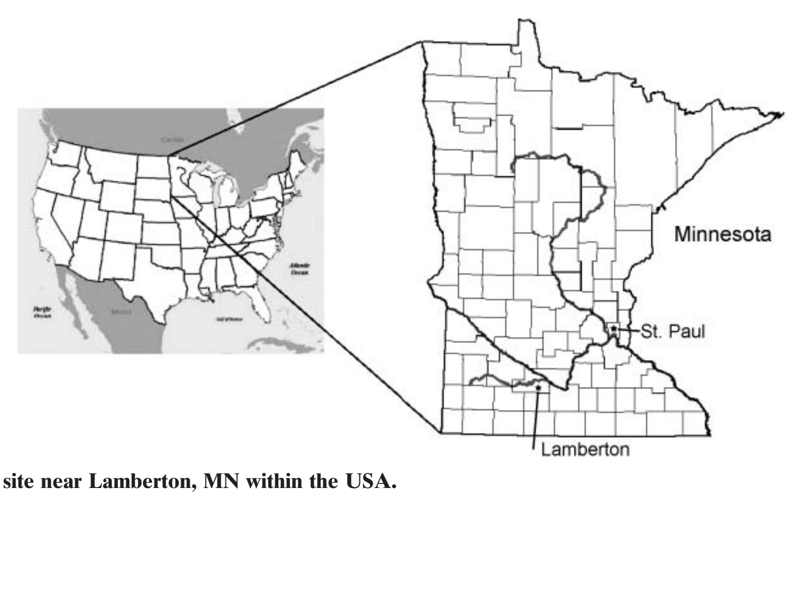

Fig. 1. Location of the study site near Lamberton, MN within the USA.

Table 1. Classification and area of soils underlying alternative and conventional farming practices at Lamberton, MN (Oquist et al., 2006).

Soil series	Taxonomic class†	Area Alternative	Area Conventional
		ha	
Estherville	Sandy, mixed, mesic Typic Hapludolls	1.8	0.1
Linder	Coarse-loamy, mixed, superactive, mesic Aquic Hapludolls	2.0	0.0
Normania	Fine-loamy, mixed, superactive, mesic Aquic Hapludolls	14.1	28.5
Okoboji	Fine, smectitic, mesic Cumulic Vertic Endoaquolls	2.4	0.0
Revere	Fine-loamy, mixed, superactive, mesic Typic Calciaquolls	6.1	3.6
Storden	Fine-loamy, mixed, superactive, mesic Typic Eutrudepts	1.7	0.1
Ves	Fine-loamy, mixed, superactive, mesic Calcic Hapludolls	15.7	14.9
Webster	Fine-loamy, mixed, superactive, mesic Typic Endoaquolls	21.2	17.8

† Classification information taken from USDA (1985).

farming practices fields before 1959 can be found in Porter et al. (2003).

Between 1959 and 1989, the alternative farming practices field was also planted in corn–soybean rotations. However, the alternative farming practices field was managed without inorganic fertilizer or pesticide inputs during that time. Since 1989 various cropping systems and management practices have been planted and implemented in the alternative farming system. A long-term cropping system study was established in 1989 on 17% of the alternative area and consisted of various nutrient and pest management strategies involving a 2-yr corn and soybean rotation and a 4-yr rotation involving corn, soybean, oat (*Avena sativa* L.), and alfalfa (*Medicago sativa* L.). Minimal inputs of inorganic fertilizers were applied to this area. In 1991, 4.3 ha of the alternative site were planted to native prairie grasses. The grasses were planted in a different portion of the alternative farming practices field than the long-term cropping system study established in 1989. In 1997 the alternative farming practices field, excluding the long-term cropping system study and the native prairie grasses, was planted to crops including corn, soybean, oat, alfalfa, buckwheat (*Fagopyrum esculentum*), and rye (*Secale cereale*); some of these crops were interseeded with other crops, mainly hairy vetch (*Vicia villosa*) (Table 2). These diverse cropping systems and the native prairie grasses encompassed the 48.5 ha of certified organic management lands in the alternative farming practices field. No inorganic fertilizers or pesticides were applied to this land. The remaining 16.5 ha of the alternative farming practices field, including the long-term cropping system study established in 1989, had minimal inorganic fertilizer inputs.

Animal manures including: beef, liquid hog, and beef compost, as well as legumes in rotation were used to provide nitrogen to the soil in the alternative farming system, while anhydrous ammonia was used in the conventional system (Table 3). Urea was applied in both the alternative and conventional systems, although minimal amounts were applied in the alternative system. Typically beef manure and anhydrous ammonia were applied in the fall, while the other fertilizer sources were applied in the spring. Nitrogen applied or released to the soil in the alternative system, from primarily organic sources, was 69.9 kg ha^{-1} in 2002, 147.7 kg ha^{-1} in 2003, and 100.2 kg ha^{-1} in 2004. Rates for the alternative system include nitrogen released to the soil following incorporation of green manures and legume crops. Nitrogen credits for various crops ranged from 45 to 168 kg N ha^{-1} (Rehm et al., 2006). Tillage practices included chisel, moldboard plow, and no-till (Oquist et al., 2006). Nitrogen applied in the conventional system, from primarily inorganic fertilizers, was 95.9 kg ha^{-1} in 2002, 108.8 kg ha^{-1} in 2003, and 95.9 kg ha^{-1} in 2004.

The fields are drained by subsurface tile drains spaced approximately 55 m apart and 1.2 m below the ground surface. The drainage system includes plastic and clay tile that was installed primarily between 1970 and 1990. The area drained on the alternative and conventional systems is 58.2 and 46.9 ha, respectively. The tile density is 204 m ha^{-1} for the alternative system and 230 m ha^{-1} for the conventional system. The drainage design includes four surface inlets in the alternative farming system and one surface inlet in the conventional farming system. Surface flow was rarely observed entering surface inlets in the alternative farming system, only once in 2002 and once in 2004. No surface water was observed entering the inlet in the conventional farming system during the 3-yr study period (Fig. 2). Surface inlets were installed in the 1960s in closed depressions to rapidly drain excess surface water to minimize crop loss. The northwest corner (4.9 ha) of the conventional field drains to the north and was not included in the analysis.

Table 2. Field area planted with corn, soybean, small grains, alfalfa, and native prairie grasses in the alternative (AL) and conventional (CN) fields during the study period.

Crop	Crop area 2002 AL	2002 CN	2003 AL	2003 CN	2004 AL	2004 CN
	ha					
Corn	8.4	35.2	17.5	29.9	15.2	28.4
Soybean	15.3	14.8	7.3	20.7	12.5	23.1
Small grains	16.1	0.8	19.0	0.9	13.5	0.9
Alfalfa	8.9	1.5	6.2	1.5	8.5	0.6
Native grasses	5.6	0	5.6	0	5.4	0

Sample Collection and Analysis

Subsurface water quantity and quality data were collected with portable samplers (3700, Teledyne ISCO, Inc., Lincoln, NE) equipped with either ISCO 4120 submerged probes or 4150 area velocity flow loggers. The samplers were powered by 12-V batteries that were connected to solar panels. Monitoring

Table 3. Nutrient sources, application season, and total nitrogen applied for alternative and conventional farming practices.†

Nutrient source	Application season	Total nitrogen applied 2002	2003	2004
		kg		
Alternative				
Beef manure	autumn	2584	5897	3212
Liquid hog manure	spring	0	608	0
Beef compost	spring	0	0	790
Legumes	spring	594	1208	1180
Urea	spring	495	514	360
Conventional				
Anhydrous ammonia	autumn	2868	4144	2264
Urea	spring	1070	1013	1874

† Alternative area receiving manure or fertilizer was 65 ha. Conventional area receiving fertilizer was 65 ha.

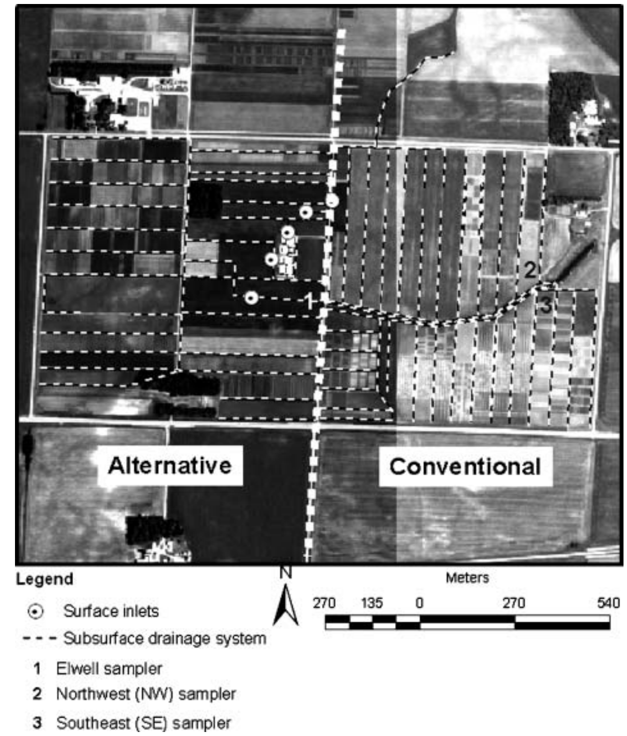

Fig. 2. Subsurface drainage design for the alternative and conventional fields.

systems were installed in 2002 at three locations: the main tile draining Elwell, the alternative farming system, and two tiles draining the conventional system (Fig. 2). The northwest (NW) conventional sampling system collected subsurface drainage water from the northern portion of the conventional farming practices field, and the southeast (SE) conventional sampling system collected subsurface drainage water from the southern portion of the conventional farming practices field. Since surface water runoff was not monitored in this study, runoff volume was modeled using the Hydrologic Simulation Program-Fortran (HSPF) model.

Surface flow was not measured as it entered the inlets but was measured in combination with subsurface drainage flow in the tile, resulting in overestimates of drainage during those rare times when surface inlets were active. The HSPF model was used to simulate hourly surface volume so that runoff volume and N and P loads could be subtracted from the measured subsurface drainage runoff (Bicknell et al., 2004). The HSPF model simulated the hydrological processes by simulating the water supply moving through the following storages: interception, surface retention, soil, and active groundwater. The HSPF model was calibrated using subsurface drainage flow measured at the site in 2002, resulting in a correlation coefficient of 0.86 for observed versus simulated flows (data not shown). The HSPF model was validated using subsurface drainage flow measured in 2004, with a correlation coefficient of 0.78. The hourly surface flows for 2002 and 2004 were then subtracted from the subsurface drainage flows to obtain the corrected subsurface flow used for analysis.

Drainage volume and nitrate N losses are known to vary seasonally. In geographic areas where soils remain unfrozen throughout the winter, subsurface drainage occurs primarily during the late fall, winter, and early spring. In geographic regions, including Minnesota, where soils remain frozen from early December through late March, subsurface drainage primarily occurs between April and July (Gast et al., 1978). In a 13-yr study conducted in south central Minnesota, 65% of the annual drainage and 70% of the annual nitrate N loss occurred between April and June (Randall, 2000). Subsurface drainage flow and quality were monitored from the alternative and conventional practices on a continuous basis during frost-free periods of flow from April through October 2002, April through July 2003, and April through November 2004. Samples were not collected from the NW conventional sampler (contributing area 4.9 ha) after July 2002 due to mechanical difficulties with the sampler. A 45-mL water sample was collected after every 7570 L of flow during the 2002 and 2003 sampling seasons. Samples were multiplexed with 20 samples per bottle and frozen immediately after collection until analysis. In 2004, the flow-paced sampling method was used through June 1 and then converted to storm-paced sampling. A 63.5-mm rise in water level triggered the samplers to collect a 1000-mL sample and another 1000-mL sample every 15 min. thereafter for the first 2 h of the rain event, followed by a 1000-mL sample every 2 h until 24, 1000-mL bottles were filled. A 1000-mL grab sample was collected once each week to examine nutrient losses between storm events.

Water samples were gathered within 24 h of collection and immediately frozen and stored at $-4°C$ until prepared for analysis. Water samples were filtered on thawing and analyzed for nitrate N, ammonium nitrogen (ammonium N), orthophosphorus (OP), and total phosphorus (TP) concentrations using a Lachat Quickchem 8000 Flow Injection Analysis Analyzer (Hach Company, Loveland, CO). Nitrate N + nitrite N analysis was conducted using the cadmium-reduction method (Wendt, 2000). Data are reported for nitrate N + nitrite N as nitrate N, as the concentration of nitrite N was assumed negligible. Ammonium N was measured with the Berthelot reaction method (Switala, 2001). Orthophosphorus was analyzed by reaction with ammonium molybdate and antimony potassium tartrate under acidic conditions (Franson, 1998; Diamond, 2000), and TP was measured using an in-line persulfate UV digestion (Franson, 1998; Laio and Westphalen, 2003). Total nutrient flux through the subsurface drainage was calculated by multiplying nitrate N concentration for each sample by total calculated flow for the same time period. Flow-weighted nutrient concentrations were calculated by dividing the total nutrient flux for the period of interest by total flow volume. A flow-weighted mean nutrient concentration is mass normalized for flow. Flow-weighted mean nutrient concentrations account for variability in flow that are not taken into account for measured concentrations.

Nutrient concentrations from 25 July 2002 (base flow conditions) were extrapolated through 27 Aug. 2002 due to equipment malfunctions during that time period; therefore, when rainfall occurred, the data are assumed to be underestimates of actual nutrient losses. Data were not collected at the alternative sampling site during the 29 July 2002 rain event because the data logger malfunctioned.

Precipitation

Precipitation data were collected from various sources. Throughout the study period, snowfall data were collected at the University of Minnesota climatology station located at the Southwest Research and Outreach Center 0.05 km north of the alternative farming practices field. During 2002, rainfall data were also collected at the climatology station. In 2003 and 2004, rainfall data were collected with a tipping bucket rain gauge (674, Teledyne ISCO, Inc., Lincoln, NE) located in the east portion of the alternative farming system. Precipitation for 2002 was collected on a daily basis, and 2003 and 2004 data were collected at 10 and 5-min intervals, respectively.

Data Analysis

Analysis of variance (ANOVA) was conducted using SYSTAT 11 (SYSTAT Software, Inc., 2004) to compare the mean daily drainage and nutrient loads and flow-weighted mean concentrations from alternative and conventional farming practices. Mean daily data were investigated to provide a large enough sample population for statistical analysis. Statistical significance was determined at the 0.05 probability level. Analyses were conducted for the periods of data collection during the study: 13 Apr. through 27 Aug. 2002, 1 May through 11 July 2003, and 23 May through 17 Nov. 2004 which varied depending on spring snowmelt and timing of spring and summer rainfall.

Annual drainage (cm), flow-weighted mean nutrient concentrations (mg L^{-1}), and nutrient loads (kg ha^{-1}) were calculated to determine losses of water and nutrients during the entire sampling season. Monthly drainage and nutrient flow-weighted mean concentrations and loads were compared to investigate the timing of nutrient losses. For annual and monthly values, data from the NW and SE conventional sampling locations were added to obtain the total conventional value. Statistical comparisons were not conducted on yearly and monthly data due to the small sample population.

RESULTS AND DISCUSSION

Precipitation is an important factor affecting the loss of nutrients and sediment through subsurface drainage; therefore, it is important to investigate precipitation patterns during subsurface drainage studies. Cumulative precipitation for this study is presented in Fig. 3. Below average rainfall occurred in 2003 and above average rainfall in 2004. Overall, rainfall during the 2002 sampling season was relatively close to the 40-yr cumulative average. Through the end of June, typically the period when most of the nitrate N losses in subsurface drainage occur (Lucey and Goolsby, 1993; Randall, 2000), cumulative rainfall patterns did not differ significantly between 2002 and 2003. Cumulative precipitation through the end of June was greater in 2004 than in previous years, and there was a large increase in precipitation during September of 2004, relative to the previous years.

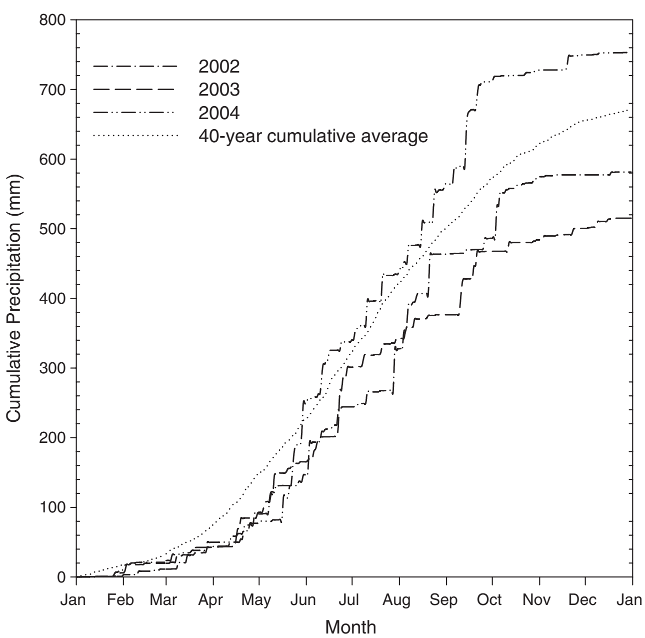

Fig. 3. Cumulative precipitation (mm) for the period of study (2002–2004). The 40-yr average precipitation at Lamberton, MN is 670 mm.

Subsurface Drainage

Subsurface tile drainage varied depending on precipitation. Drainage was lowest in 2003, corresponding to a dry year and highest in 2004, corresponding to a wet year. Subsurface tile flow patterns under alternative farming practices differed from conventional farming practices. While drainage flows from both practices responded quickly to rainfall, recession of drainage from peak to base flow conditions occurred more slowly under alternative farming practices than conventional practices (Fig. 4–6). Differences in crop evapotranspiration rates and soil physical properties help to explain differences in drainage flow patterns between the conventional and alternative cropping systems. There was a greater diversity of crops within the alternative system, including corn–soybean–oat–alfalfa rotations and small grains and native grasses plantings compared with the corn and soybean rotation in the conventional system. The crop diversity of the alternative system provided a greater range of evapotranspiration rates than in the conventional system, allowing for more water removal upward through the plants and lower soil moisture content at the onset of precipitation events. In a study conducted in southern Minnesota under dryland conditions, Copeland et al. (1993) reported evapotranspiration rates for corn ranged from 228 to 314 mm yr^{-1} and soybean ranged from 218 to 338 mm yr^{-1}. Evapotranspiration for small grains ranged from 300 to 818 mm yr^{-1} and evapotranspiration for alfalfa was 1100 mm yr^{-1} (Johnston et al., 1981; Musick and Porter, 1990). Greater maximum evapotranspiration from crops planted in the alternative field allowed for greater release of water through the soil and plants.

Differences in soil saturated hydraulic conductivity also help explain the differences in flow patterns between the alternative and conventional systems. Soils in the A horizon exhibited higher K_s under alternative farming practices (45.5 cm d^{-1}) compared with conventional practices (18.1 cm d^{-1}); however, the reverse trend occurred in subsurface soils (123.7 and 166.5 cm d^{-1} in the B horizon and 57.2 and 71.9 cm d^{-1} in the C horizon for alternative and conventional practices, respectively), allowing for faster recession of drainage from peak flow to base flow under conventional practices (Fig. 6) (Oquist et al., 2006).

In 2002 (an average climatic year), mean daily drainage losses were significantly lower under alternative farming practices compared with conventional practices, while in 2003 (a dry year) drainage losses were significantly greater under alternative practices (Table 4). Mean daily drainage did not differ between alternative farming practices and conventional practices in 2004 (a wet year). In average and above-average precipitation years (Fig. 3), alternative farming practices either

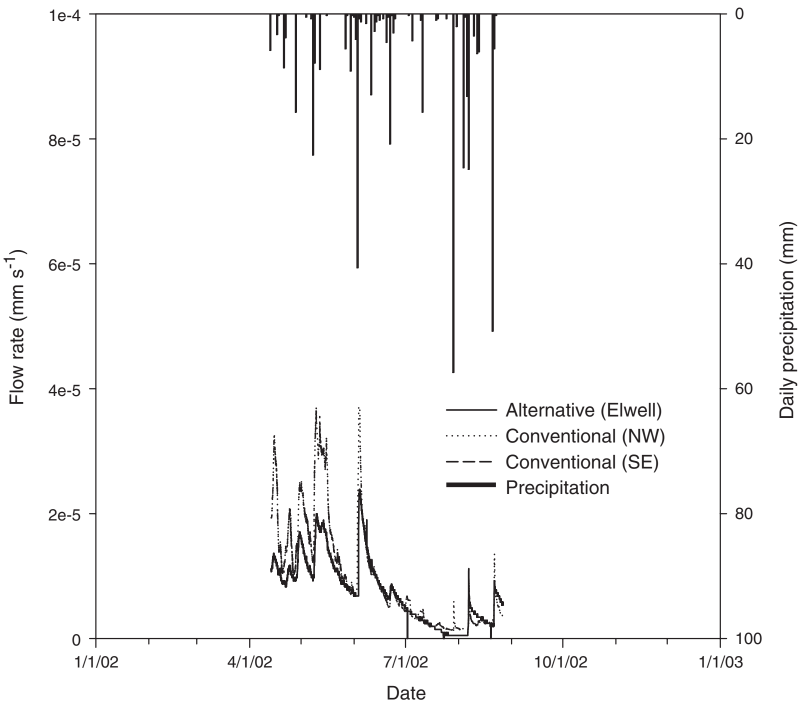

Fig. 4. Alternative (Elwell) and conventional (northwest [NW], southeast [SE]) drainage flow rates (mm s^{-1}) and daily precipitation (mm) for 2002.

reduced water loss through subsurface drainage or caused no difference in comparison with conventional practices, while the opposite occurred during dry years.

Annual subsurface drainage losses for 2004 (wet year) were significantly larger under conventional farming practices than under alternative practices. These results differed from those of mean daily results because there were more drainage events under conventional farming practices than under alternative practices. In 2003 (dry year), total drainage water loss under alternative farming practices was less than water loss from conventional practices, even though cumulative annual drainage results were greater under alternative practices (Table 5). This is again due to the greater number of drainage events that occurred under conventional farming practices than under alternative practices. Annual drainage

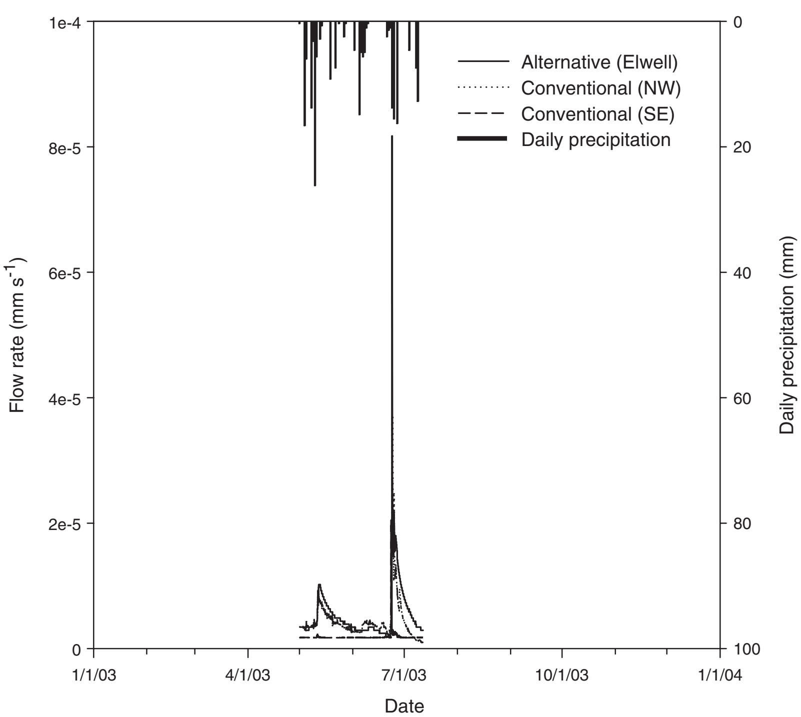

Fig. 5. Alternative (Elwell) and conventional (northwest [NW], southeast [SE]) drainage flow rates (mm s^{-1}) and daily precipitation (mm) for 2003.

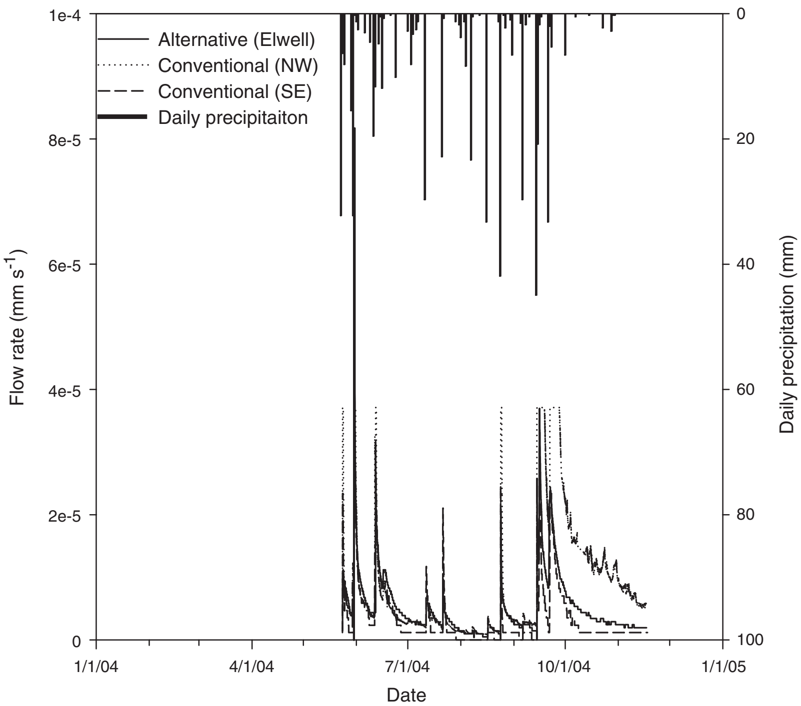

Fig. 6. Alternative (Elwell) and conventional (northwest [NW], southeast [SE]) drainage flow rates (mm s^{-1}) and daily precipitation (mm) for 2004.

losses in 2002 (average year) were less under alternative practices than under conventional practices, consistent with significantly lower average daily drainage losses under alternative practices.

Drainage as a percent of precipitation under alternative management practices compared with conventional practices was 21.9 versus 28.4% in 2002 (average year), 16.0 versus 17.5% in 2003 (dry year), and 13.7 versus 32.0% in 2004 (wet year), respectively. These results suggest that subsurface drainage represents a greater proportion of precipitation received under conventional farming practices in comparison with alternative practices, especially during wet years. Perennial species in alternative crop systems exhibit higher annual evapotranspiration in comparison with corn and soybean in conventional cropping systems, thereby potentially reducing the amount of water lost through subsurface drainage (Johnston et al., 1981; Copeland et al., 1993; Musick and Porter, 1990). Alternative farming practices have a greater impact on reducing water loss in average and wet years (2002 and 2004, respectively) compared with dry years (2003).

Nutrient Loads

Mean daily nitrate N loads were significantly less under alternative farming practices compared with conventional practices in 2002 and 2004 (Table 4). In 2003, mean daily losses under alternative and conventional farming practices were similar due to dry weather conditions. Annual nitrate N loads were smaller in subsurface drainage under alternative farming practices in comparison with conventional practices in all years (Table 5). These results parallel those of drainage loss, indicating that reduced water loss was a major factor contributing to reduced nitrate N losses under alternative practices.

Annual N loads from the alternative system were less than loads from the conventional system. Annual N load

Table 4. Mean daily drainage and nitrate-nitrogen (NO_3), ammonium-nitrogen (NH_4), orthophosphorus (OP), and total phosphorus (TP) loads in subsurface drainage from alternative (AL) and conventional (CN) farming practices for sampling seasons 13 Apr. to 27 Aug. 2002, 1 May to 11 July 2003, and 23 May to 17 Nov. 2004. Standard deviations are presented in parentheses.

		Water quality parameter			
Farming practice	**Drainage**	**NO_3**	**NH_4**	**OP**	**TP**
	cm	kg ha^{-1}			
2002 (N = 137)					
AL	**0.07a† (0.05)**	**0.05a (0.03)**	**<0.01a (0.01)**	**<0.01a (<0.01)**	**<0.01a (<0.01)**
CN	**0.09b (0.08)**	**0.13b (0.13)**	**0.01b (0.01)**	**<0.01a (<0.01)**	**<0.01a (<0.01)**
2003 (N = 72)					
AL	**0.05b (0.04)**	**0.04a (0.04)**	**<0.01a (<0.01)**	**<0.01a (<0.01)**	**<0.01a (<0.01)**
CN	**0.03a (0.02)**	**0.04a (0.04)**	**<0.01a (<0.01)**	**<0.01a (<0.01)**	**<0.01a (<0.01)**
2004 (N = 179)					
AL	**0.05a (0.05)**	**0.05a (0.05)**	**<0.01a (<0.01)**	**<0.01a (<0.01)**	**<0.01a (<0.01)**
CN	**0.05a (0.07)**	**0.12b (0.16)**	**<0.01a (<0.01)**	**<0.01a (<0.01)**	**<0.01a (<0.01)**

† Within column and year, mean daily drainage and nutrient loads followed by the same letter are not significantly different at the 0.05 significance level.

Table 5. Cumulative annual drainage and total annual nitrate-nitrogen (NO_3), ammonium-nitrogen (NH_4), orthophosphorus (OP), and total phosphorus (TP) loads in subsurface drainage from alternative (AL) and conventional (CN) farming practices for sampling seasons 13 Apr. to 27 Aug. 2002, 1 May to 11 July 2003, and 23 May to 17 Nov. 2004.

Farming practice	Drainage	NO_3	NH_4	OP	TP
	cm	kg ha^{-1}			
2002					
AL	9.01	6.27	0.55	0.01	0.02
CN	11.70	17.16	0.81	0.02	0.03
2003					
AL	3.36	2.88	0.04	0.01	0.01
CN	3.97	5.71	0.04	0.00	0.01
2004					
AL	8.18	8.34	0.08	0.06	0.08
CN	19.08	42.95	0.16	0.15	0.19

from the alternative system versus the conventional system as a percent of N applied was 9.0 versus 17.9%, 1.9 versus 5.2%, and 8.3 versus 44.8% in 2002, 2003, and 2004, respectively. Annual load from the conventional system in 2004 (wet year) was higher than losses in the other years due to the preceding dry year (2003). Greater loss of nitrate N in subsurface drainage from conventional farming practices in 2004 compared with 2003 supports the conclusion that N builds up in the soil during dry years, making it available for leaching in subsequent wet years, as exhibited in previous studies (Lucey and Goolsby, 1993; Randall and Iragavarapu, 1995; David et al., 1997; Randall and Mulla, 2001).

Reduced loss of nitrate N under alternative versus conventional management practices could be partially due to differences in fertilizer source, rate, and timing for the two systems, as well as increased nitrate N uptake due to earlier planting and a longer growing season for some alternative crop species. Nitrogen application rate and source most likely had the greatest effect on nitrogen leaching from the soil (including N released from organic sources). Although nitrogen application rates in the alternative system were greater than in the conventional system in both 2003 and 2004, animal manures release nitrate N more slowly than synthetic fertilizers. A slow release of nitrate N may allow for more nitrogen uptake by plants in alternative farming practices compared with conventional practices, reducing the concentration of nitrate N leached from the soil. Additionally, uptake of nitrogen by autumn seeded small grains and winter cover crops may have contributed to the smaller amount of nitrogen lost from the alternative system.

Reduced nitrate N load in subsurface drainage from alternative farming practices in comparison with conventional practices shows that under midwestern climatic conditions, alternative farming practices can be used to reduce nitrate N losses to surface water. It has been shown that precipitation greatly impacts nutrient losses, so results may differ under other climatic conditions.

A comparison of mean daily nitrate N loads between years showed that nitrate N losses under alternative farming practices were similar between years, but nitrate N loads under conventional practices were greater in 2002 and 2004 compared with 2003, a below-average precipitation year; however, statistical analyses were not conducted due to the small sample size. This indicates that nitrate N losses under alternative farming practices did not vary as much in response to changes in precipitation as losses through subsurface drainage from conventional practices.

Results from the study indicated that alternative farming practices reduced losses of nitrogen in subsurface drainage compared with conventional practices, especially during years when precipitation was average or above average. Alternative farming practices are a potential means to lessen agricultural impacts on surface water pollution. Alternative farming practices may reduce Upper Midwest nitrate N contributions to the Mississippi River and ultimately hypoxia in the Gulf of Mexico.

Flow-Weighted Mean Nutrient Concentrations

The amount of water lost through subsurface drainage affects the mass of nutrients exported from the system. Flow-weighted mean nitrate concentrations (mg L^{-1}), were significantly less under alternative farming practices compared with conventional practices for the duration of the study (Table 6). Flow-weighted mean nitrate concentrations under alternative farming practices were less than the 10 mg L^{-1} drinking water standard for all three sampling seasons, while flow-weighted mean nitrate concentrations under conventional farming practices exceeded the drinking water standard throughout the study. This indicates that under similar climatic conditions, there is a greater potential risk of polluting drinking water sources with conventional farming practices in comparison to the risks with alternative farming practices. Concentration differences were likely due to differences in fertilizer rate, timing, and source as well as different plant N uptake rates.

Observed phosphorus and ammonium N concentrations were less than 0.10 and 0.7 mg L^{-1}, respectively, during the study period. Total phosphorus loss in subsurface drainage from both systems was generally below USEPA water quality criteria (76.25 μg L^{-1}, USEPA, 2000) with the exception of the conventional system in 2004. Phosphorus loss via surface runoff was not measured in this study. Since generally the major proportion

Table 6. Daily flow-weighted mean concentrations for nitrate-nitrogen (NO_3) ammonium-nitrogen (NH_4), orthophosphorus (OP), and total phosphorus (TP) in subsurface drainage from alternative (AL) and conventional (CN) farming practices.

	Water quality parameter			
Farming practice	NO_3	NH_4	OP	TP
	mg L^{-1}			
2002 (N = 137)				
AL	7.01a†	0.51a	0.011a	0.03a
CN	17.01b	0.68b	0.014b	0.03a
2003 (N = 72)				
AL	7.76a	0.10a	0.02a	0.03a
CN	14.74b	0.10a	0.02a	0.03a
2004 (N = 179)				
AL	9.78a	0.01a	0.04a	0.06a
CN	19.98b	0.07b	0.07b	0.09b

† Within column and year, daily flow-weighted mean concentrations followed by the same letter are not significantly different at the 0.05 probability level.

of phosphorus transport in runoff from cultivated land occurs as particulate P, it is likely that our measurements, which only considered losses from subsurface drainage, would underestimate the potential total amount of phosphorus lost from these sites from rainfall- and snowmelt-induced runoff and erosion.

Monthly Drainage and Nitrate-Nitrogen

Monthly drainage, flow-weighted mean nitrate N concentration, and nitrate N load were investigated to determine when during the growing season most water and N is lost. These data can help determine what types of farming practices are most effective at improving water quality. For example, monthly data may help us determine whether or not spring application of fertilizer could improve water quality relative to fall application.

Although subsurface drainage primarily occurs between April and July in Minnesota it is notable that no drainage was measured during April in 2003 and 2004. Lack of fall soil moisture recharge, mild winter conditions with below average snowfall, and delayed spring rainfall all contribute to these results. For both alternative and conventional farming practices, more water was lost as drainage in May 2002, June 2003, and September 2004 than in any other month of their respective years (Fig. 7). With the exception of 2004, more rainfall was lost as drainage in the early growing season when plants need the most water. Above-average precipitation fell in the fall of 2004. Had that not occurred, it is probable that more water would have been lost as drainage in June rather than September and October. Although statistical analyses were not conducted on monthly data due to a small number of samples, the monthly data along with the mean daily drainage data show that adoption of alternative farming practices may reduce water loss in drainage relative to loss under conventional practices. As water movement through the soil leaches nitrate N, a reduction in water loss may decrease the loss of nutrients as well.

Monthly flow-weighted mean nitrate N concentrations were investigated to determine when nitrate N pollution poses the greatest risk to surface water sources and if alternative farming practices can reduce the risk in those months. The highest monthly flow-weighted mean nitrate N concentrations by year occurred in August 2002, July 2003, and June 2004 (Fig. 8). These flow-weighted mean concentrations all occurred with conventional farming practices. Flow-weighted mean nitrate N concentrations were lower under alternative farming practices compared with conventional practices during these months. The results show that monthly flow-weighted mean nitrate N concentrations from conventional farming practices were higher in October 2004 than September 2004, both months during which unusually high amounts of precipitation fell.

For both alternative and conventional farming practices, monthly nitrate N loads in subsurface drainage were highest in May 2002 and June 2003 (Fig. 9). These data correspond to the months of greatest water loss in drainage, indicating that a reduction in drainage would reduce agricultural contributions of nitrate N to surface waters. As indicated earlier, alternative farming practices were an effective means of reducing drainage and nitrate N loads in subsurface drainage relative to conventional practices. In 2004, the greatest nitrate N loss from conventional farming practices occurred in September, corresponding to the greatest amount of monthly drainage. With alternative farming practices, nearly equal amounts of nitrate N were lost in June and September 2004, but the amounts were seven times smaller

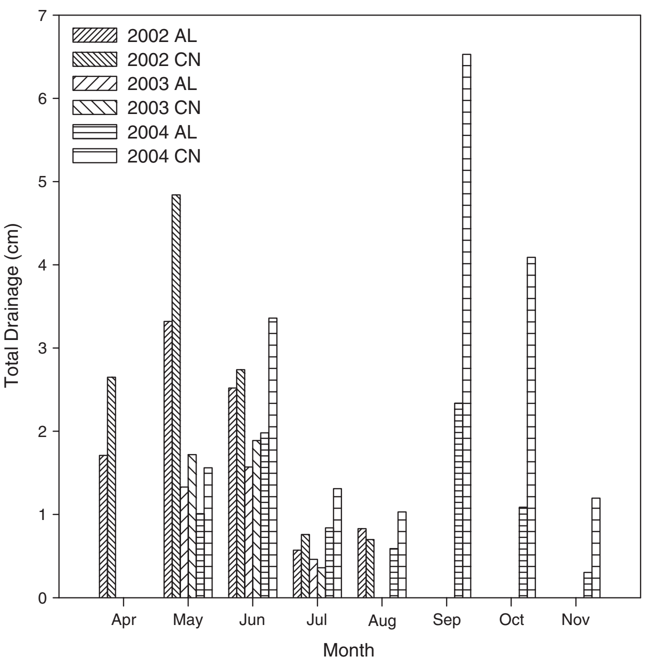

Fig. 7. Monthly subsurface drainage (cm) from alternative (AL) and conventional (CN) farming practices for the duration of the study.

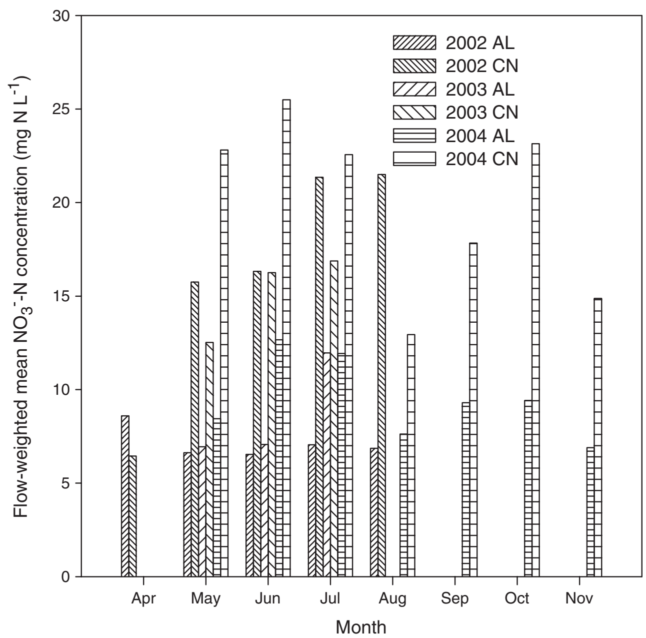

Fig. 8. Monthly flow-weighted mean nitrate-nitrogen concentrations (mg N L^{-1}) in subsurface drainage from alternative (AL) and conventional (CN) farming practices for the duration of the study.

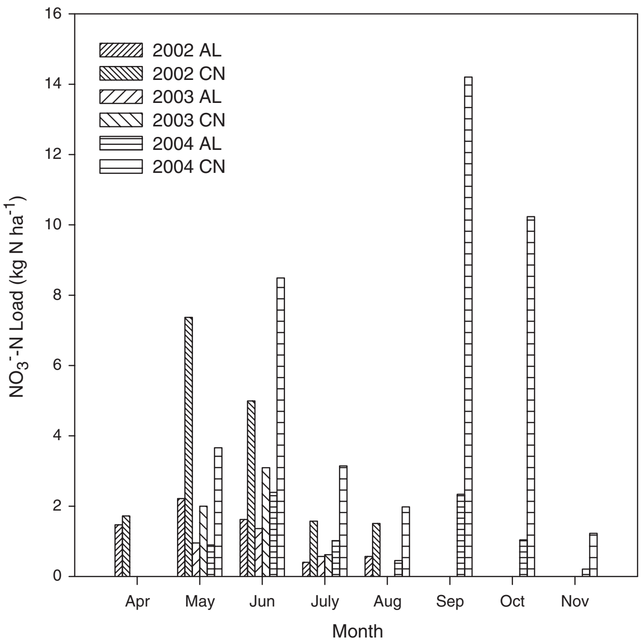

Fig. 9. Monthly nitrate-nitrogen load (kg N ha^{-1}) in subsurface drainage from alternative (AL) and conventional (CN) farming practices for the duration of the study.

than losses from the conventional system in September. Monthly drainage under alternative farming practices was only slightly greater in September than June 2004, explaining the similar amounts of nitrate N leached during these 2 mo. Monthly nitrate N loads indicate that losses of nitrate N correlate with drainage, and drainage reductions would likely result in reduced nitrate N losses. This further supports the conclusion that alternative farming practices may reduce agricultural contributions to surface water pollution compared with conventional practices.

Monthly drainage, flow-weighted mean concentration, and nitrate N load results show that alternative farming practices reduce agricultural contributions to surface water pollution in comparison with conventional practices.

SUMMARY AND CONCLUSIONS

Section 303(d) of the Clean Water Act requires states to develop TMDLs for all surface waters that exceed water quality standards. While subsurface drainage is important for agriculture production in the Upper Midwest, changes to current agricultural practices will be necessary to meet emerging TMDLs. One potential strategy for meeting TMDLs is adoption of alternative farming practices. The results of this study show that alternative farming practices have the potential to reduce agricultural contributions to surface water pollution.

In this study, flow-weighted mean nitrate N concentrations for both the alternative and conventional farming systems were always greater than the suggested EPA criteria (0.63 mg L^{-1}) for rivers and streams in nutrient Ecoregion VI (USEPA, 2000). In the presence of sufficient levels of dissolved phosphorus, the nitrogen levels measured in this study would contribute to aquatic plant and algal growth that would contribute to surface water quality impairments. Mean daily drainage was significantly lower from alternative farming practices compared with conventional practices in 2002 and significantly higher in 2003. Annual drainage from alternative farming practices was lower than that from conventional practices in all years. The amount of water lost had an important effect on nitrate N leaching from the soil. Mean daily nitrate N loads were significantly lower in subsurface drainage from alternative farming practices compared with conventional practices in 2002 and 2004, while mean daily loads were similar in 2003 due to the dry weather. Annual nitrate N losses were less under alternative farming practices compared with conventional practices in all years. Ammonium N, OP, and TP losses from subsurface drainage were not considered a substantial pollution threat.

Alternative farming practices compared with conventional farming practices reduced mean daily losses and annual losses of nitrogen and phosphorus in subsurface drainage, especially during years when precipitation was average or above average. Alternative farming practices have the potential to reduce agricultural contributions to surface water pollution. Alternative farming practices may reduce Upper Midwest nitrate N contributions to the Mississippi River and ultimately hypoxia in the Gulf of Mexico.

The results of this study are only relevant to regions under similar climatic conditions and soil types. Precipitation is the most important factor contributing to leaching of soil nitrogen, while soil type affects the rate of water movement through the soil (Oquist et al., 2006). More research is necessary in different regions to determine if conversion to alternative farming practices will improve water quality in other locations.

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