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# SOIL MANAGEMENT

## Subsurface Drain Losses of Water and Nitrate following Conversion of Perennials to Row Crops

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### ABSTRACT

**Nitrate losses through subsurface drains in agricultural fields pose a serious threat to surface water quality. Substantial reductions in drainage losses of $NO_3$–N can occur with alfalfa (*Medicago sativa* L.) or perennial grasses as used in Conservation Reserve Program (CRP) plantings. Conversion of perennials to annual row crops, however, could have rapid, adverse affects on water quality. We evaluated water and N use efficiency of row crops following perennials, and losses of water and $NO_3$–N to subsurface drains. Four cropping systems: continuous corn (*Zea mays* L.), a corn–soybean [*Glycine max* (L.) Merr.] rotation, alfalfa (ALF), and CRP, were established in 1988. The ALF and CRP were converted to a corn–corn–soybean sequence from 1994 through 1996 while continuous corn (C-C) and corn–soybean (C-S) rotations were maintained. Following CRP, corn yield was 14% and water use efficiency (WUE) 20% greater as compared with C-C. Yield was 19% and WUE 21% greater for soybean following corn in CRP and ALF as compared with C-S. Residual soil $NO_3$–N (RSN) increased 125% in first year corn following CRP and was 32% greater than C-C by 1996. High N uptake efficiencies of corn following alfalfa slowed the buildup of RSN, but levels were equal to row crop systems after 2 yr. Nitrate losses in drainage water remained low during the initial year of conversion, but were similar to row crop systems during the subsequent 2 yr. Beneficial effects of perennials on subsurface drainage characteristics were largely negated following 1 to 2 yr of corn.**

PRODUCTION of annual row crops on large areas of poorly drained soils in the Upper Midwest requires artificial drainage to improve timeliness of field operations and suitability of the soil environment for annual crop growth (Wheaton, 1977). Adverse environmental consequences of intensive row-crop production with artificial drainage, however, are well documented and include sediment, nutrient (N, P), and pesticide delivery to surface waters via subsurface drain lines (Gast et al., 1978; Logan et al., 1980, 1993; Kladivko et al., 1991; Buhler et al., 1993; Randall et al., 1997). Recently, riverborne nutrients, mainly $NO_3$–N from farmland in the Upper Midwest, have been implicated in the spread of hypoxic bottom waters in the Gulf of Mexico near the mouth of the Mississippi River (Antweiler et al., 1995; Burkhart and James, 1999). A major source of $NO_3$–N found in the upper Mississippi River is from agricultural fields that are artificially drained (Goolsby, 1999). The contamination of surface and ground waters from sediment and land-applied agri-chemicals (CAST, 1985) combined with spreading hypoxia in the Gulf of Mexico raises concerns about the sustainability of annual row-crop production in the Upper Midwest.

Crop rotation can have a substantial effect on the quantity and quality of water entering subsurface drains. Most investigations in the Midwest have evaluated the influence of annual row-crop (e.g., corn and soybean) production on nutrient loss via subsurface drains (Gast et al., 1978; Logan et al., 1980, 1993; Baker and Johnson, 1981; Kladivko et al., 1991; Randall and Iragavarapu, 1995; Randall et al., 1997). These studies concluded that: (i) annual losses of $NO_3$–N through subsurface tile drains are substantial, ranging up to 120 kg N ha$^{-1}$; (ii) $NO_3$–N concentrations of drainage water often exceed the USEPA drinking water standard of 10 mg L$^{-1}$; and (iii) $NO_3$–N losses in row-crop systems are dependent on drain flow volumes and fertilizer N management. In contrast to annual crops, perennial crops such as alfalfa and grass can reduce $NO_3$–N concentrations in the soil profile (Mathers et al., 1975; MacLean, 1977; Russelle and Hargrove, 1989; Randall et al., 1997), decrease $NO_3$–N concentrations and flux in drainage waters, and

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**Abbreviations:** CRP, Conservation Reserve Program; RSN, residual soil $NO_3$–N; C, corn; S, soybean; ALF, alfalfa; NUE, nitrogen use efficiency; PVC, polyvinyl chloride; WUE, water use efficiency; ET, evapotranspiration.

lower drainage volumes (Bolton et al., 1970; Logan et al., 1980; Bergstrom, 1987; Owens, 1990; Randall et al., 1997). In a comparison of four rotations—continuous corn (C-C), corn–soybean (C-S), alfalfa (ALF), and alfalfa–grass mixture (CRP)—Randall et al. (1997) reported average $NO_3$–N concentrations from subsurface drains of 32 mg $L^{-1}$ for C-C, and 24 mg $L^{-1}$ for C-S, but only 3 mg $L^{-1}$ for ALF and 2 mg $L^{-1}$ for CRP. In addition, drainage from the row-crop systems exceeded that from perennial crops by up to fivefold. Greater drain flows and $NO_3$–N concentrations in C-C and C-S rotations (Randall et al., 1997) produced annual losses of $NO_3$–N that were 35 times (avg. loss of 53 kg N $ha^{-1}$) greater than $NO_3$–N losses in the perennial systems (avg. loss of 1.5 kg N $ha^{-1}$).

The Conservation Reserve Program (CRP) was initiated in 1985 and was designed to assist landowners in conserving and improving soil and water resources of highly erodible and environmentally sensitive land (Cubbage, 1992; Osborn, 1993). The CRP reached 16.2 million ha by 1993, with 14.7 million ha in grassland and 1.5 million ha in forestland (Osborn, 1993). By 1999, total area in the CRP was reduced slightly to 12.7 million ha. Historically, states in the Corn Belt have had significant participation in the CRP accounting for 13% of the national CRP-land area (USDA, 1999).

The conversion of land from intensive annual crop production to permanent vegetative cover under CRP has resulted in substantial benefits to soil quality (Gebhart et al., 1994; Huggins et al., 1997; Staben et al., 1997; Karlen et al., 1999) and water quality (Randall et al., 1997). These benefits, however, can be short-lived as CRP contracts expire after only 10 to 15 yr and if post-CRP management includes a return to annual cropping. Management strategies for returning CRP-land to crop production should consider options that attempt to maintain environmental benefits gained by the CRP. Improvements in soil aggregation, structural stability, C sequestration, and water infiltration on CRP-land can largely be maintained through conservation tillage practices, notably no-tillage (Lindstrom et al., 1994; Huggins et al., 1997). The effects of CRP land conversion on water quality are largely unknown and take on further significance as riparian buffer areas are included in the CRP or in the Wetlands Reserve Program (WRP).

Conversion of CRP-land to row crops will likely result in a return to pre-CRP water flow volumes and $NO_3$–N concentrations in subsurface drains. How long water quality benefits might persist following CRP-land conversion to row crops, and what management strategies may extend those benefits were the over-riding questions of our research. Specifically, our objectives were to determine the effects of converting perennial cropping systems (e.g., alfalfa and CRP plantings) to annual row-crop systems (corn and soybean) on (i) aboveground biomass and N accumulation, (ii) water and N use efficiency, and (iii) water and $NO_3$–N losses to subsurface drains. Furthermore, we expected this evaluation to provide (i) insights into the persistence of crop and water quality benefits acquired from perennial cropping systems including CRP-land; and (ii) a basis for devising crop rotation and CRP-land conversion strategies that would optimize water and N use.

## MATERIALS AND METHODS

### Site Description and Experimental Design

The study was conducted on a long-established subsurface drainage site at the University of Minnesota Southwest Research and Outreach Center near Lamberton, MN. In 1972, perforated PVC subsurface drains (10-cm diam.) were installed 1.2-m deep on 15 plots, 13.7 by 15.3 m, to simulate 28-m spacing on a Normania clay loam (fine-loamy, mixed, mesic Aquic Haplustolls). Previous studies have examined N rate effects on drain nitrate losses (Gast et al., 1978), perennial vs. annual row crop effects on nitrate losses through drains (Randall et al., 1997), and modeling of water quality with DRAINMOD-N (Zhao et al., 2000). Further details on the establishment of the subsurface drainage plots, soil characteristics, past management, and previous research findings can be obtained from these studies.

In the spring of 1988, four cropping systems—continuous corn (C-C), corn after soybean (S-C), soybean after corn (C-S), alfalfa (ALF), and a perennial grass–alfalfa mixture (CRP) representing CRP-land—were established in 15 subsurface drainage plots in a randomized complete-block design with three replications. The C-S and S-C treatments were included to allow representation of each crop every year in the 2-yr corn–soybean rotation. The first phase of the experiment was completed in the fall of 1993 after six cropping seasons (Randall et al., 1997). Phase two of the study was initiated in the fall of 1993 when the ALF and CRP treatments were moldboard plowed and rotated to corn in 1994 and 1995, and then to soybean in 1996 (ALF-C-C-S and CRP-C-C-S, respectively). The C-C, S-C, and C-S cropping system treatments were continued as established in 1988 through the fall of 1996 when phase two was completed.

### Field and Laboratory Procedures

Annual experimental procedures for each cropping system are given in Table 1. Tillage following corn consisted of fall moldboard plowing and spring cultivation before planting and row cultivation (one operation) after planting. The soil was left untilled in the fall following soybean and plots were spring cultivated before corn planting. Best management practices (BMPs) were used for N fertilization of corn (Rehm and Schmitt, 1989). Nitrogen was side-dressed at application rates based on spring soil $NO_3$–N (0–1.2 m), previous crop (corn, soybean, alfalfa, CRP-perennial grass), and a corn yield goal of 8.8 Mg $ha^{-1}$. Starter fertilizer was applied during corn planting, and urea was surface side-dressed and immediately incorporated with row cultivation (Table 1). No fertilizers were applied to soybean.

Corn and soybean grain yields were measured with a plot combine following physiological maturity from two 12.2-m row subsamples. Corn stover biomass was determined from the dry-weight ratio of grain to stover of 10 plants hand-sampled just before harvest, and applied to the overall grain yield from the larger plot harvest. Soybean stover biomass was assessed by collecting all leaves, petioles, and stems within a wire-caged, 1-m length of row in each plot.

Detailed methods for the collection and analysis of subsurface drainage water and nitrate flux are given in Randall et al. (1997). Briefly, drain flow rates were determined daily, except Saturday and Sunday unless precipitation occurred. Water samples for $NO_3$–N analysis were collected manually

**Table 1. Management procedures for corn and soybean in each of the cropping systems (1994–1996). Underlined crops denote specific crop within crop sequence that information refers to.**

| Cropping system | Procedure | Year 1994 | 1995 | 1996 |
|---|---|---|---|---|
| Corn† | Pioneer hybrid | 3 563 | 3 531 | 3 531 |
| | Planting rate, seeds $ha^{-1}$ | 71 630 | 74 100 | 74 100 |
| | Planting date | 4 May | 4 May | 16 May |
| | Starter, kg $ha^{-1}$, N–P–K | 17–15–18 | 17–15–18 | 17–15–18 |
| | Urea appl. date | 6 June | 7 June | 24 June |
| | Cultivation date | 6 June | 7 June | 24 June |
| | Harvest date | 19 Oct. | 9 Oct. | 9 Oct. |
| Continuous corn | Urea, kg N $ha^{-1}$ | 148 | 143 | 112 |
| Soybean-Corn‡ | Urea, kg N $ha^{-1}$ | 95 | 91 | 67 |
| Alfalfa-Corn-Corn§ | Urea, kg N $ha^{-1}$ | 0 | 60 | n.a.¶ |
| CRP-Corn-Corn# | Urea, kg N $ha^{-1}$ | 160 | 132 | n.a. |
| Soybean†† | Variety | Parker | Parker | Parker |
| | Planting date | 4 May | 17 May | 20 May |
| | Cultivation date | 13 June | 7 June | 24 June |
| | Harvest date | 19 Oct. | 15 Oct. | 1 Oct. |
| All crops | Sampling for soil | 18 April | 17 May | 1 May |
| | water and $NO_3$–N | 1 Nov. | 17 Oct. | 15 Oct. |

† Procedures used for all corn plots.
‡ Corn following a previous crop of soybean.
§ Corn following alfalfa in 1994 and corn in 1995 (soybean grown in 1996).
¶ n.a. = not applicable (soybean grown in 1996).
# Corn following the Conservation Reserve Program (CRP) in 1994 and corn in 1995 (soybean grown in 1996).
†† Procedures used for all soybean plots.

in 250-mL plastic bottles three times per week (Monday, Wednesday, Friday) and frozen until analyzed. Nitrate-N was determined colorimetrically by Cd-reduction and levels of $NO_2$–N were assumed to be negligible. Nitrate-N levels were linearly interpolated for days when samples were not taken. Total flux of $NO_3$–N through drains was calculated by multiplying sample $NO_3$–N concentration by total water flow for the same time period. Flow-weighted average $NO_3$–N concentrations were calculated by dividing total $NO_3$–N flux by total water flow for the same time period.

Nitrogen concentration of aboveground biomass (grain and stover) of corn and soybean was determined by grinding subsamples to pass a 1-mm sieve and analyzing for total N (Technicon Industrial Method no. 325-74W Sept. 1974; Ammoniacal Nitrogen/BD Acid Digests; Technicon Industrial Systems, Tarrytown, NY).[1]

Nitrogen content of aboveground biomass was expressed on an area basis using grain and stover values from harvested biomass of corn and soybean. Following harvest, two soil cores (4.1-cm diam.) were collected from each plot to a depth of 3.0 m with a hydraulic probe and composited in 30-cm increments. Gravimetric water content was determined after oven drying (105°C) and $NO_3$–N was measured on air-dried samples ground to pass a 2-mm sieve, extracted with 2 $M$ KCl, and analyzed colorimetrically using Cd-reduction. Soil $NO_3$–N and water were expressed on a volume basis using soil bulk densities determined in 1994.

## Calculation of Nitrogen and Water Use Efficiency

Components of N use efficiency (NUE) were based on major plant physiological processes (Huggins and Pan, 1993). Nitrogen use efficiency was defined as grain production ($G_w$) per unit of N supply ($N_s$), where $N_s$ is the sum of all sources of available N. In turn, two primary factors of NUE were defined as (i) N uptake efficiency ($N_t/N_s$), the amount of aboveground plant N ($N_t$) at maturity per unit of $N_s$; and (ii) N utilization efficiency ($G_w/N_t$), the amount of grain production per unit of $N_t$. In this study, $N_s$ and net mineralized N ($N_m$) were estimated using the following equations:

$$N_s = N_r + N_f + N_m \quad [1]$$

$$N_m = (N_t + N_h + N_{sd}) - (N_r + N_f) \quad [2]$$

where $N_r$ is residual soil $NO_3$–N (0–1.5 m) from the fall of the previous year, $N_f$ is applied fertilizer N, $N_m$ is net mineralized N, $N_t$ is aboveground plant N, $N_h$ is soil $NO_3$–N (0–1.5 m) following harvest, and $N_{sd}$ is $NO_3$–N loss through subsurface drains. These calculations do not consider losses of N due to denitrification, volatilization, or leaching below 1.5 m, and therefore underestimate $N_m$ and $N_s$.

Components of water use efficiency (WUE) were based on a similar analysis where WUE was defined as grain production ($G_w$) per unit of water supply ($W_s$). Two primary factors of WUE were defined as (i) water uptake efficiency (ET/$W_s$), the amount of evapotranspiration (ET) per unit of $W_s$; and (ii) water utilization efficiency ($G_w$/ET), the amount of grain production per unit of evapotranspiration. In this study, $W_s$ and ET were estimated using the following two equations:

$$W_s = W_r + W_p \quad [3]$$

$$\mathrm{ET} = W_d + W_p - W_{sd} \quad [4]$$

where $W_r$ is residual soil water from the previous fall (0–3 m), $W_p$ is hydrologic year precipitation (October–September), $W_d$ is soil water depletion (Residual soil water from previous fall − Residual soil water after harvest, 0–3 m), and $W_{sd}$ is loss of water through subsurface drainage. The calculation of ET is slightly overestimated because losses of water below 3 m are not considered. Estimates of annual water flow to groundwater are relatively small; however, <3 cm (Baker et al., 1979). Runoff is negligible from this site as slopes are <1%.

## Statistical Analyses

Analysis of variance (ANOVA) was used to determine significant (0.05 probability level) cropping system effects for

[1] Names are necessary to report factually on available date; however, the USDA and the Univ. of Minnesota neither guarantee nor warrant the standard of the product, and the use of the name by the USDA and the Univ. of Minnesota implies no approval of the product to the exclusion of others that may be suitable.

**Table 2. Cropping system effects on corn and soybean grain yield and stover biomass (1994–1996).**

| Cropping system† | 1994 | | 1995 | | 1996 | |
|---|---|---|---|---|---|---|
| | Grain | Stover | Grain | Stover | Grain | Stover |
| | dry matter, kg ha$^{-1}$ | | | | | |
| C-C | 8 709 | 6 842 | 5 713 | 8 180 | (6 573) | (5 642) |
| C-S | 9 126 | 7 313 | 7 050 | 11 653 | (6 553) | (5 874) |
| S-C | (2 932) | (3 501) | (2 210) | (2 421) | 2 210 | 2 930 |
| ALF-C-C-S‡ | 9 031 | 7 788 | 5 829 | 10 436 | 2 621 | 3 761 |
| CRP-C-C-S | 9 386 | 7 647 | 7 097 | 12 089 | 2 630 | 3 684 |
| LSD (0.05) | *423** | *1 221* | *896** | *2 432** | *167** | *438** |

* Significant differences occurred according to Fischer's least significant difference (LSD) test (0.05 level of probability). Mean comparisons exclude values in parentheses in each column. Therefore, the LSD's for grain and stover are for corn sequences in 1994 and 1995, and soybean sequences in 1996.
† C = corn; S = soybean; ALF = alfalfa; CRP = Conservation Reserve Program. Values are for underlined crop.
‡ C-C-S signifies corn in 1994, corn in 1995, and soybean in 1996.

each year of the study (SAS Inst., 1996). A multiple mean comparison of cropping system effects was performed using Fischer's least significant difference (LSD) test (0.05 probability level). Fischer's LSD tests are reported for all variables as a measure of variance; however, LSD tests are indicated as significant only when the ANOVA had significant $F$ ratios for cropping system effects. Least squares regression analysis was used to relate subsurface drainage to water supply and the coefficient of determination ($r^2$) calculated (SAS Inst., 1996).

## RESULTS AND DISCUSSION

### Grain Yield and Stover Biomass

Corn grain yields in 1994 were 8% greater following 6 yr of CRP compared with continuous corn, whereas yields following alfalfa (6 yr), soybean, or continuous corn were not significantly different (Table 2). These data contrast with our expectations that beneficial rotation effects on yield would be greater for corn following alfalfa compared with grass (Porter et al., 1997a). Both grain yield reductions and increases, however, have been reported for corn grown after either alfalfa or grass. Soil water deficits created by high water use crops such as alfalfa and perennial grasses can negatively impact subsequent crop growth and yield (Shrader and Pierre, 1966; Grecu et al., 1988). Precipitation was 166% of normal during the 1993 growing season, which recharged soil water deficits in CRP and ALF, and resulted in nearly equivalent residual soil water levels across cropping systems in the fall of 1993 (Randall et al., 1997). Despite high precipitation in 1993, $W_s$ was still 5% greater in C-C compared with ALF-C (Table 3) for 1994, which may have depressed beneficial rotation effects expected when corn follows alfalfa. When minimal differences in soil water occur and adequate nutrient levels are supplied, increased yields of corn following alfalfa or hay crops compared with continuous corn have been reported (Barber, 1972; Hesterman et al., 1986). Overall, corn yields in 1994 were greater than yield goals as a result of favorable in-season growing conditions. Beneficial rotation effects of alfalfa and CRP on subsequent corn yields would be expected to be less pronounced under a high yielding environment (Barber, 1972; Roder et al., 1989; Porter et al., 1997b).

In 1995, overall corn yields were less than those of 1994, below yield goals, and differences in yield among the cropping systems were more pronounced (Table 2). Corn yields were 20% greater in S-C and CRP-C-C-S rotations than in C-C and ALF-C-C-S.[2] Differences in cropping system $W_s$ were not significant in 1995 (Table 3); however, insufficient available N may have reduced second-year corn yields following alfalfa as N uptake efficiencies were similar but $N_s$ was reduced in ALF-C-C-S compared with CRP-C-C-S and S-C (Table 4).

Soybean grain yields in 1996 were 19% and stover production 25% greater in CRP-C-C-S and ALF-C-C-S sequences compared with C-S (Table 2). These data support the conclusion of Porter et al. (1997b), that the C-S rotation does not maximize rotation benefits for soybean yield. Soybean had not been grown on this site for >25 yr, and the 19% yield increase is greater than the 6% yield increase reported by Porter et al. (1997b) for soybean following 5 yr of C-C compared with a C-S rotation. Management strategies for initial conversion of CRP to annual row-crops in the Midwest should consider soybean, as crop rotation effects on yield will likely be greater than for corn.

### Water Use and Subsurface Drain Flow

During phase one, the average annual $W_s$ for alfalfa and CRP (1989–1993) was lower than for row crops (Table 5). This occurred as greater ET in alfalfa and CRP depleted quantities of residual water in the upper 3 m of soil (Randall et al., 1997). In phase two, $W_s$ was still greater in the C-C sequence compared with ALF-C-C-S in 1994, but $W_s$ was similar in 1995 and 1996 (Table 3). No differences in residual soil water occurred among the cropping systems in the 0- to 1.5-m depth by the fall of 1994, whereas levels of soil water in the 1.5- to 3.0-m depths were slightly elevated in C-C compared with ALF-C-C-S (Table 6). Differences in fall residual soil water were not significant in 1995 and only marginally different in 1996 (Table 6). Although the magnitude of ET changed from year to year, no differences occurred in ET among crops or cropping systems from 1994 through 1996 (Table 3). These results agree with those of Copeland et al. (1993), who found that ET estimates for corn and soybean did not differ significantly among rotation sequences at the Lamberton site.

Subsurface drain flow was directly related to annual

[2] Underlined letter denotes specific crop within crop sequence that information refers to.

**Table 3. Cropping system effects on water supply, losses, and use (1994–1996).**

| Cropping system† | Precip.‡ | $W_s$§ | Subsurface drainage | ET¶ | $G_w/W_s$# | $ET/W_s$†† | $G_w/ET$‡‡ |
|---|---|---|---|---|---|---|---|
| | cm | | | | kg cm$^{-1}$ | cm cm$^{-1}$ | kg cm$^{-1}$ |
| 1994 | 70.6 | | | | | | |
| C-C | | 169.0 | 12.7 | 59.9 | 51.5 | 0.35 | 145.9 |
| C-S | | 162.7 | 13.3 | 56.1 | 56.1 | 0.34 | 162.8 |
| S-C | | 164.5 | 14.0 | 58.1 | (17.8) | 0.35 | (50.5) |
| ALF-C | | 161.0 | 10.3 | 59.9 | 56.1 | 0.37 | 151.1 |
| CRP-C | | 163.9 | 11.6 | 61.1 | 57.3 | 0.37 | 154.6 |
| LSD (0.05) | | *7.0** | *4.0* | *6.8* | *2.6** | *0.04* | *20.2* |
| 1995 | 72.8 | | | | | | |
| C-C | | 169.2 | 19.7 | 55.1 | 33.8 | 0.33 | 105.1 |
| C-S | | 165.2 | 23.1 | 48.8 | 42.7 | 0.29 | 145.6 |
| S-C | | 166.1 | 19.9 | 52.7 | (13.3) | 0.32 | (42.3) |
| ALF-C-C | | 163.6 | 17.5 | 56.0 | 35.7 | 0.34 | 104.3 |
| CRP-C-C | | 164.0 | 21.2 | 51.0 | 43.3 | 0.31 | 139.2 |
| LSD (0.05) | | *6.5* | *6.0** | *9.4* | *6.0** | *0.05* | *35.6** |
| 1996 | 75.0 | | | | | | |
| C-C | | 169.5 | 17.9 | 62.6 | (38.8) | 0.37 | (105.5) |
| C-S | | 168.5 | 16.1 | 62.5 | (38.9) | 0.37 | (105.1) |
| S-C | | 168.2 | 17.5 | 62.3 | 13.1 | 0.37 | 35.4 |
| ALF-C-C-S | | 165.2 | 13.3 | 61.6 | 15.9 | 0.37 | 42.6 |
| CRP-C-C-S | | 166.9 | 15.2 | 61.1 | 15.9 | 0.37 | 43.2 |
| LSD (0.05) | | *7.0* | *3.9** | *7.5* | *1.1** | *0.04* | *3.6** |

* Significant differences occurred according to Fischer's least significant difference (LSD) test (0.05 level of probability). The LSD's for $G_w/W_s$ and $G_w/ET$ are for corn sequences in 1994 and 1995, and soybean sequences in 1996; therefore, mean comparisons exclude values in parentheses in each of these columns.
† C = corn; S = soybean; ALF = alfalfa; CRP = Conservation Reserve Program. Values are for underlined crop.
‡ Precip. = hydrologic year precipitation (October–September).
§ $W_s$ = water supply.
¶ ET = evapotranspiration.
\# $G_w/W_s$ = water use efficiency.
†† $ET/W_s$ = water uptake efficiency.
‡‡ $G_w/ET$ = water utilization efficiency.

$W_s$ for both phase one and phase two studies (Fig. 1). Calculated $W_s$ includes the soil water depletion effects of the previous crop(s) as well as precipitation (Eq. [3]).

Soil water deficits created by alfalfa and CRP reduced $W_s$ compared with annual row crops (Table 5). Low cropping system $W_s$ is an indication of greater consump-

**Table 4. Cropping system effects on nitrogen uptake, losses, and use efficiency (1994–1996).**

| Cropping system† | Grain N | Stover N | Drain N | $N_s$‡ | $N_m$§ | $G_w/N_s$¶ | $N_t/N_s$# | $G_w/N_t$†† |
|---|---|---|---|---|---|---|---|---|
| | kg N ha$^{-1}$ | | | | | kg kg$^{-1}$ | | |
| 1994 | | | | | | | | |
| C-C | 87 | 29 | 15 | 211 | −18 | 42.6 | 0.57 | 75.0 |
| C-S | 87 | 29 | 13 | 174 | 7 | 52.7 | 0.68 | 78.3 |
| S-C | (121) | (34) | 13 | n.c.‡‡ | n.c. | n.c. | n.c. | n.c. |
| ALF-C | 82 | 25 | 3 | 137 | 95 | 65.7 | 0.78 | 84.6 |
| CRP-C | 99 | 34 | 1 | 188 | −10 | 51.6 | 0.71 | 71.4 |
| LSD (0.05) | *10** | *13* | *6** | *76* | *76** | *17.3** | *0.19** | *11.1** |
| 1995 | | | | | | | | |
| C-C | 69 | 40 | 22 | 248 | 8 | 23.1 | 0.44 | 52.4 |
| C-S | 72 | 64 | 25 | 260 | 97 | 27.1 | 0.52 | 52.1 |
| S-C | (88) | (25) | 17 | n.c. | n.c. | n.c. | n.c. | n.c. |
| ALF-C-C | 57 | 44 | 14 | 203 | 98 | 28.8 | 0.50 | 57.7 |
| CRP-C-C | 86 | 75 | 17 | 312 | 108 | 22.9 | 0.52 | 44.0 |
| LSD (0.05) | *14** | *13** | *9** | *45** | *39** | *3.3** | *0.06** | *5.8** |
| 1996 | | | | | | | | |
| C-C | (38) | (76) | 13 | 179 | −66 | 37.0 | 0.64 | 57.6 |
| C-S | (36) | (77) | 9 | 171 | −12 | 38.3 | 0.66 | 58.4 |
| S-C | 105 | 49 | 10 | n.c. | n.c. | n.c. | n.c. | n.c. |
| ALF-C-C-S | 136 | 78 | 7 | n.c. | n.c. | n.c. | n.c. | n.c. |
| CRP-C-C-S | 133 | 76 | 11 | n.c. | n.c. | n.c. | n.c. | n.c. |
| LSD (0.05) | *12** | *34* | *4** | *16* | *47** | *6.4* | *0.19* | *6.5* |

* Significant differences occurred according to Fischer's least significant difference (LSD) test (0.05 level of probability). The LSD's for grain N and stover N are for corn sequences in 1994 and 1995, and soybean sequences in 1996; therefore, mean comparisons exclude values in parentheses in each of these columns.
† C = corn; S = soybean; ALF = alfalfa; CRP = Conservation Reserve Program. Values are for underlined crop.
‡ $N_s$ = nitrogen supply.
§ $N_m$ = net nitrogen mineralization.
¶ $G_w/N_s$ = nitrogen use efficiency.
\# $N_t/N_s$ = nitrogen uptake efficiency.
†† $G_w/N_s$ = nitrogen utilization efficiency.
‡‡ n.c. = not calculated.

**Table 5. Previous cropping system effects on annual water use (avg. of 1989–1993).**

| Cropping system† | Precip.‡ | $W_s$§ | Subsurface drainage | ET¶ | ET/$W_s$# |
|---|---|---|---|---|---|
| | cm | | | | cm cm$^{-1}$ |
| | 71.5 | | | | |
| C-C | | 161.5 | 15.4 | 53.1 | 0.33 |
| C-S | | 160.9 | 18.1 | 52.3 | 0.33 |
| S-C | | 160.6 | 18.0 | 53.1 | 0.32 |
| ALF | | 144.9 | 8.3 | 59.1 | 0.41 |
| CRP | | 149.8 | 12.8 | 55.2 | 0.37 |

† C = corn; S = soybean; ALF = alfalfa; CRP = Conservation Reserve Program. Values are for underlined crop.
‡ Precip. = hydrologic year precipitation (October–September).
§ $W_s$ = water supply.
¶ ET = evapotranspiration.
# ET/$W_s$ = water uptake efficiency.

tive use, resulting in lower quantities of water that contribute to saturated flow. In this case, annual $W_s$ <143 cm resulted in no drain flow, whereas overall, each cm greater than 143 increased subsurface drainage by 0.85 cm (Fig. 1).

Conversion of CRP and alfalfa to row crops increased $W_s$ and consequently, subsurface drainage (Fig. 1). Drainage was not significantly different among cropping systems in 1994 and 1995, but treatments formerly in alfalfa averaged 20% less drain flow than continuous annual cropping throughout the study period (Table 3). These data show that cropping systems can readily impact drain flows and confirm that perennial crops are able to reduce quantities of gravitational water that would otherwise be lost via subsurface drains under annual row cropping. These data are also an example of cropping system feedbacks that occur when $W_s$ and crop water use are not well matched. The C-C and C-S rotations do not effectively use available water resources in this environment, leaving relatively high residual levels of soil water. Subsurface drainage becomes necessary to remove water so that management operations can proceed on a timely basis and grain yield can be optimized (Zhao et al., 2000). Employing crop rotations where water demand is more suitably matched to available water can reduce tile flows and potential adverse effects to surface waters. In this environment, a rotation of perennial and annual crops is likely necessary to achieve this goal.

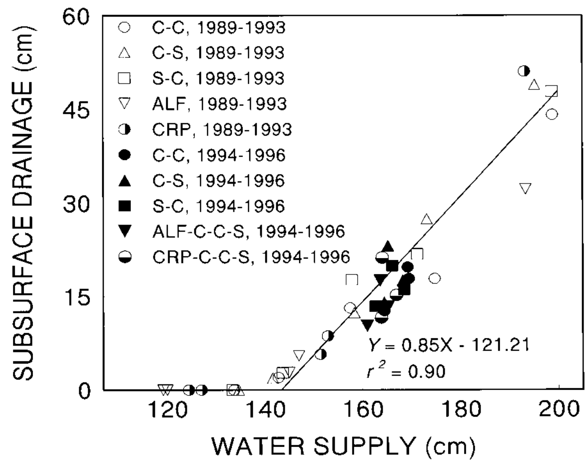


**Fig. 1. Relationship between water supply ($W_s$) and subsurface drainage ($W_{sd}$) for cropping systems in phase one (1989–1993) and after conversion of CRP and ALF in phase two (1994–1996).**

One consequence of the rotation effect is reported to be enhanced crop water uptake and utilization (Copeland et al., 1993), although causal mechanisms remain elusive. In 1994, WUE ($G_w/W_s$) was 10% greater in CRP-C-C-S, ALF-C-C-S, and S-C than in C-C (Table 3). Greater yields in CRP-C-C-S compared with C-C contributed to differences in WUE, but neither $W_s$ nor ET were significantly different in 1994, 1995, or 1996. Greater water uptake efficiency (ET/$W_s$) suggests that the crop had improved root function, but ET/$W_s$ was not significantly different among cropping systems in this study. Water utilization efficiency ($G_w$/ET) of corn tended to be different among the cropping systems in 1994 and significant differences occurred in 1995 (Table 3). These data suggest that rotation benefits arose from factors other than increased efficiency of water uptake. Pierce and Rice (1988) hypothesized that increases in WUE may lead to reduced leaching losses; however, gains in WUE achieved through greater $G_w$/ET rather than ET/$W_s$ are unlikely to affect water losses through subsurface tile lines.

**Table 6. Cropping system effects on residual fall soil water and $NO_3$–N (1994–1996).**

| Cropping system† | 1994 Depth, m | | 1995 Depth, m | | 1996 Depth, m | |
|---|---|---|---|---|---|---|
| | 0–1.5 | 1.5–3.0 | 0–1.5 | 1.5–3.0 | 0–1.5 | 1.5–3.0 |
| | Soil water, cm | | | | | |
| C-C | 42.0 | 54.4 | 43.1 | 51.3 | 38.4 | 50.6 |
| C-S | 40.9 | 51.4 | 42.0 | 51.1 | 39.2 | 49.2 |
| S-C | 42.3 | 50.9 | 43.1 | 50.3 | 40.1 | 49.8 |
| ALF-C-C-S‡ | 41.4 | 49.4 | 41.3 | 48.8 | 42.0 | 48.3 |
| CRP-C-C-S | 41.0 | 50.2 | 42.0 | 49.8 | 40.9 | 49.6 |
| LSD (0.05) | *4.2* | *4.4** | *4.7* | *3.2* | *2.2** | *1.9** |
| | Soil $NO_3$–N, kg ha$^{-1}$ | | | | | |
| C-C | 80 | 105 | 116 | 185 | 52 | 102 |
| C-S | 45 | 70 | 99 | 131 | 50 | 87 |
| S-C | 55 | 56 | 99 | 121 | 59 | 76 |
| ALF-C-C-S‡ | 27 | 14 | 87 | 95 | 54 | 36 |
| CRP-C-C-S | 54 | 10 | 133 | 98 | 69 | 50 |
| LSD (0.05) | *44** | *44** | *33** | *14** | *16** | *29** |

* Significant differences occurred among cropping systems according to Fischer's least significant difference (LSD) test (0.05 level of probability).
† C = corn; S = soybean; ALF = alfalfa; CRP = Conservation Reserve Program. Values are for underlined crop.
‡ C-C-S signifies corn in 1994, corn in 1995, and soybean in 1996.

## Residual Soil Nitrate, Nitrogen Use, and Losses through Tile Drainage

In the fall of 1993, after the conclusion of phase one, residual soil $NO_3$–N (RSN) (0- to 3-m profile) was markedly greater in C-C (168 kg N ha$^{-1}$) and C-S (119 kg N ha$^{-1}$) than in alfalfa (51 kg N ha$^{-1}$) and CRP (47 kg N ha$^{-1}$) (Randall et al., 1997). A greater proportion of the difference in RSN occurred in the 1.5- to 3.0-m profile, an indication of excess N leaching below the row-crop rooting depth. High levels of RSN are typically found with continuous corn rotations in southwestern Minnesota, even when soil test values and realistic yield goals are used to formulate optimal N rates and time of application (Nelson and MacGregor, 1973; Gast et al., 1974; Randall et al., 1997). On conversion of alfalfa and CRP to corn, RSN began to increase in the upper portion of the soil profile (Table 6, Fig. 2). The increase in RSN was particularly evident with CRP-C-C-S, where by 1996, $NO_3$–N had risen to levels greater than C-C in the 0- to 1.5-m profile (Table 6). Increases in RSN following conversion of alfalfa were less rapid but by 1996 no significant differences in RSN (0- to 1.5-m) occurred between ALF-C-C-S and other cropping sequences.

Residual effects of alfalfa and CRP on RSN below the root zone of row crops (1.5- to 3.0-m) persisted throughout the 3 yr (Table 6, Fig. 2). Here, accumulation of RSN in the 1.5- to 3.0-m profile of ALF-C-C-S and CRP-C-C-S occurred more slowly than in the upper profile and RSN remained relatively low, particularly with ALF-C-C-S compared with C-C and C-S. In 1996, RSN below the root zone was lower than in 1995, likely due to a shift from corn to unfertilized soybean. Under the environmental conditions of the study, >3 yr was required for row crops to negate perennial system depletion of deep RSN.

Nitrogen supply ranged from a low of 137 kg N ha$^{-1}$ for ALF-C to 211 kg N ha$^{-1}$ for C-C in 1994, but no significant differences were detected among cropping systems (Table 4). In 1995, $N_s$ for the second year of corn in ALF-C-C̲-S was 203 kg N ha$^{-1}$, significantly lower than the other cropping systems, which ranged up to 312 kg N ha$^{-1}$ for CRP-C-C̲-S. Adjustments in N fertilizer recommendations for corn following alfalfa (N credit) have been as large as 180 kg N ha$^{-1}$ (Kurtz et al., 1984). In southwest Minnesota, N credits for first-year harvested alfalfa range from 45 to 168 kg N ha$^{-1}$, depending on stand characteristics (Rehm et al., 1994). Nitrogen credits for the second year following alfalfa are 50% of first-year credits. Our estimates of net mineralized N ($N_m$) following alfalfa were consistent for 1994 and 1995, averaging just under 100 kg N ha$^{-1}$ (Table 4). Net $N_m$ contributed 69% of $N_s$ in 1994, when only 17 kg N ha$^{-1}$ was applied, and 48% of $N_s$ in 1995 when 77 kg N ha$^{-1}$ was applied (Table 1). These $N_m$ values were significantly greater than $N_m$ for C-C, which averaged $-5$ kg N ha$^{-1}$ for 1994 and 1995 (Table 4). The N credit is based on comparisons with C-C; therefore, the 2-yr $N_m$ total was close to expected values. But unexpectedly, the distribution was nearly equal during the 2 yr and indicates that N credits following alfalfa can be difficult to predict. This uncertainty often results in overapplications of N by farmers (Lory et al., 1995).

The adequacy of N for optimal yields depends not only on $N_s$ but also on N uptake efficiency. In 1994, calculated efficiency of N uptake was very high in ALF-C̲-C-S (78%) compared with C-C̲ (57%), whereas CRP-C̲-C-S (71%) and S-C̲ (68%) were intermediate in value but not significantly different than the other treatments (Table 4). Fertilizer N uptake efficiency usually ranges from 30 to 80% (Stanford, 1973; Hesterman et al., 1987; Jokela and Randall, 1989) and is reported to be greater than uptake efficiencies of N derived from residues of previous legumes (Hesterman et al., 1987). This occurs, in part, from the relatively low availability of first-year N from legume residues (10–48%) (Ladd et al., 1981, 1983; Hesterman et al., 1987) compared with

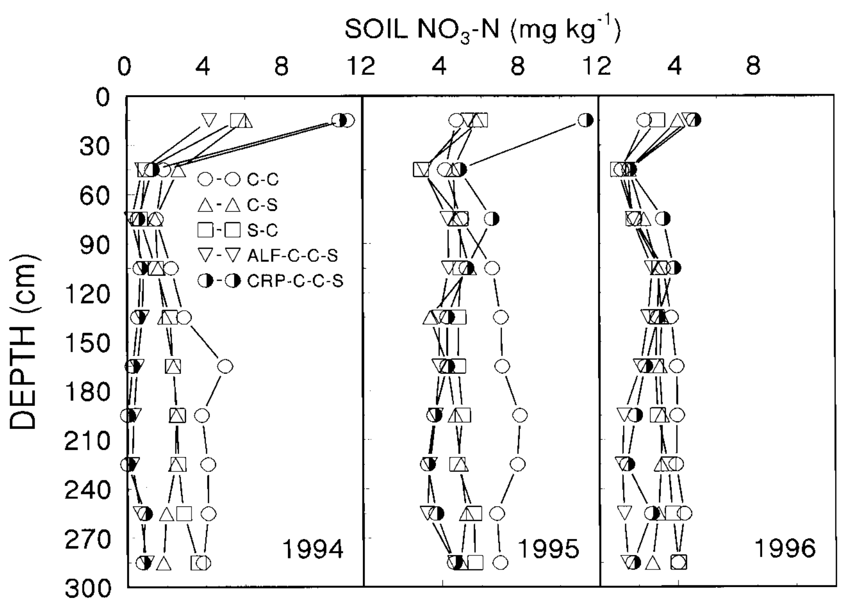


**Fig. 2. Cropping system effects on soil profile distribution of residual fall $NO_3$–N (0–3.0 m).**

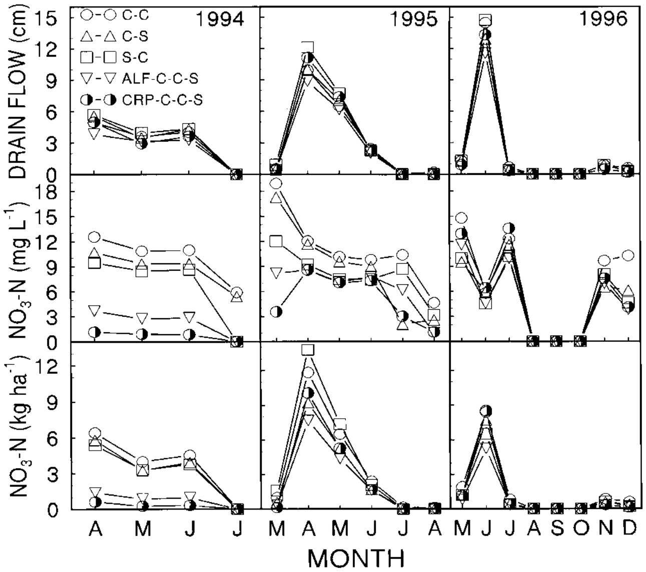


**Fig. 3. Cropping system effects on flow volumes, flow-weighted $NO_3$–N concentrations, and $NO_3$–N losses through subsurface drains. Data are reported for only those months when subsurface drainage occurred.**

fertilizer-derived N. The N uptake efficiencies of 78% achieved with ALF-C̲-C-S are contrary to this conclusion and demonstrate that under environments that favor N mineralization and subsequent N uptake, corn following alfalfa can approach upper N efficiency limits. Nitrogen uptake efficiency usually decreases with greater $N_s$ (Kurtz et al., 1984; Pierce and Rice, 1988; Huggins and Pan, 1993). Equal $N_s$ is difficult to achieve in studies with varying cropping system treatments and the lower N uptake efficiencies of C-C are in part due to the tendency of greater $N_s$ under C-C compared with ALF-C-C-S. Rotation effects on crop yields can be divided into two effects: one from legume N supply, and an additional effect observed when N is not limiting (Baldock et al., 1981). The high N uptake efficiencies found with ALF-C̲-C-S, CRP-C̲-C-S, and C̲-S in 1994 indicate that rotation effects increased efficiency of N use, regardless of whether or not $N_s$ was limiting. Corn N uptake efficiencies were markedly lower in 1995 than in 1994, averaging about 50% for S-C̲, CRP-C-C̲-S, and ALF-C-C̲-S and 44% for C-C̲ (Table 4). In ALF-C-C̲-S, low $N_s$ and N uptake efficiencies likely limited grain yield in 1995 as $N_s$ was significantly less than greater yielding CRP-C-C̲-S and S-C̲.

The ALF-C-C-S and CRP-C-C-S rotations had contrasting $N_s$, $N_m$, and NUE. In 1994 and 1995, a total of 326 kg N ha$^{-1}$ was applied to corn in CRP-C̲-C̲-S compared with 94 kg N ha$^{-1}$ in ALF-C̲-C̲-S. Net N immobilization (10 kg N ha$^{-1}$) following CRP (predominantly perennial grasses) contrasted with net mineralization (95 kg N ha$^{-1}$) following alfalfa in 1994. However, N uptake efficiency was high in both cases and grain N was 21% greater for first-year corn after CRP compared with alfalfa (Table 4). In 1995, $N_m$ was about 100 kg N ha$^{-1}$ for both sequences. The net mineralization during the second year of corn following CRP was 100 kg N ha$^{-1}$ greater than found under C-C̲ (8 kg N ha$^{-1}$), often considered an equivalent cropping sequence with respect to N fertility management of corn. The large mineralization of N following CRP is due to the buildup of labile forms of organic C and N that occur under CRP (Huggins et al., 1997). Rapid turnover of labile organic C and N pools likely occurred following conversion of CRP resulting in net N immobilization during the first growing season followed by net N mineralization during the second season. Because in-season N mineralization must be anticipated (N credit) and cannot be accounted for through spring soil testing, overapplication of fertilizer N occurred in second-year corn following CRP and resulted in 26% greater $N_s$ than under C-C. One consequence of N overfertilization was the rapid buildup of RSN under CRP-C-C-S (Fig. 2, Table 6). These data indicate that N fertilizer recommendations for second-year corn following CRP or perennial grasses need to be modified to consider available N contributions from delayed effects of N mineralization.

Greater N uptake efficiencies in 1994 with ALF-C̲-C-S compensated for low $N_s$, and grain and stover N were not significantly different than C-C̲ or S-C̲ (Table 4). In contrast, the relatively low N uptake efficiencies of 1995 contributed to low grain yields and N accumulation of ALF-C-C̲-S compared with CRP-C-C̲-S and S-C̲, despite 48% greater $N_s$ than in the previous year. The largest grain and stover N accumulations occurred in CRP-C̲-C̲-S in 1994 and 1995 as a result of high $N_s$ and N uptake efficiencies (Table 4).

Losses of $NO_3$–N through subsurface drains in 1994 were 4 to 5 times greater in C-S̲, S-C̲ and C-C̲ than in ALF-C̲-C-S, and 13 to 15 times greater than in CRP-C̲-C-S (Fig. 3, Table 4). In addition, concentrations of $NO_3$–N were <5 mg L$^{-1}$ in ALF-C̲-C-S and CRP-C̲-C-S compared with concentrations >9 mg L$^{-1}$ for most of the season under C-S̲, S-C̲, and C-C̲ (Fig. 3). High N uptake efficiencies of CRP-C̲-C-S and ALF-C̲-C-S combined with low RSN limited $NO_3$–N loss through drains (Table 4). By 1995, early season (March) losses and concentrations of $NO_3$–N in drain flows were still significantly lower in ALF-C-C̲-S and CRP-C-C̲-S (Fig. 3); however, total seasonal $NO_3$–N losses were only less for ALF-C-C̲-S compared with S-C̲. Nearly equivalent losses and concentrations of $NO_3$–N occurred in drains across cropping systems by 1996, although ALF-C-C-S̲ still had significantly lower losses than C-C (Fig. 3, Table 4). Thus, the benefits of CRP and alfalfa in reducing concentrations and losses of $NO_3$–N through subsurface drainage had essentially ceased following the second year of corn. This occurred as RSN in the root zone (0–1.5 m) rapidly increased following conversion to 2 yr of corn. Benefits likely remained, however, to improved ground water quality as quantities and concentrations of $NO_3$–N in the subroot zone (1.5–3.0 m) were still lower in ALF-C-C-S and CRP-C-C-S compared with C-S, S-C and C-C (Fig. 2, Table 6).

## Strategies for Optimizing Crop Rotation and Conservation Reserve Program Conversion for Water and Nitrogen Use Efficiency

Although our data are limited, they do indicate some potential rotation strategies for CRP–land conversion to row-crops. Corn yielded well after CRP; however, these yields benefitted from abnormally high precipitation in 1993 that recharged depleted soil water. If moisture deficits had persisted into the 1994 season, corn grain yields may have been reduced (as likely was the case with ALF-C-C-S). Soybean may be a better crop option than corn following CRP, because effects of water deficits and N immobilization (Table 4) can be comparatively reduced and positive rotation benefits on grain yield realized (Table 2). The buildup of RSN would also be slowed because no fertilizer N is applied to soybean and benefits to subsurface drainage water quality could be extended. Following soybean with corn in the subsequent year of CRP takeout could capture additional rotation benefits, including greater NUE and water utilization efficiency, compared with a second year of corn. In addition, a CRP-S-C sequence may position corn to be synchronized with the availability of large quantities of N mineralization from decomposing CRP grass residues (Table 4). If CRP benefits to water quality are to be extended by maintaining low RSN, N fertilizer strategies for corn must be developed to efficiently use this release of mineralized N from CRP. Lower RSN and reduced losses of $NO_3$–N to tile drainage are likely to be prolonged with CRP followed by a S-C rotation compared with an initial sequence of C-C that rapidly rebuilds RSN.

Although not evaluated, tillage practices are fundamental to the development of strategies for converting perennials to row crops. The use of conservation tillage to convert CRP and alfalfa to row crops would likely have slowed N mineralization rates and changed N use efficiency, buildup of RSN, and losses of water and $NO_3$–N to subsurface drains.

In conclusion, adding perennial grasses and legumes to cropping systems can have substantial effects on the water quality of artificial subsurface drainage by lowering flow volumes, and $NO_3$–N concentrations and losses. Devising crop sequences to convert perennials back to row crops may have an initial effect on delaying increases in RSN and reducing $NO_3$–N losses to subsurface drains. But despite these strategies, continued row-cropping that consists of corn and soybean sequences will soon develop high RSN, $W_s$, and drain flow volumes that combine to give high drain $NO_3$–N concentrations and losses. If $NO_3$–N losses to subsurface drainage are to be significantly reduced and maintained at low concentrations, improvements are needed in water and N use efficiency. Adjusting N fertilizer recommendations to include second-year credits for N mineralization following perennial grass conversion to row crops could improve N use efficiency and reduce losses. Currently, the only cropping sequences that achieve sufficient efficiencies in water and N use in the Upper Midwest include perennial crops in rotation with annual row crops.

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