Nitrate Leaching in Irrigated Corn and Soybean in a Semi-arid Climate

N. L. Klocke, D. G. Watts, J. P. Schneekloth, D. R. Davison, R. W. Todd, A. M. Parkhurst

Abstract. *Nitrate-nitrogen leached from the root zone of land in intensive corn production is a major groundwater contaminant in some of the intensively irrigated regions of the western Cornbelt, including central and western Nebraska. To obtain a clearer understanding of the amount and timing of nitrate leaching losses from irrigated crops, 14 monolithic percolation lysimeters were installed in 1989-1990 in sprinkler irrigated plots at the University of Nebraska's West Central Research and Extension Center near North Platte, Nebraska. The lysimeters were used to provide a direct measure of leachate depth from continuous corn and a corn-soybean rotation. Both cropping systems were sprinkler irrigated and used current best management practices (BMPs) in the region for water and nitrogen management. Leachate was collected from 1990 through 1998 and analyzed for nitrate-N concentration. Results for the period 1993-1998 are reported here. In the semi-arid climate of West-Central Nebraska, the interaction of rainfall patterns with the period of active uptake of water by crops played a major role in defining leaching patterns. Careful irrigation scheduling did not eliminate leaching during the growing season. There was no significant difference in drainage depth between continuous corn and the corn-soybean rotation. The average drainage depth among the lysimeters was 218 mm yr^{-1}. This was more than expected, and in part resulted from above normal precipitation during several years of the study. No water quality benefit was found for the corn-soybean rotation as compared to continuous corn. Nitrate-N concentration in the leachate from continuous corn averaged 24 mg L^{-1}, while that from the corn-soybean rotation averaged 42 mg L^{-1}. Total yearly nitrate leaching loss averaged 52 kg ha^{-1} for continuous corn and 91 kg ha^{-1} for the rotation. This represents the equivalent of 27% and 105% of the amount of N fertilizer applied over the six years of study. In calculating N fertilizer needs for corn in Nebraska, the recommended legume N credit of 50 kg ha^{-1} for a preceding crop of soybean may be too low under irrigated production.*

Keywords. *Chemical transport, Leaching, Irrigation water management, Crop rotation, Nitrogen management, Lysimeter.*

Contamination of aquifers by nitrate-N is a growing problem in irrigated regions of the Midwest, particularly in the western Cornbelt. In Nebraska, where over 95% of the population uses groundwater as the primary source of potable water, concentrations of nitrate-N in some areas of shallow groundwater are already well above the EPA's maximum contaminant level (MCL) of 10 mg L–1 for public water supplies. Some municipalities have developed deeper sources of groundwater, only to find increasing nitrate levels in their new water supplies. Nitrate leached from the root zone of Nebraska's two million hectares of irrigated corn has been identified as the principal source of the nitrate contamination problem in the state. Leachate sampling in irrigated corn fields has shown nitrate-N concentrations of 30 to 60 mg L–1 in soil water at or below the bottom of the root zone (Hergert, 1986; Klocke et al., 1993; Watts et al., 1997). High nitrate concentrations in root zone drainage are of major concern in areas of extensive irrigation development, where much of the recharge to groundwater percolates through irrigated crop land. In such case, nitrate levels in the aquifer are very likely to increase to the MCL, or greater.

To reduce nitrate losses to groundwater, best management practices (BMPs) for nitrogen fertilizer and irrigation water are being promoted. However, it is not clear whether implementation of presently designated BMPs will be sufficient to maintain nitrate-N levels in groundwater at or below the MCL. A possible alternative is to switch from continuous corn to a corn-soybean rotation, where less N fertilizer is applied. Analyses of drainage water from lysimeters and subsurface drains in the sub-humid central and eastern Cornbelt indicate that the production of continuous corn under rainfed conditions usually results in greater leaching loss of nitrate-N than occurs under a corn-soybean rotation. However, losses are quite variable from year to year from a given field, and also vary greatly from location to location.

Randall et al. (1997) reported average flow-weighted nitrate-N concentrations of 32 and 24 mg L^{-1} for continuous corn and a corn-soybean rotation in a six-year

Article was submitted for publication in December 1998; reviewed and approved for publication by the Soil & Water Division of ASAE in August 1999.

Published as Paper No. 12462 Journal Series, Nebraska Agricultural Experiment Station.

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study of drain outflow in southwestern Minnesota. However, total N leaching loss was essentially equal, averaging 54.5 and 50.8 kg ha^{-1}, respectively, for the two cropping systems during the four wet years in which significant drainage occurred. Kanwar et al. (1997) found N leaching losses and nitrate-N concentration in drainage waters were greater for continuous corn as compared to either corn or soybean in rotation. Losses and concentrations also varied with tillage systems. Under ridge-till, N loss from continuous corn averaged 55 kg ha^{-1} over three years, while under the rotation the average was only 25 kg ha^{-1}. Flow-weighted nitrate-N concentrations in drainage water averaged 25 mg L^{-1} and 16.5 mg L^{-1} for the two cropping systems. Logan et al. (1994) found that the concentration of nitrate-N in drainage from soybean in a corn-soybean rotation was as great as from corn in the rotation, in a study on poorly drained, fine textured soil in Northwestern Ohio. However, much of the N loss during soybean production was attributed to the leaching of residual nitrate-N from corn production the previous year. Owens et al. (1995) measured nitrate leaching over six years in a corn-soybean rotation planted in monolithic lysimeters containing two different silt loam soils at Coshocton, Ohio. Annual leaching losses were different for the two soils, averaging 38 and 25 kg N ha^{-1} for corn and soybean, respectively, on one soil, and 51 and 43 kg N ha^{-1} on the other. Randall and Iragavarapu (1995) in a study on a poorly drained, fine textured soil in South Central Minnesota found nitrate-N concentrations in drain outflow averaged 13.4 mg L^{-1} over 11 years of measurement under continuous corn with conventional tillage. Leaching loss of nitrate-N averaged 43 kg ha^{-1}, ranging from 139 kg ha^{-1} in a wet year to only 2.5 kg ha^{-1} during a very dry year.

Most corn is irrigated In the semi-arid western Cornbelt. In comparison to more humid areas, the absence of subsurface drainage systems and a typically greater depth to the water table make it much more difficult and costly to obtain information on N leaching loss. Smika et al. (1977) measured N loss during the growing season in three fields of center pivot irrigated corn on fine sandy loam soils in northeastern Colorado. They used 3.2-m-long ceramic vacuum extractors placed horizontally in metal troughs below the root zone, to make continuous collections of unsaturated drainage flow. Average losses over three years ranged from 19 to 60 kg ha^{-1}, depending on water and nitrogen management. Katupitiya et al. (1997) reported results of continuous core sampling from the bottom of the root zone to a depth of 18 m in the zone of aeration beneath cropping systems of continuous corn and corn-soybean rotation in South central Nebraska. The systems had been in furrow-irrigated production for 18 years. Under a conventional disk-plant tillage system, the average annual N loss was approximately 75 kg ha^{-1} for continuous corn, and only slightly less under the rotation.

Both the timing and amount of rainfall and the scheduling and amounts of irrigation affect leaching in the western Cornbelt. Winter and spring precipitation is extremely variable. Many years there may be little or no leaching during the spring, so that residual nitrate is retained in the root zone for subsequent crop use. Occasionally, however, spring rains are excessive, resulting in leaching of residual nitrate and early applied N fertilizer (Klocke et al., 1993, 1996). During the growing season, soil water deficits are often smaller than in rainfed production regions, seldom exceeding 40 to 50% of plant available water and are often less. Rain immediately following an irrigation will usually accelerate nitrate leaching.

Irrigation method is also important in determining leaching amounts. Ritter and Manger (1985) concluded that improved irrigation efficiency can reduce drainage volume and thereby reduce the mass of nitrate-N leached during the growing season. Irrigation depths are typically much greater and irrigation efficiencies much lower under furrow irrigation than under modern sprinkler systems. Accordingly, nitrate leaching losses during the growing season should be less under sprinkler irrigation. Off-season losses will depend on the amount of residual nitrate (a function of N management) and precipitation. Since sprinkler irrigation is the most efficient irrigation system that is widely used in the western Cornbelt, N losses from well managed sprinkler irrigated corn should provide a baseline for evaluating the degree to which water and N loss under conventional or surge flow furrow irrigation systems may be excessive.

The purpose of our research was to gain a better understanding of the timing and level of N loss from sprinkler irrigated production of both monoculture corn and a corn-soybean rotation, using currently accepted BMPs for N and water management in the western Cornbelt. The objectives were to (1) compare the amount of N lost through leaching from continuous corn, with that from a corn-soybean rotation; (2) evaluate the potential reduction of nitrate leaching to groundwater by changing from continuous corn to a corn-soybean rotation; and (3) define a minimum level of N loss to be expected from the two irrigated production systems.

Methods and Materials

Site Conditions

Research to assess water and nitrate-N leaching loss in percolation lysimeters was initiated during 1989 at the West Central Research Center of the University of Nebraska near North Platte, Nebraska. The lysimeters were installed in the *fully irrigated* treatments of a study initiated in 1981 to evaluate crop response to both full and limited irrigation (Hergert et al., 1993). The soil at the site is mapped as a Cozad silt loam (*Fluventic Haplustoll*). However, the surface texture within the plots is predominately loam. The soil is on the edge of the Platte River Valley and has genetic influences from both alluvium and loess derived colluvial parent material. A typical profile in the research plots is shown in figure 1. The water table is at a depth of approximately 5.0 m. The surface slope varies from 0 to 1%. Average values for organic matter through the profile are: 0 to 0.15 m, 1.47%; 0.15 to 0.30 m, 0.82%; 0.3 to 1.80 m, 0.54%; and 1.80 to 2.40 m, 1.03%. The latter represents an old buried profile. Soil pH averages 7.3 in the upper 0.15 m, 7.8 from 0.15 to 0.30 m, and varies between 8.0 and 8.2 to the bottom of the lysimeters at 2.4 m.

The average plant available water holding capacity of the soil is 0.17 m^3 m^{-3} in the 1.2-m irrigated root zone. Field capacity water content averages 0.29 m^3 m^{-3} through the root zone and changes very little with depth. The lower

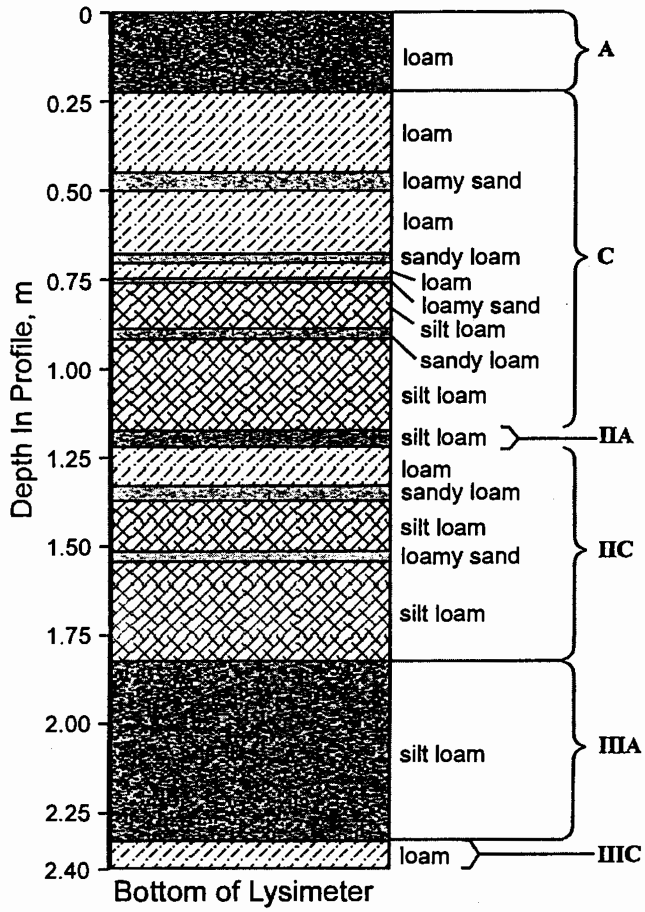


Figure 1–Typical soil profile in the research plots where the lysimeters are located.

limit of available water is approximately 0.11 m^3 m^{-3}. Field capacity was measured to a depth of 1.5 m with a neutron probe following drainage from an excessive rainfall event in the spring. Below this depth, field capacity was determined in the same way when drainage became very slow later in the growing season. The lower limit of plant available water was estimated from neutron probe measurements in non-irrigated plots of the experiment, when the plants approached permanent wilting. Further details of soil physical characteristics are given by Klocke et al. (1993).

Lysimeter Characteristics and Operation

Leaching was directly measured in two fully irrigated cropping systems: continuous corn and a corn-soybean rotation. The measurements were made using 14 monolithic percolation lysimeters. The lysimeter casings were epoxy-coated steel tubing, 0.9 m inside diameter and 2.4 m deep. They were filled with undisturbed soil using a hydraulic pull-down method (Schneider et al., 1988). Details of design and installation were reported in Klocke et al. (1993). In brief, after filling, each lysimeter was dug out and an extractor assembly and sealed collection pan were installed on the bottom. The lysimeter was then moved to its permanent plot location where it was installed inside a slightly larger outside containment cylinder. Vacuum lines were connected; insulation material was placed between the lysimeter tube and the containment cylinder; and a rain-cap was installed to provide a top seal between the lysimeter and the containment cylinder. The rain cap extended about 12 cm above the soil surface, preventing any water from running onto or off the lysimeter. The only water entering the lysimeter column was that which fell as rainfall or was applied by sprinkler irrigation.

Six lysimeters for production of fully irrigated, continuous corn were installed in contiguous, 24 m × 24 m plots prior to the 1990 growing season. The monoliths were obtained just outside of the plots, where the soil had been in corn for the previous four years. An additional eight lysimeters were placed in the corn-soybean rotation before the 1991 season. The monoliths were taken from border areas that had been in the same rotation during the four previous years. The rotation lysimeters were placed in the fully irrigated plots that were part of an on-going corn-soybean rotation experiment under different levels of irrigation. The plots containing the continuous corn lysimeters were adjacent to the plots of the rotation experiment, but were not randomized within the rotation.

At planting time, all lysimeters in corn were initially seeded to obtain a high plant density. Then while the plants were quite small, the stand was thinned to leave the four most vigorous plants. This was a population equivalent to 62,850 plants ha^{-1}. Soybean was seeded to obtain 32 plants per lysimeter, equivalent to 503,000 plants ha^{-1}.

After operation began, we had a series of difficulties with one lysimeter in the continuous corn study and two in the rotation. We elected to omit the data from those units from the study. Accordingly, the six-year analysis reported here includes data from five lysimeters in continuous corn and six in the rotation, with three of the latter being in corn and three in soybean in any given year.

To assure adequate drainage, 12 porous stainless steel extractors were installed vertically upward into the bottom of each lysimeter. A continuous vacuum of 34 kPa was applied to the extractors to remove leachate from the soil. Soil water was monitored weekly with neutron attenuation in both the center of the lysimeter and in the soil of the adjacent plot. When soil in the lower 0.3 m depth of a lysimeter was drier or matched the water content of the soil at the same depth outside the lysimeter, the vacuum was discontinued. This usually occurred when soil water content was 20 to 25% on a volumetric basis. Vacuum was reapplied when the bottom layer of soil in the lysimeter became wetter than adjacent soil. This procedure was used to avoid over-drying the soil around the extractors to the extent that a hydraulic discontinuity developed between the soil and extractors.

Neutron attenuation data indicated that in spite of the vacuum drainage system, the lysimeter bottom tended to create an artificial lower boundary for water flow. However, the soil water content in the lysimeters matched that in the surrounding plots from the surface to a depth of 2.1 m. While the bottom 0.3 m of soil in the lysimeters was often wetter than the surrounding plot until late in the growing season, the extractors maintained unsaturated flow in this zone throughout the study.

The drainage water was collected weekly from each lysimeter. The reservoir on the bottom of a lysimeter was large enough to retain more than seven days of drainage. However, to avoid any possible loss of percolate, a secondary catch container was in place in the system. After collection, two samples from each lysimeter were retained for analysis. One sample was refrigerated to hold for a few days for analysis for nitrate-N; the other was frozen as a backup. Samples were analyzed on a Lachat auto-analyzer.

Irrigation Management

Irrigations were scheduled using currently recommended best management practices. Soil water was measured weekly to a depth of 3 m in each plot and 2.4 m in each lysimeter. Irrigation amounts were determined from soil water deficits in the top 2 m of the soil, and projected evapotranspiration (ET) needs of the crop. ET projections were based on historical averages estimated using a modified Penman equation and stage of crop growth. Irrigations were begun when neutron measurements showed that available soil water content was 50% depleted in the root zone or when ET projections indicated that 50% depletion would be reached within the next two days. Near the end of the growing season, allowable depletion was increased to 60%. A minimum soil water deficit (rainfall allowance) of 25 mm was maintained to store possible rainfall. The plots were irrigated at a minimum interval of three days with a solid-set sprinkler irrigation system, with sprinklers set on a 12.2-m × 12.2-m spacing. The application amount was generally 25 mm/irrigation, although amounts were adjusted occasionally. The interval was extended if irrigation was not needed. This procedure simulated the typical operating practices for center-pivot irrigation in the area. Irrigation was applied at a rate of 10 mm h^{-1} in both cropping systems. All lysimeters within a given cropping treatment were irrigated at the same time.

Nitrogen Management

Nitrogen fertilizer amounts for corn were estimated using the University of Nebraska recommended procedure (Hergert et al., 1995). N amounts were based on estimated yield potential and preplant soil tests for residual nitrate. Yield potential was estimated as 105% of the average production for the previous five years. Nine years of site yield data were available (Hergert et al., 1993). Years with severe damage from hail or corn rootworm were omitted from the average. Residual nitrate-N in the soil was determined by sampling plots just outside the lysimeters to a depth of 1.2 m each spring before planting. Nitrogen application rates for the estimated yield potential were computed using an algorithm that included potential yield, soil organic matter, residual nitrate-N in the upper 1.2 m of the soil, and, for the corn in rotation, a 50 kg ha^{-1} legume credit for N supplied by the previous year's soybean crop. In 1998, the legume credit was increased to 90 kg ha^{-1}. Nitrogen fertilizer was broadcast as ammonium nitrate (34-0-0) at the four to six leaf stage.

Period of Study

Data were collected from 1990 through 1998 from the continuous corn lysimeters, and 1991 through 1998 from the lysimeters in rotation. Soil samples taken from lysimeters when neutron access tubes were installed indicated that initial residual nitrate amounts were higher in some of the lysimeters than in the field. This was the result of a different irrigation and fertilizer regime in the border areas from which the monoliths were taken. To avoid biasing results, we are presenting data on N loss and nitrate concentration for the six-year period of 1993-1998, after the high initial nitrate residuals had moved through the lysimeter. Since drainage amounts were not affected by this problem, rainfall, irrigation and drainage data from 1991 and 1992 are included in parts of the analysis.

Statistical Analysis

The design was a strip-plot with year as a repeated measure. A mixed model analysis was used to test for statistically significant differences among the sets of lysimeters, with respect to drainage amounts, nitrate-N leaching loss, and nitrate concentration in the drainage water. The compound symmetric covariance structure was used to make the final inference. The model-fit criteria computed in SAS (1996) by PROC MIXED, Akaike's Information Criteria (AIC) and Schwarz' Bayesian Criteria (SBC) were used to decide the most desirable covariance structure.

Results and Discussion

Precipitation Patterns

The precipitation history during the project shows that only one year of the study, 1995, had precipitation below the 80-year average of 493 mm (table 1). Three years averaged 10% above normal, while two years were 39% and 47% above normal. A sequence of 2 to 3 months of above normal precipitation usually contributed to the above normal years, although in 1996 there were 5 consecutive above normal months. Above normal precipitation during fall and winter influenced leaching the following year, as soil water extraction by the crops ended during September. Fall rain was important in recharging upper profile soil water. Significant soil water extraction by the crop usually did not start until late May for corn and mid June for soybean. Crop ET lagged spring rainfall in several years, resulting in significant early season water and nitrate losses.

Irrigation

Irrigation was withheld from soybean late in the growing season to cause the plants to dry for harvest. As a result, corn in rotation with soybeans usually began the season with less available soil water as compared with continuous corn. In four of six years, more irrigation was applied to the rotation corn than to either continuous corn or soybean. The monthly irrigation amounts over the six years of study are summarized in table 2. The average

Table 1. Precipitation (mm) at North Platte, Nebraska, 1993-1998

Year	Jan-Mar	Apr	May	Jun	Jul	Aug	Sep	Oct-Dec	Total
1991	20	81*	122	107	33	10	53	97	523
1992	150	5	61	76	109	165	3	41	610
1993	63	38	63	167	104	141	31	77	684
1994	30	46	58	98	129	36	17	119	533
1995	49	88	124	65	50	18	69	14	477
1996	19	20	119	100	185	73	181	26	723
1997	17	42	43	88	122	91	36	84	523
1998	49	17	51	144	89	61	49	98	558
80 Yr. Avg.	46	56	84	86	69	56	43	53	493

* Underlined values are above normal.

Table 2. Irrigation amounts and reference crop ET (mm), 1993-1998

Year	Crop Rotation*	Jun	Jul	Aug	Sep	Total	Ref Crop ET†
1993	CC & C̲S	–	–	50	–	50	734
	CS̲	–	–	–	–	0	
1994	CC	25	25	76	25	151	922
	C̲S	25	25	100	25	175	
	CS̲	–	–	–	–	0	
1995	CC	–	127	229	25	381	880
	C̲S	–	178	229	25	431	
	CS̲	–	127	127	25	279	
1996	CC	–	90	–	25	115	695
	C̲S	–	90	–	25	115	
	CS̲	–	30	–	25	55	
1997	CC	–	109	25	–	134	814
	C̲S	–	109	76	–	185	
	CS̲	–	51	76	–	127	
1998	CC	–	127	52.0	–	179	895
	C̲S	–	127	101	0	228	
	CS	–	51	156	0	207	

6-Year Average

* CC = Continuous corn — CC = 168

C̲S = Corn in rotation — C̲S = 197

CS̲ = Soybean in rotation — CS̲ = 111

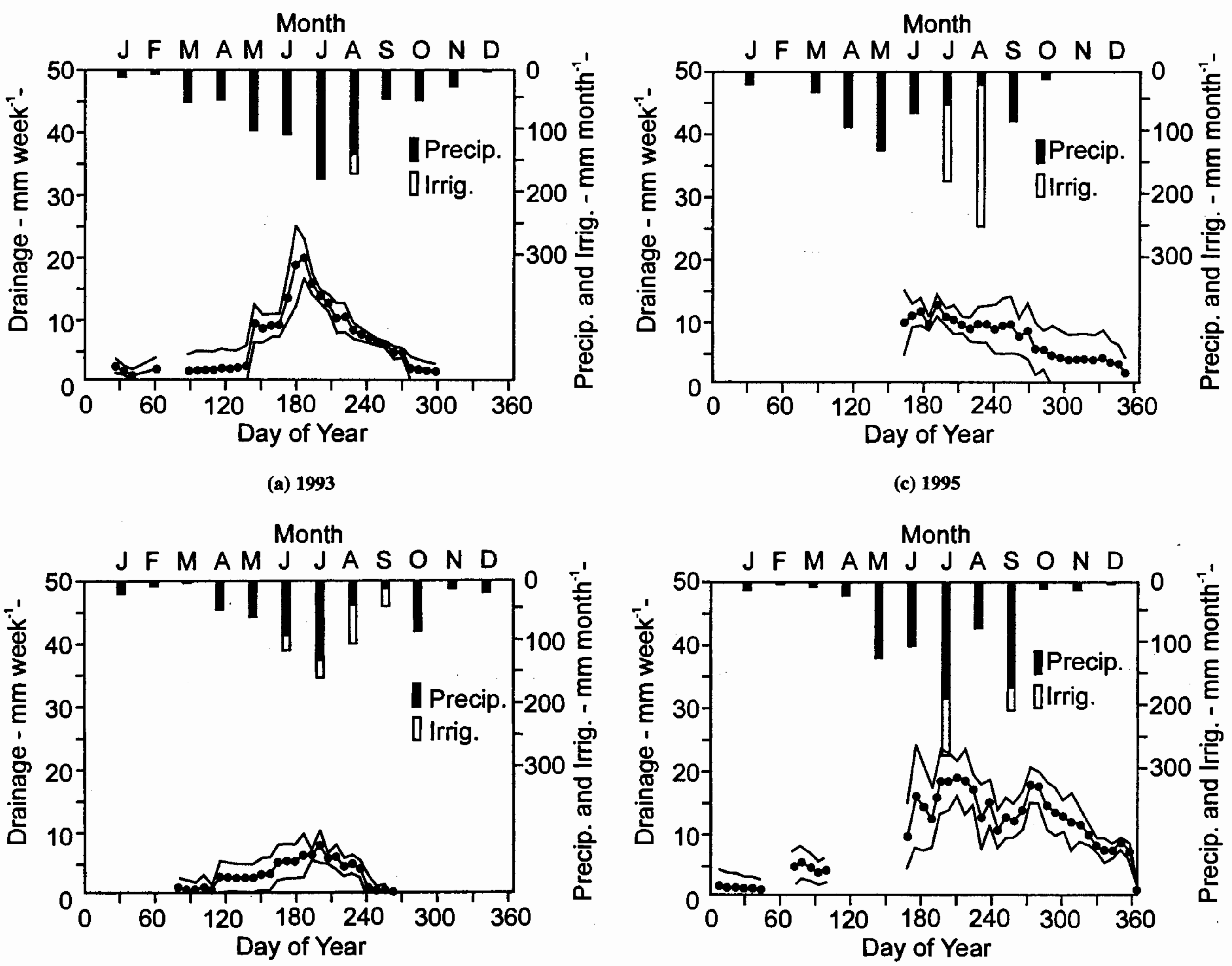
† Alfalfa reference crop ET (15/5-30/9), from modified Penman equation.

yearly applications were 168 mm for continuous corn, 197 mm for corn in rotation, and 111 mm for soybean in rotation. These values are substantially lower than the mean gross irrigation requirement of 419 mm for a sandy soil at this location, estimated for the 26-year period of 1952-1978 (Martin et al., 1989). Irrigation requirements were notably variable from year to year, and in general were low because of above average rainfall. Only 1995 had irrigation requirements that were more typical for the area.

Growing season estimates of evapotranspiration for an alfalfa reference crop (ET_R) are also included in table 2. The calculations were made by the University of Nebraska's High Plains Climate Center, using data from the automated weather station at the site and a modified Penman equation to estimate reference ET. These values indicate a substantial variability in evaporative demand from one year to another, with the largest being 28% greater than the smallest.

Root Zone Drainage

The pattern of weekly root zone drainage was also quite different from one year to another. This is illustrated in figures 2 (a to d), which show four years of average weekly



(a) 1993

(c) 1995

(b) 1994

(d) 1996

Figure 2–Average weekly drainage amounts and monthly precipitation and irrigation for lysimeters in continuous corn. The thin lines on the drainage curves represent the 95% confidence bands.

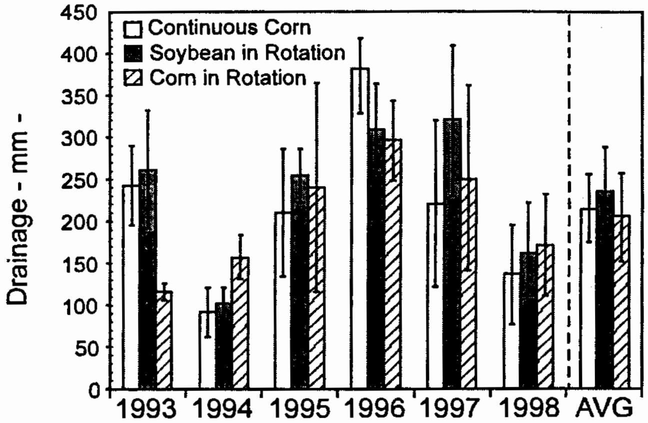


Figure 3–Average yearly drainage from five continuous corn lysimeters, and three corn and three soybean lysimeters in rotation. The error bars represent ± one standard deviation.

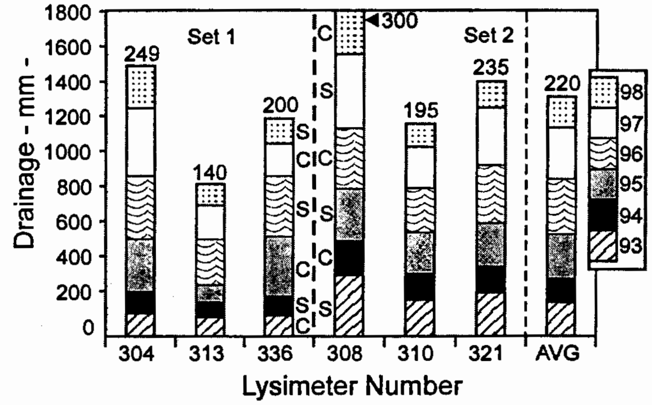


Figure 5–Annual and cumulative drainage from six lysimeters in a corn-soybean rotation, 1993-1998. Values above the bars represent the six-year average. The symbols C and S indicate which crop was planted in the indicated set of three lysimeters in any given year.

drainage for continuous corn. In 1993, most drainage was due to excess rainfall (fig. 2a). Only 50 mm of irrigation were applied (in August). The irrigation was immediately followed by additional rainfall. Timely rains during the 1994 growing season closely matched ET demand, and resulted in smallest amount of drainage, 92 mm, during the years of measurement (fig. 2b). In contrast, the highest rainfall year (1996), had the greatest amount of drainage, 381 mm (fig. 2d). Drainage was essentially zero during some periods such as early and late in 1994 (fig. 2b), the first half of 1995 (fig. 2c), and the spring of 1996 (fig. 2b).

The yearly and six-year average drainage amounts for continuous corn and each crop in the corn-soybean rotation are shown in figure 3. Since the principal concern is the long term trend, we focused the analysis on the six-year averages. Differences in the six year average drainage for soybean and corn in rotation were not statistically significant ($p = 0.373$). Neither was there any significant difference between drainage from the rotation and continuous corn ($p = 0.843$). The six year combined average for the two cropping systems was 218 mm yr^{-1}.

Drainage over the period of study averaged 29% of precipitation plus irrigation for continuous corn, 26% for corn following soybean and 34% for soybean following corn. For both cropping systems, an average of about 57%

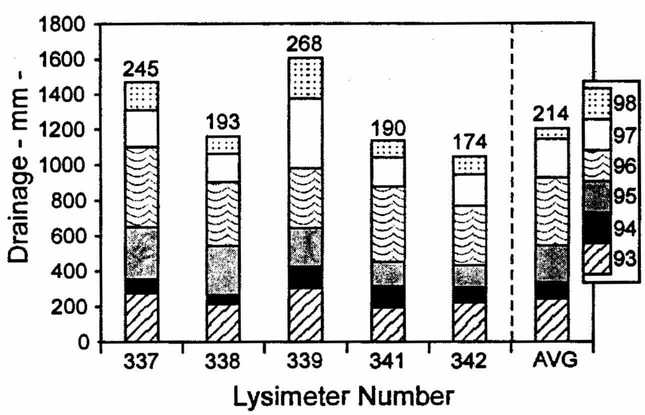


Figure 4–Annual and cumulative drainage from five lysimeters in continuous corn, 1993-1998. Values above the bars represent the six-year average.

of yearly drainage occurred during the three month period of 15 June to 15 September.

The annual and six-year cumulative drainage depths for each lysimeter in the continuous corn and rotation systems are shown in figures 4 and 5. The coefficient of variation (C_v) among continuous-corn lysimeters for yearly drainage amounts ranged from 14% in 1996 to 45% in 1997. However, the C_v for six-year total drainage in continuous corn was only 19%. The corresponding C_v among all rotation lysimeters for six-year total drainage was 23%.

Time Lag Between Inputs of Excess Water and Drainage

An analysis was made to determine the time lag between inputs of water and drainage outflow. Time series analysis, specifically autocorrelations and cross-correlations, were used to examine the relationships between drainage and total precipitation and irrigation inputs to the lysimeters in continuous corn. Bartlett's (1946) test based on approximate standard errors and assumptions of normality was used to detect significance of cross-correlations for specified lags at the 5% level. Autocorrelations, cross-correlations and lags were estimated from correlograms using the crosscorr option in *Proc Arima* (SAS, 1993) as well as the time series module in *STATISTICA* (1995). Both *SAS* and *STATISTICA* gave identical results.

The years 1991, 1993, and 1994 were chosen for this analysis due to the continuous operation of the extractors and more clearly defined peak outflows. Cumulative totals for one to eight weeks were analyzed. The stability magnitude and lag of cross-correlations were examined. The correlograms from the analysis were similar for the individual lysimeters, so the measurements were averaged over all continuous corn lysimeters. The magnitude of the correlations held steady after three weeks of accumulation, suggesting a maximum lag of three weeks between an input of excess water and the resulting drainage. Marked increase in outflow is correlated with increase in precipitation. Results suggest more precipitation leads to stronger correlations with outflow and little to no lag. There was above normal precipitation in April, May and early June 1991, when crop ET was low. This resulted in correlations of 0.70 and lags of either zero or one. This suggests a very rapid drainage response when the entire soil profile is at or above field capacity. Lower correlations and larger lags were found in 1993 and 1994. In those years the periods of above average precipitation occurred after crop ET was high enough that the plants could take up more of the free water moving through the root zone. Under this condition, a smaller part of a pulse of water entering the soil surface would appear as drainage.

Drainage Amount Required to Move Solute Through the Lysimeter

In the lysimeters, drainage water is extracted at the bottom of a 2.4-m soil column, about 1.5 m below the bottom of the root zone. It was necessary to have some measure of solute transit time through the lysimeter to better associate measured N loss with events or processes on the soil surface or in the root zone. In mid May of 1992, a chloride tracer, KCl, was applied at a rate of 167 kg ha^{-1} to the surface of four lysimeters planted to corn, including two in continuous corn and two in the rotation (Aziz, 1996). Drainage water samples were analyzed for chloride at the time of application and again later in the year, to establish a background chloride concentration. All samples of drainage water from the treated lysimeters were analyzed for chloride beginning in late 1992 and continuing through 1994.

A typical curve of chloride concentration in drainage water is shown in figure 6 as a function of accumulated drainage since chloride application. Arrival of the chloride pulse is easily separated from background concentration. Results from the four lysimeters are presented in figure 7 as double mass curves of chloride leached vs drainage outflow since chloride application. The accumulation was begun for each lysimeter when the chloride concentration began to deviate from the background concentration. All lysimeters responded in a similar manner with 500 to 550 mm of drainage being required to move the surface application out of the lysimeter. This included 180 to 210 mm to transport the leading edge of the pulse to the bottom of the lysimeter, and 300 to 350 mm of additional drainage to return the concentration to near background level.

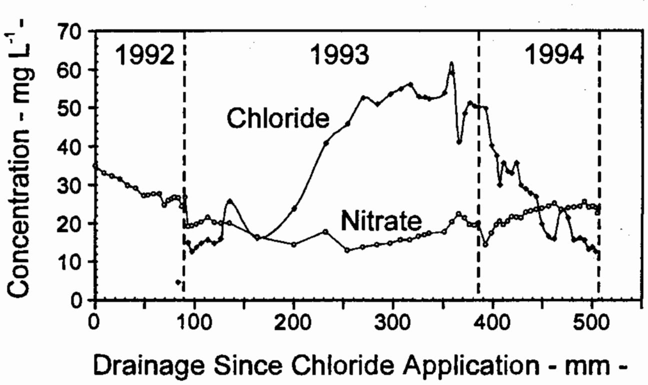


Figure 6–Chloride and nitrate-N concentration in drainage from a continuous corn lysimeter (lys. 339), following chloride tracer application on 15 May 1992.

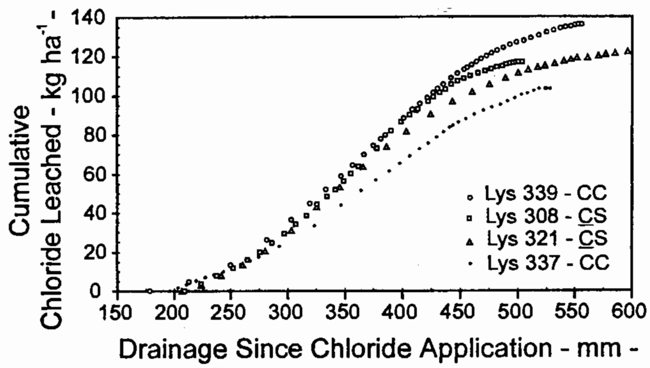


Figure 7–Cumulative chloride leached from four lysimeters since the beginning of breakthrough above background levels. Two lysimeters were in continuous corn (CC) and two were in corn in the rotation (CS) when the chloride tracer was applied.

Determining When N Loss Occurred from the Root Zone

It is difficult to determine exactly when nitrate leaching loss occurred at the bottom of the root zone. Actual rooting depth is not precisely known, but is generally found to be about 1 m in irrigated crops in the region. Assuming this to be the case, any solute leaving the bottom of the root zone must pass through an additional 1.4 m of soil before moving out of the lysimeter. The chloride tracer data show that transit time for solute movement from the soil surface to the bottom of the lysimeter may exceed one cropping season. Depending on the amount of drainage during a year, nitrate loss measured at the 2.4-m depth may have passed the 1-m depth during the same year, the prior year, or even earlier. This makes it difficult to assign the measured N loss to a given point in time or to one crop or the other in the rotation. Accordingly, the average for the rotation is used in most of the analysis which follows. The exception is where a "pulse" of nitrate moved through the soil profile. In those cases we used the tracer results to estimate transit times and to try to identify the crop source of the pulse. This is discussed later.

N Leaching Loss and Concentration in Root Zone Drainage

The average yearly leaching loss of nitrate-N was significantly greater ($P < 0.01$) from the corn-soybean rotation than from continuous corn (fig. 8). The flow-weighted nitrate-N concentration in drainage water was significantly greater for the rotation ($P < 0.01$) (fig. 9). Leaching loss under continuous corn averaged 52 kg N ha^{-1}. The mean flow-weighted concentration of nitrate-N in the drainage water was 24 mg L^{-1} over six years. During the same period, the average N loss and concentration values for the rotation were 91 kg ha^{-1} and 42 mg L^{-1}, respectively.

Yearly and cumulative N losses from individual lysimeters in the two management systems are documented in figures 10 and 11. As with the drainage losses, the C_v among lysimeters in a management system could be high in any year. However, for the six-year totals, the C_v among the continuous corn lysimeters was 18% and 11% among the rotation lysimeters.

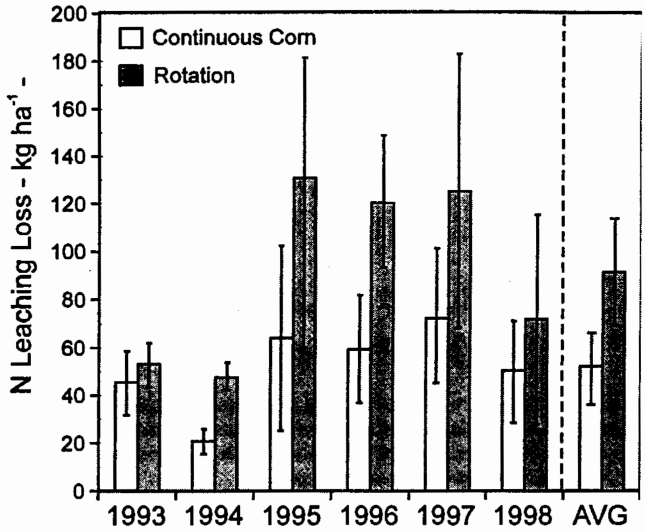


Figure 8–Average yearly nitrate-N leaching loss from five continuous corn lysimeters and six lysimeters in a corn-soybean rotation. The error bars represent ± one standard deviation.

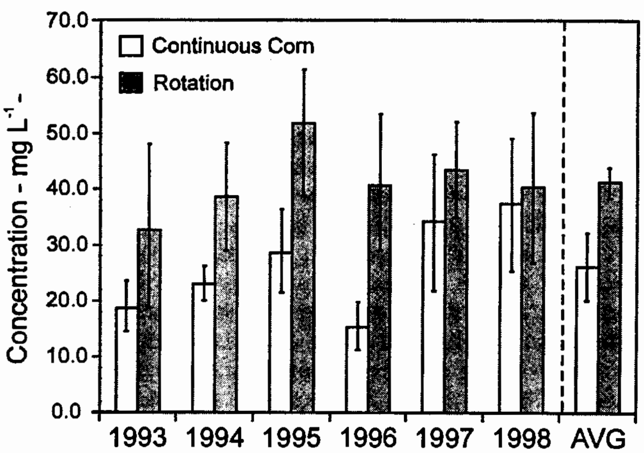


Figure 9–Average nitrate-N concentration in five continuous corn lysimeters and six lysimeters in a corn-soybean rotation. The error bars represent ± one standard deviation.

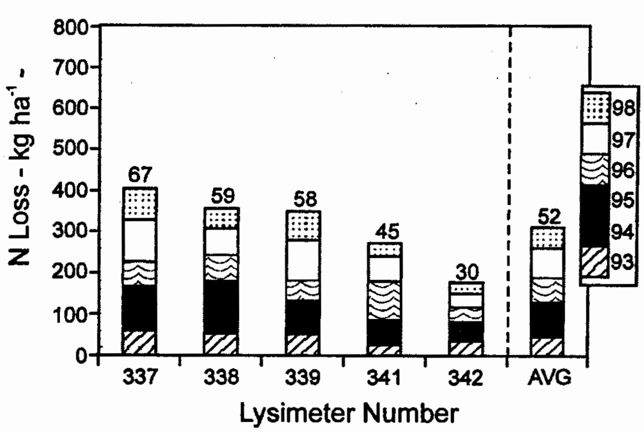


Figure 10–Annual and cumulative nitrate-N leaching loss from five lysimeters in continuous corn, 1993-1998. Values above the bars represent the six-year average loss (kg ha^{-1}).

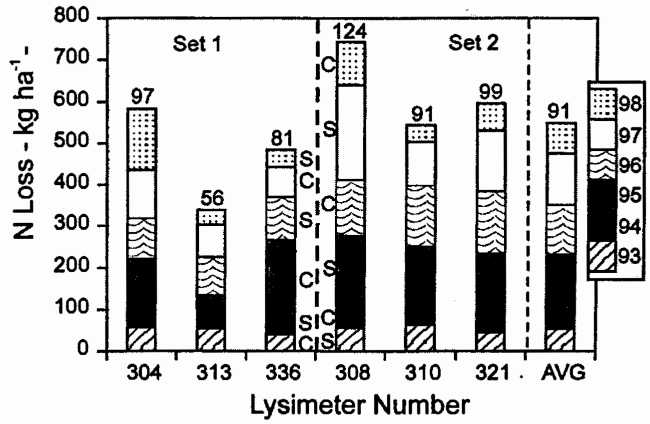


Figure 11–Annual and cumulative nitrate-N leaching loss from six lysimeters in a corn-soybean rotation, 1993-1998. Values above the bars represent the six-year average loss (kg ha^{-1}). The symbols C and S indicate which crop was planted in the indicated set of three lysimeters in any given year.

Comparing N Loss from Continuous Corn and the Corn-soybean Rotation

Cumulative N leaching loss for both continuous corn and the corn-soybean rotation was examined as a function of cumulative drainage over the years of study (fig. 12). The increasing difference in N loss with time between the two cropping systems is obvious. Yearly N fertilizer applications averaged 195 kg ha^{-1} for continuous corn and 174 kg ha^{-1} for corn in rotation. However, the rotation was fertilized only during corn production, every second year. This made the effective annual N rate in the rotation only 87 kg ha^{-1}. Total leaching loss over six years was 312 kg ha^{-1} for continuous corn, equivalent to 27% of applied N. For the rotation, the total N loss was 548 kg ha^{-1}, equivalent to 105% of applied N.

The reasons for the greater N loss from the rotation are not totally understood. Nitrogen fertilizer amounts for corn were based on expected corn grain yields, soil organic matter content, and residual nitrate in the root zone before planting (samples collected adjacent to the lysimeters during early spring). Springtime residual nitrate-N following soybean averaged 39 kg ha^{-1} less in the top 1.2 m of the profile than residual nitrate following corn in

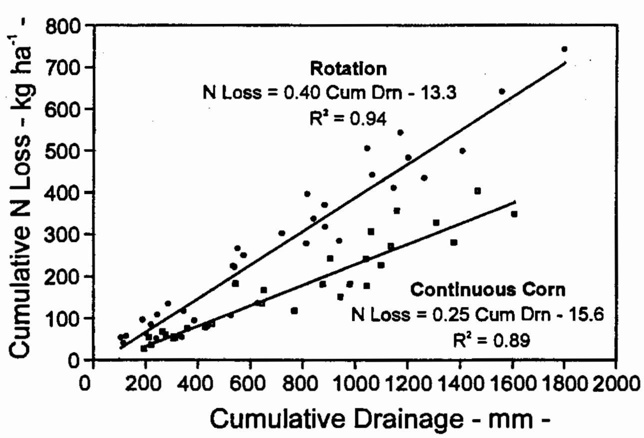


Figure 12–Cumulative nitrate-N leaching loss as a function of cumulative drainage from six lysimeters in continuous corn and five lysimeters in a corn-soybean rotation (1993-1998).

rotation. Taken alone, this factor would have increased the amount of N fertilizer required for corn. However, this was offset by a 50 kg ha^{-1} N credit for the prior soybean crop. The fertilizer algorithm may underestimate the amount of N supplied by soybean. The algorithm was developed from a data base which had primarily rainfed sites where corn followed soybean. Other unpublished University of Nebraska research shows that under irrigation, the apparent nitrogen credit can range from 20 to 100 kg ha^{-1}, averaging 60 to 70 kg ha^{-1} (Hergert, 1998). There may be some other unrecognized factor(s) involved. Whatever the reason, it is clear that N fertilizer recommendations for corn in rotation with soybean must be further examined.

Changes in Nitrate-N Concentration Over Time Under Different Management Systems

While nitrate-N concentrations tended to change slowly in drainage water, responses to relatively large inputs of water and/or N were quite apparent. This was most evident under the rotation. We earlier showed that about 200 mm of drainage were required to move the leading edge of a pulse of chloride from the soil surface to the bottom of the lysimeter. That information was used to analyze concentration data from the rotation, to estimate when the leading edge of a nitrate pulse left the upper root zone and, therefore, which crop was the more likely source.

Concentration changes over six years in one of the rotation lysimeters are shown in figure 13. There was a large increase in concentration in 1995. Application of the 200 mm transit delay factor indicates that a pulse of N entered the system following the soybean crop in 1993, probably as the result of mineralization of soybean residue. The pulse that began in late 1996 resulted from a combination of mineralization in the fall of 1995 and early 1996 and spring fertilization of corn in 1996. Drainage did not begin in this lysimeter until early August, near the end of the rapid N uptake period in the corn. The pulse beginning in 1997 was most probably the result of leaching of residual N from the 1996 corn crop. The general trend in concentration was upward from early 1993 until 1998. More N was being introduced into the system than was being removed by the cropping system. There was a sharp decline in concentration during 1998. This was most likely

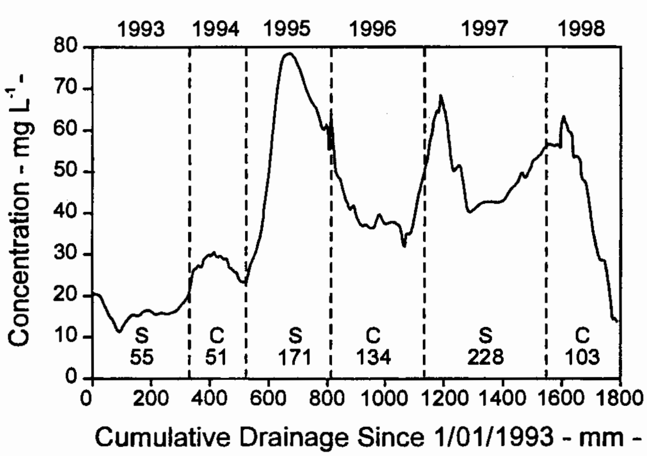


Figure 13–Nitrate-N concentration in root zone drainage from a corn-soybean rotation (lys. 308). Values below crop symbols (C or S) indicate annual N loss in kg ha^{-1}.

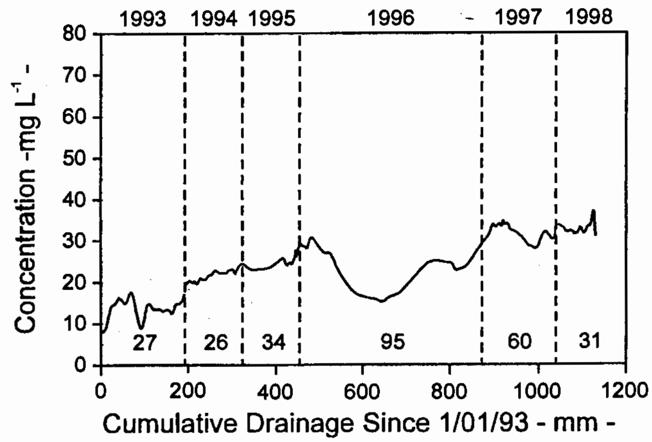


Figure 14–Nitrate-N concentration in root zone drainage from a continuous corn lysimeter (lys. 341). Values just above the x-axis indicate annual N loss in kg ha^{-1}.

the result of the reduced N application on rotation corn, following the increase in the legume credit from 50 to 90 kg ha^{-1}. This would seem to indicate that the legume credit for soybean was underestimated in previous years.

Nitrate-N concentration changes in drainage from a continuous corn lysimeter are shown in figure 14. Large nitrate pulses are not as prominent as in the drainage from the rotation system. Decline of nitrate-N concentration in 1996 probably resulted from dilution by the large volume of drainage water and associated preferential flow. The general trend of concentration is upward from 1993 until mid 1997 and then is relatively constant between 30 to 35 mg L^{-1} for the next year and a half.

Conclusions

Using current BMPs for N fertilizer and irrigation management, we found the six-year average nitrate-N leaching loss from continuous corn to be 52 kg $ha^{-1}yr^{-1}$, while that from a corn-soybean rotation was 91 kg ha^{-1}, 75% greater. The corresponding flow-weighted concentrations in lysimeter drainage water were 24 mg L^{-1} and 42 mg L^{-1}, respectively. Under the climatic conditions of the research site and the management practices used, our results showed no environmental advantage to a corn-soybean rotation as compared to continuous corn. The amount of N loss from continuous corn was consistent with that found when BMPs were applied in more humid areas, and is probably near the minimum expected loss when current BMPs are applied. In contrast, the rate of N loss under the rotation was much greater than expected and probably does not represent a reasonable minimum. The algorithm currently used in Nebraska for determining N fertilizer requirements for corn in rotation with soybean should be reevaluated. The legume credit for soybean may be underestimating the amount of N available from the previous soybean crop, particularly in an environment where there is very limited fall and winter leaching, and where denitrification plays a relatively small role in N loss. It would appear that present production systems using currently recommended BMPs cannot be managed to concurrently deliver both full crop yields and drainage water with a concentration of nitrate-N that is equal to or less than the MCL of 10 mg L^{-1} for public water supplies. If drainage concentrations are to be reduced to the MCL in zones of extension irrigation development, further management adjustments that reduce crop yields will be required.

ACKNOWLEDGMENTS. The authors wish to acknowledge the assistance provided by Gary Hergert as supporting soil scientist on the project. We also wish to thank Jim Petersen for his generous help with soils data collection. This research was partially funded by the USDA's Management Systems Evaluation Areas (MSEA) water quality project.

REFERENCES

Aziz, A. H. 1996. Evaluation of nitrate and chloride leaching, residual soil nitrate distribution and nitrogen uptake under no-till irrigated continuous corn and corn-soybean rotation. M.S. thesis. Lincoln, Nebr.: Dept. of Agronomy, University of Nebraska.

Bartlett, M. S. 1946. On the theoretical specification of sampling properties of autocorrelated time series. *J. Royal Stat. Soc.* B8: 27-41.

Hergert, G. W. 1986. Nitrate leaching through sandy soils as affected by sprinkler irrigation management. *J. Environ. Qual.* 15(3): 272-278.

Hergert, G. W., N. L. Klocke, J. L. Petersen, P. T. Nordquist, R. T. Clark, and G. A. Wicks. 1993. Cropping systems for stretching limited irrigation supplies. *J. Prod. Agric.* 6(6): 520-529.

Hergert, G. W., R. B. Ferguson, and C. A. Shapiro. 1995. Fertilizer suggestions for corn. University of Nebraska IANR, NebGuide G74-174-A (Rev. July 1995). Lincoln, Nebr.: University of Nebraska.

Hergert, G. W. 1998. Personal communication with author. North Platte, Nebr., 15 December.

Kanwar, R. S., T. S. Colvin, and D. L. Karlen. 1997. Ridge, moldboard, chisel and no-till effects on tile water quality beneath two cropping systems. *J. Prod. Agric.* 10(2): 227-234.

Katupitiya, A, D. E. Eisenhauer, R. B. Ferguson, R. F. Spalding, F. W. Roeth, and M. W. Bobier. 1997. Long-term tillage and crop rotation effects on residual nitrate in the crop root zone and nitrate accumulation in the intermediate vadose zone. *Transactions of the ASAE* 40(5): 1321-1327.

Klocke, N. L., R. W. Todd, G. W. Hergert, D. G. Watts, and A. M. Parkhurst. 1993. Design, installation, and performance of percolation lysimeters for water quality sampling. *Transactions of the ASAE* 36(2): 429-435.

Klocke, N. L, J. P. Schneekloth, and D. G. Watts. 1996. Potential for reducing leaching by managing water and crop rotations. *J. Soil & Water Cons.* 51(1): 84-90.

Logan, T. J., D. J. Eckert, and D. G. Beak. 1994. Tillage, crop and climatic effects on runoff and tile drainage losses of nitrate and four herbicides. *Soil & Tillage Res.* 30(1): 75-103.

Martin, D. L., J. R. Gilley, and R. J. Supalla. 1989. Evaluation of Irrigation Planning Decisions. *J. Irrig. & Drain. Engng.* 115(1): 58-77.

Owens, L. B., W. M. Edwards, and M. J. Shipitalo. 1995. Nitrate leaching through lysimeters in a corn-soybean rotation. *Soil Sci. Soc. Am. J.* 59(3): 902-907.

Randall, G. W., and T. K. Iragavarapu. 1995. Impact of long-term tillage systems for continuous corn on nitrate leaching to tile drainage. *J. Environ. Qual.* 24(2): 360-366.

Randall, G. W., D. R. Huggins, M. P. Russelle, D. J. Fuchs, W. W. Nelson, and J. L. Anderson. 1997. Nitrate losses through subsurface tile drainage in conservation reserve program, alfalfa, and row crop systems. *J. Environ. Qual.* 26(5): 1240-1247.

Ritter, W. F., and K. A. Manger. 1985. Effect of irrigation efficiencies on nitrogen leaching losses. *J. Irrig. & Drain. Engng. ASCE* 111(3): 230-240.

SAS. 1993. *SAS/ETS User's Guide*, Ver. 6, 2nd Ed. Cary, N.C.: SAS Institute Inc.

_____. 1996. *SAS System for Mixed Models.* Cary, N.C.: SAS Institute Inc.

Schneider, A. D., T. H. Marek, L. L. Ebeling, T. A. Howell, and J. L. Steiner. 1988. Hydraulic pull down procedure for collecting large soil monoliths. *Transactions of the ASAE* 31(4): 1092-1097.

Smika, D. E., D. F. Heerman, H. R. Duke, and A. R. Bathchelder. 1977. Nitrate-N percolation through irrigated sandy soil as affected by water management. *Agron. J.* 69(4): 623-626.

STATISTICA. 1995. 2nd Ed. *STATISTICA for Windows*, Vol. III: *Statistics II.* Tulsa, Okla.: StatSoft.

Watts, D. G., J. S. Schepers, and R. F. Spalding. 1997. Field scale evaluation of water and nitrogen management impacts on ground water quality. In *Proc. Conference on Best Management Practices for Irrigated Agriculture and the Environment*, 73-88, Fargo, N.Dak., 16-19 July. Denver, Colo.: U.S. Committee on Irrigation and Drainage.