Using the Late Spring Nitrate Test to Reduce Nitrate Loss within a Watershed

D. B. Jaynes,* D. L. Dinnes, D. W. Meek, D. L. Karlen, C. A. Cambardella, and T. S. Colvin

ABSTRACT

Excessive nitrate leaching from the U.S. Corn Belt has created serious water quality problems and contributed to the expansion of the hypoxic zone in the Gulf of Mexico. We evaluated the effect of implementing the late spring nitrate test (LSNT) for corn (*Zea mays* L.) grown within a 400-ha, tile-drained subbasin in central Iowa. Surface water discharge and NO_3 concentrations from the treated subbasin and two adjacent subbasins receiving primarily fall-applied, anhydrous ammonia were compared. In two of four years, the LSNT method significantly reduced N fertilizer applications compared with the farmers' standard practices. Average corn yield from LSNT fields and nonlimiting N fertilizer check strips was not significantly different. Autoregressive (AR) models using weekly time series in surface water NO_3 concentration differences between the LSNT and control subbasins indicated no consistent significant differences during the pre-LSNT (1992–1996) period. However, by the second year (1998) of the treatment period (1997–2000), NO_3 concentrations in surface water from the treated subbasin were significantly lower than the concentrations coming from both control basins. Annual average flow-weighted NO_3 concentrations for the last two years (1999–2000) were 11.3 mg N L^{-1} for the LSNT and subbasin and 16.0 mg N L^{-1} for the control subbasins. Based on these values and the AR models, widespread adoption of the LSNT program for managing N fertilizer where fall N application is typically practiced could result in a ≥30% decrease for NO_3 concentrations in surface water.

Excess NO_3 in drinking water can be toxic to humans (Heathwaite et al., 1993), requiring costly treatment of water for human consumption. Excess N in estuaries and coastal waters enhances algal growth (Ocean Studies Board and Water Science and Technology Board, Commission on Geosciences, Environment, and Resources, National Research Council, 2000) and is implicated in the formation of a hypoxic zone in the northern Gulf of Mexico (Rabalais et al., 1996). The principal sources of nitrogen to the Mississippi river are the agricultural basins within the Corn Belt (David and Gentry, 2000; Goolsby et al., 2001) of the U.S. Midwest. Nitrate contaminated drainage water from subsurface drains or "tiles" in the many artificially drained watersheds within the Corn Belt is the primary source of NO_3 to surface waters (David et al., 1997; Goolsby et al., 1999). For example, Jaynes et al. (1999) measured between 4 and 66 kg N ha^{-1} yr^{-1} of NO_3 lost in the surface waters of Walnut Creek, a 5130-ha agricultural watershed in central Iowa. They attributed most of this loss to tile drains that outlet into Walnut Creek. The NO_3 concentrations in the stream were often at or above the USEPA drinking water maximum contamination level (MCL) of 10 mg N L^{-1} during most years of the monitoring study.

The relationship between NO_3 concentrations in tile drainage and N fertilizer management has been extensively studied for continuous corn and corn–soybean [*Glycine max* (L.) Merr.] production systems and is predominately affected by fertilizer rate and timing. For example, Baker and Johnson (1981) found that increasing the fertilizer rate from 100 to 250 kg ha^{-1} on corn grown in rotation with either soybean or oat (*Avena sativa* L.) doubled the NO_3 concentration in tile drainage from 20 to 40 mg N L^{-1}. Similarly, for N fertilizer applied to corn in a corn–soybean rotation, Jaynes et al. (2001) found yearly average mass losses of NO_3 in tile drainage of 29 and 48 kg N ha^{-1} for average N fertilizer rates of 62 and 187 kg N ha^{-1}, respectively. Thus, applying the appropriate rate of N fertilizer is critical for minimizing NO_3 concentrations in tile drainage.

Timing of N fertilizer application can have a substantial effect on tile drainage NO_3 concentration. More than half of the corn land in Iowa and Illinois receives fall application of N, primarily as anhydrous ammonia (Hatfield et al., 1999; Economic Research Service, 1999; Shankar et al., 2000; Dinnes et al., 2002). This practice greatly increases the risk that the applied N will nitrify and leach with fall and spring precipitation. In a study reported by Randall and Mulla (2001), annual losses of NO_3 in tile drainage averaged 36% higher with fall application compared with spring application of N for corn production.

Therefore, to reduce N losses in tile drainage from corn production, "the correct rate of N at the optimum time" must be applied (Randall and Mulla, 2001). Combining a split application of N with the pre-sidedress nitrate test (PSNT) proposed by Magdoff et al. (1984) and confirmed for a range of conditions (Blackmer et al., 1989; Roth et al., 1992; Klausner et al., 1993; Sims et al., 1995) is one approach for accomplishing both of these goals. With the PSNT, the quantity of NO_3 in the surface 30 cm of soil is measured when the corn is 15 to 30 cm tall. If the soil NO_3 content is below a critical level, additional N fertilizer is immediately sidedressed. Currently, the PSNT in the form of the late spring nitrate test (LSNT) is the recommended practice for N fertilization of corn in the state of Iowa (Blackmer et al., 1997) and is suggested as an option in surrounding states as well. A typical scenario for using the LSNT involves applying a nominal rate of N fertilizer before corn emergence followed by measuring residual soil NO_3 in the top 30 cm of the soil during early crop growth and

USDA-ARS, National Soil Tilth Laboratory, 2150 Pammel Drive, Ames, IA 50011. Names are necessary to report factually on available data; however, the USDA neither guarantees nor warrants the standard of the product, and the use of the name by USDA implies no approval of the product to the exclusion of others that may also be suitable. Received 5 May 2003. *Corresponding author (jaynes@nstl.gov).

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

Abbreviations: AR, autoregressive; LSNT, late spring nitrate test; MCL, maximum contaminant level.

sidedressing additional N fertilizer based on soil NO_3 concentrations.

Plot-scale and field studies using a PSNT approach have been positive with regard to measured or potential NO_3 leaching (Durieux et al., 1995; Bjorneberg et al., 1998; Guillard et al., 1999; Bakhsh et al., 2002). However, the effect on surface water quality at a watershed scale has not been quantified. The objective of this research was to quantify changes in NO_3 concentration in surface flow as a result of implementing the LSNT N fertilizer management system across a watershed. Our goal was to modify N management within a watershed to lower NO_3 concentrations below the 10 mg N L^{-1} MCL, while maintaining economically viable crop production levels.

MATERIALS AND METHODS

Study Site

Walnut Creek watershed, located in central Iowa (41°55′ to 42°00′ N, 93°32′ to 93°45′ W), served as one of many study sites for the Management Systems Evaluation Area (MSEA) program (Onstad et al., 1991). Weather and cropping patterns have been monitored within the watershed since 1991 (Hatfield et al., 1999). The 5130-ha watershed is characterized by a gently undulating surface of a few meters vertical relief and a poorly defined surface drainage system. Soils within the watershed are in the Clarion (fine-loamy, mixed, superactive, mesic Typic Hapludolls)–Nicollet (fine-loamy, mixed, superactive, mesic Aquic Hapludolls)–Webster (fine-loamy, mixed, superactive, mesic Typic Endoaquolls) association. Soils within the watershed are characterized as being moderately permeable, with about 33% of the soils being well drained, 10% being somewhat poorly drained, 50% being poorly drained, and 5% being very poorly drained. A dense network of distributed subsurface drain lines (tiles) had been installed over the past century within the watershed to enable modern intensive row crop farming (Hewes and Frandson, 1952). Corn and soybean are typically grown in rotation and their production comprises more than 80% of the land use within the watershed. Detailed descriptions of the watershed's location, geology, soils, climate, land use, and farming practices can be found in Hatfield et al. (1999) and Eidem et al. (1999).

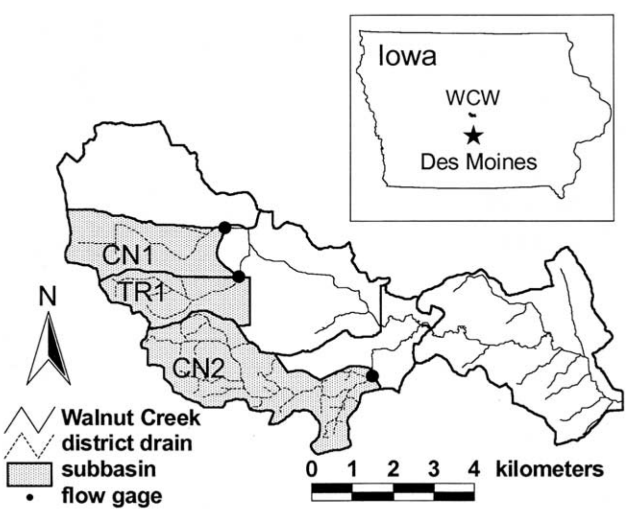

Fig. 1. Location of Walnut Creek watershed (WCW) within the state of Iowa (inset), and the location of the stream, district drains, discharge gaging stations, control subbasins (CN1 and CN2), and treatment subbasin (TR1) within WCW.

Treatment and control subbasins within Walnut Creek watershed were selected for this study by their similar size, soils, and position within the upper, extensively tiled reaches of the watershed. A 405-ha subbasin (TR in Fig. 1) was selected as the subbasin for implementation of the LSNT N fertilizer management program. Cooperative research agreements were secured with the eight farmers operating sixteen of the fields that were either completely or partially within the subbasin. These fields represented 90% of the area within the subbasin. Subbasins CN1 (491 ha) and CN2 (863 ha) were selected as controls for a paired-watershed research design (Clausen et al., 1996). Farmers within these control subbasins were encouraged to continue following their normal production practices.

Nitrogen Fertilizer Management

Beginning in 1997, we implemented the LSNT N fertilizer management program on the 16 fields within Subbasin TR1 (Fig. 2). Fourteen of the fields had been in a corn and soybean rotation with N fertilizer applied before corn only. Two of the fields had been in continuous corn before the start of the N treatment. Historically, manure was not used as a soil amendment within the watershed. Both control subbasins (CN1 and CN2) were managed by local farmers following their normal N fertilizer programs, which was predominantly fall application of anhydrous ammonia without a stabilizing compound after the soil temperature had dropped below 10°C.

The LSNT program consisted of applying an initial 56 kg ha^{-1} application of N at or shortly before planting. After the corn plants had grown to a height of 15 to 30 cm (typically mid-June), soil samples were taken and analyzed for NO_3 content to determine the required rate of N to apply by sidedressing. To acquire representative soil samples, we divided the fields into 4-ha blocks and each block into four 1-ha subblocks. A diagonal transect was walked across each subblock during which a series of eight 30-cm-deep soil cores were taken. The core samples were taken at approximately equal distances along each transect, but pothole and hilltop areas were avoided as recommended by Blackmer et al. (1997). The first core along a transect was taken in a corn row. The second core was taken one-eighth of the distance between two adjacent corn rows. The third core was taken two-eighths of the distance between two adjacent corn rows. This pattern was continued until the eighth soil core was taken seven-eighths of the distance between two corn rows. The eight cores from each of the four subblocks were then composited into a single sample representing the 4-ha block for NO_3 analysis.

Soil NO_3 results for all the blocks within a given field were averaged and a single N fertilizer application rate computed for the field. Nitrogen fertilizer rates were calculated using the formula:

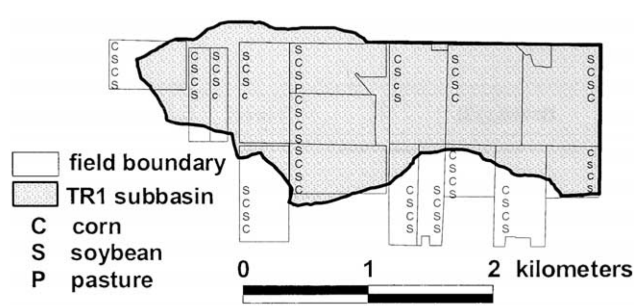

Fig. 2. Late spring nitrate test (LSNT) treatment fields within Subbasin TR1 of Walnut Creek. Letters within each field identify the crop rotation starting in 1997. Lowercase letters indicate years when the LSNT was not followed for applying N fertilizer.

$$y = 1.121 \times 8 \times (25 - x) \quad [1]$$

where x is the average NO_3 concentration (mg N kg^{-1}) in the soil, y is the N fertilizer rate in kg N ha^{-1}, the factor 8 is considered a first approximation for the conversion rate between fertilizer N application and resulting soil N concentration, 25 is the required soil N concentration for full yield (Blackmer et al., 1997), and 1.121 converts the recommendation from lb $acre^{-1}$ to kg ha^{-1}. The computed fertilizer rate was sidedressed using 32% urea ammonium nitrate (UAN) and Blu-Jet (Thurston Manufacturing Co., Thurston, NE) sidedressing machines within 1 to 2 wk of soil sampling. In addition to the LSNT rate, a field-long strip, either 12 or 16 rows wide (depending on farmer's planter width), was treated with the initial 56 kg ha^{-1} N fertilizer in every field, but had no additional N added (no sidedress strip). Also, a field-long strip in each field had extra N fertilizer applied to assure that N was nonlimiting (nonlimiting N). These strips received two or three times the LSNT rate at sidedressing time to assure a total N fertilizer rate of more than 220 kg ha^{-1}. Both the nonsidedress and the nonlimiting N strips were strategically placed to include all soil types that existed within each field.

Tile Drainage Sampling

The fields within each subbasin were extensively drained by subsurface field tiles that had been installed over the past 120 yr. The field tiles drained into subsurface drainage district pipes that drained each subbasin. The partially submerged district drains were instrumented to measure flow rate as they emptied into Walnut Creek (Fig. 1) by simultaneously measuring water depth and velocity using Flowtote meters (Marsh-McBirney, Frederick, MD). Water samples were taken manually once a week at the flow gage on each subbasin. All water samples were refrigerated until analysis. Nitrate was analyzed by quantitative reduction to NO_2 and measuring the NO_2 concentration colorimetrically with a Lachat Autoanalyzer (Zellweger Analytics, Lachat Instrument Division, Milwaukee, WI). The method had a quantitation limit of 1.0 mg N L^{-1} as NO_3. Flow-weighted yearly average NO_3 concentrations were computed by summing the product of the weekly NO_3 concentration and total weekly discharge.

Grain Yield

Grain yield from both corn and soybean were measured with the farmers' combines that were equipped with yield monitors and differential global positioning system (DGPS). Seven of the eight farmers installed Yield Monitor 2000 yield monitors (Ag Leader Technology, Ames, IA) and DGPS systems that used the U.S. Coast Guard differential correctional signal. The remaining farmer installed a GreenStar (Deere and Co., Moline, IL) and DGPS system that used an orbiting satellite source differential correction signal. Each farmer-cooperator was guided in calibration and use of the yield monitors. Yield data were organized with ArcView geographical information system software (ESRI, 2002) for mapping and for preparing further statistical analyses.

Corn yield data were first censored by eliminating data points below 0.63 Mg ha^{-1} and above 18.9 Mg ha^{-1}. These limits were selected to remove yield monitor source errors due to beginning and ending harvest passes, and factors causing inconsistent grain flow through the combines not due to yield variation (i.e., plugging within the combine platform). Yield data were then mapped by individual data points and organized by field and N treatment for all fields and years of study.

Yield information from the nonlimiting N field-long strips and neighboring combine passes within the LSNT N rate areas were identified by GPS benchmarks of the strip borders and labels applied to the combine harvest passes by the farmers. A single harvest pass was selected from each N rate area to obtain data free of border effects from the different N rates.

Corn yields for the LSNT program were evaluated by comparing the yield within the nonsidedressed and nonlimiting N strips within each field to the yield from the adjacent LSNT yield strip. Comparisons were accomplished by using SAS one-way analysis of variance (ANOVA) and grouping the yields for all fields by year (SAS Institute, 1990). In this paper, we summarize only the basin-wide results for yields from the nonlimiting N strips and adjacent LSNT-recommended N rate. Detailed yield results for individual fields and for the nonsidedressed strips will be presented in a future paper.

Statistical Comparison of Paired Watersheds

Analysis of covariance methods (ANCOVA) have been recommended for examining paired watershed data (Grabow et al., 1998, 1999a, 1999b). Because serial correlation commonly exists in stream monitoring data and model residuals, which can cause underestimation of error variance (Salas, 1993), either time aggregation over hydrological events or autoregressive ANCOVA models have been used as comparison methods. However, Meek et al. (2001) pointed out that several of the underlying assumptions for these approaches, in particular that the covariate is fixed, measured without error, and independent of treatments, are not valid for stream monitoring datasets.

Instead, the method described by Meek et al. (2001) and used by Jaynes et al. (2001) was used to compare between the NO_3 concentrations in the LSNT-treated subbasin, TR1, and the concentrations from the control subbasins, CN1 and CN2. In this method, a model was fitted to the difference in paired weekly NO_3 concentrations between the treated and each control subbasin. The model had two parts: a trend component and an autoregressive (AR) residual component to correct for the effects of residual autocorrelation. While conceptually the trend component can be almost any known function from a line to intrinsically nonlinear functions, we used rational and logistic polynomials. A nonlinear regression procedure was used to fit an appropriate trend model to the NO_3 concentration difference data. Autocorrelation of the residuals was used to select the appropriate lag for the AR component. In all cases, a Lag 1 model was found to be appropriate. A Lag 1 residual AR component was added to the trend model and the combined model simultaneously fitted to the data using an iterative least squares method and Ramsay's weighting function to reduce the effect of outliers (Montgomery and Peck, 1982). Residual lag values were set to zero at the start of the time sequence and after breaks in the time series caused by periods of no drainage flow.

In addition to computing the model parameters, a 95% confidence interval was computed for each model. While many formal statistical tests are possible, for practical purposes, we assumed that there was a significant difference between the NO_3 concentrations in two subbasins whenever the 95% confidence intervals for the modeled differences no longer included the 0 line (i.e., rejected the null hypothesis that the difference in concentrations was 0). This graphical presentation used ideas suggested in Tufte (1983) and made the method of analysis easy to interpret. Models were fitted independently for each subbasin comparison and for the pretreatment (1992–1996) and treatment time periods (1997–2000). All modeling was conducted using SAS Version 6 software (SAS Institute, 1990).

RESULTS AND DISCUSSION

Climate and Cropping Patterns

Deviations from the 30-yr monthly average maximum and minimum temperatures are listed in Table 1. The 30-yr average values for the watershed can be found in Hatfield et al. (1999). Except for 2000, all of the summers during the pretreatment period (1992–1996) and treatment period (1997–2000) tended to have cooler maximum temperatures than average. In most of the years, the lower monthly maximum temperatures extended well into the fall. The cooler fall temperatures would have tended to decrease the decomposition of crop residue and lowered nitrification rates and the accumulation of soil NO_3. Conversely, the first quarter of every year except 1993 experienced warmer than average monthly maximum temperatures. Overall, the treatment years tended to have higher than average monthly maximum and minimum temperatures from January through to the June LSNT soil sampling. These warmer temperatures would have encouraged nitrification and accumulation of NO_3 within the soil profile.

Precipitation during the 9-yr period was extremely variable. During the pretreatment period, the year 1993 was characterized by much greater than average monthly precipitation in March, June, July, and August. This was reflected by widespread flooding and poor crop yields within the Walnut Creek watershed and much of Iowa and the Midwest. The climate then turned drier and monthly precipitation was mostly below average for the falls of 1993 and 1994.

During the treatment period, 2000 was also a very dry year with the monthly precipitation falling below the 30-yr average for the last quarter of 1999 and most of 2000. The low precipitation levels caused the tile drains to cease flowing and even Walnut Creek to stop flowing for much of the summer of 2000. None of the years within the treatment period could be termed flood years although precipitation in June of 1998 resulted in extensive flooding of the local potholes and may have affected the efficacy of the sidedressed N (discussed later). The greater than average November precipitation in 1996 also affected the study because the farmers were for the most part unable to apply their N that fall due to wet soil conditions and deferred N application until the spring of 1997. Changing from fall to spring N application for 1997 may have reduced NO_3 leaching losses that year (Randall et al., 2003) and reduced the difference between the LSNT treated and control subbasins. Overall, the marked variability of temperature and precipitation illustrates why watershed studies need to be conducted over extended periods of time. For this study, both the pretreatment and treatment periods had similar temperature regimes and included both wet and dry growing seasons.

During the treatment period of 1997–2000, corn was grown on 49% of Subbasin CN1, 44% of Subbasin TR1, and 45% of Subbasin CN2. For the same period, soybean was grown on 42% of Subbasin CN1, 46% of Subbasin TR1, and 51% of Subbasin CN2. Compared with the pretreatment period, the percent areas planted to corn and soybean during the treatment period were very similar for Subbasins CN1 and CN2. Corn was grown on relatively less area on average for the treatment Subbasin TR1 and soybean on relatively more area during the treatment period. This was primarily due to a single 32-ha field that switched from a corn after corn rotation in 1992–1993 to a corn after soybean rotation for the remainder of the study. Overall, corn was grown on nearly half of the subbasin areas during the treatment period and corn and soybean accounted for about 90% of the area within each subbasin.

Nitrogen Fertilizer Rates

In 1997, the LSNT program did not reduce overall N application rates compared with the farmer-cooperators' normal N programs (Table 2). However, the LSNT program dramatically reduced N rates in 1998 and 2000, and moderately reduced overall N rates in 1999, compared with what the farmers would have applied. The farmer-cooperators increased their N fertilization rates by about 20 kg ha^{-1} during the second half of the 4-yr period. The increased N fertilization rates were a result of the farmers' perception that they were losing a large amount of the fall-applied N fertilizer because of the wetter than average spring weather and they wanted to compensate for this loss.

Table 1. Deviations from the 30-yr average monthly maximum (T_{max}) and minimum (T_{min}) temperature and precipitation (Pre) in Walnut Creek, Story County, Iowa.

	Pretreatment period															Treatment period											
	1992			1993			1994			1995			1996			1997			1998			1999			2000		
Month	T_{max}	T_{min}	Pre	T_{max}	T_{min}	Pre	T_{max}	T_{min}	Pre	T_{max}	T_{min}	Pre	T_{max}	T_{min}	Pre	T_{max}	T_{min}	Pre	T_{max}	T_{min}	Pre	T_{max}	T_{min}	Pre	T_{max}	T_{min}	Pre
	— °C —		mm	— °C —		mm	— °C —		mm	— °C —		mm	— °C —		mm	— °C —		mm	— °C —		mm	— °C —		mm	— °C —		mm
January	7.0	7.0	9	1.0	−0.3	11	−3.6	−4.5	8	0.3	0.8	−2	0.5	−1.2	20	0.2	−1.0	6	3.6	4.1	14	0.4	1.1	7	4.2	2.1	−2
February	5.5	8.0	4	−2.4	−0.4	−10	−1.5	−2.1	−20	2.5	2.8	−36	1.5	1.4	−31	1.3	3.5	−8	5.8	9.1	3	6.6	7.5	−20	7.5	6.8	−23
March	4.5	4.0	26	−2.9	−0.2	72	5.0	2.3	−49	2.5	3.0	7	0.7	−2.5	−23	4.0	2.1	−7	−6.9	−4.8	27	4.1	1.5	−23	7.7	4.2	−42
April	3.8	2.1	0	2.9	1.9	−29	6.6	2.4	−28	3.0	1.2	44	5.3	0.0	−57	3.2	0.4	−4	6.7	4.9	−26	5.7	4.6	4	7.6	2.6	−66
May	−1.4	−0.9	−90	−3.3	0.8	11	−0.5	−0.5	−90	−4.6	−1.0	1	−5.8	−0.6	51	−4.9	−3.6	−44	0.2	2.1	−52	−2.9	1.3	22	0.2	1.3	−35
June	−4.4	−1.9	−113	−3.3	0.8	49	−0.5	−0.5	−38	−4.6	−1.0	60	−0.8	0.9	−20	1.3	0.4	−37	−2.0	0.5	189	−1.5	0.9	−9	−1.3	−1.1	−17
July	−4.5	−1.0	139	−2.7	2.3	230	0.2	−0.2	7	−0.1	0.7	42	−2.1	−0.8	12	−0.5	1.0	38	−0.5	2.0	7	1.2	3.6	33	−2.0	0.7	−23
August	−3.8	−3.2	−50	−1.6	2.8	152	−2.2	−4.2	−10	1.1	3.1	−44	−1.7	0.0	24	−2.1	−0.5	−69	−0.4	2.4	56	−1.9	−0.2	20	0.2	1.0	−71
September	−1.7	−1.0	−18	−4.5	−2.1	23	−0.6	−0.8	14	−1.7	−1.9	−23	−2.5	−1.2	−2	0.4	0.8	−20	3.4	2.3	−80	−1.2	−2.4	−41	2.0	−0.3	−57
October	−0.9	−1.5	−42	−3.1	−1.0	−32	−0.4	1.0	−18	−1.7	−0.9	−30	−0.7	−0.3	−3	−0.8	0.2	45	−1.2	1.6	−3	0.0	−2.4	−48	0.7	1.9	−13
November	−3.9	−0.7	69	−0.8	−1.5	−8	2.1	1.0	7	−3.1	−4.1	−4	−5.0	−3.1	75	−3.1	−1.6	−2	3.1	2.2	−5	6.5	1.9	−9	−2.6	−2.2	8
December	−1.5	−0.9	27	0.2	−0.1	−4	−0.5	−0.3	1	−0.9	−0.7	−20	−4.3	−3.3	4	−0.3	2.2	3	3.5	−0.2	−14	2.3	−0.8	−11	−9.5	−9.8	20

Table 2. Nitrogen fertilizer rates determined by the late spring nitrate test (LSNT), proposed by the farmer-collaborators, and applied within Subbasin TR1. Also, corn yields for LSNT strips and these yields as fractions of the nonlimiting N strip yields.

Year	Area-averaged N determined with LSNT	Area-averaged N proposed by farmers	Area-averaged N applied	Average corn yield from LSNT N rate strip	Corn yield as fraction of nonlimiting N strip
	kg ha^{-1}			Mg ha^{-1}	
1997	168	164	168	9.92	0.99
1998	118	164	118	9.27	0.93
1999	174	188	177†	9.94	0.98
2000	96	182	109‡	9.89	0.99

† One field had N applied at farmer-collaborator rate.
‡ Two fields had N applied at farmer-collaborator rate.

Differences in LSNT N rate recommendations among years were probably due to variations in soils within the individual fields and spring climatic conditions. Because of the 2-yr crop rotation, LSNT samples were taken from the same fields in 1997 and 1999, which were different than the fields sampled in 1998 and 2000 (Fig. 2). Differences in current and past farming practices of the different farmer-cooperators may also account for much of the differences among years. In addition, the LSNT recommended rates would have been affected by variations in climate. The lower LSNT recommendations in 1998, 1999, and 2000 may reflect the warmer than average months of April and May in those years that presumably would have increased early spring N mineralization (Table 1). The fall of 1999 and spring of 2000 were drier than average, which should have reduced the leaching and denitrification of NO_3 within the soil and increased the amount of NO_3 recovered by the LSNT. Nitrogen application rates were the lowest for 2000 and about 20 kg ha^{-1} lower than in 1998 when corn was grown on the same fields.

Actual N fertilizer rates applied to corn within Subbasin TR1 were different than recommended by the LSNT in 1999 and 2000. In 1999, a farmer mistakenly applied N in the fall to one of the fields at a rate of 168 kg ha^{-1}. Again in 2000, N fertilizer rates applied were greater than the LSNT recommendation because a farmer mistakenly applied N to one field in the fall and a second farmer withdrew from the program and also applied N in the fall. Thus, the experimental design was compromised slightly from the original plan because not all corn fields within the treatment subbasin received N as a spring split application at the LSNT-recommended rate. These deviations would have tended to diminish the effect of the LSNT program on NO_3 concentrations within the treatment subbasin.

Yield

Average corn yields for 1997 through 2000 are shown in Table 2. Yields from the LSNT-treated strips were not significantly different ($P = 0.05$) than the nonlimiting N treatment strips in any year. The lowest mean LSNT yield relative to the mean of the nonlimiting N strips yields was in 1998. In this year, a warm, dry spring caused little leaching or denitrification of the NO_3 that had mineralized. This produced relatively high soil NO_3 concentrations and correspondingly low recommended rates of sidedressed N. The sidedressing in June was followed by a 3-wk period when precipitation was 150 mm greater than average (Table 1). Much of the applied urea ammonium nitrate (UAN) may have leached below the root zone during this period, thus causing the lower yields. Deep leaching of N would agree with observations by Jaynes et al. (1992) that solute leaching may be enhanced when irrigation immediately follows application. Kluitenberg and Horton (1990) attributed this to enhanced preferential flow for solutes that were recently applied and had not diffused or been incorporated into the soil pore matrix away from the preferential pathways for leaching. Overall, the LSNT produced insignificantly lower yields in all four years.

Water Quality

Nitrate concentrations in the weekly water samples from the three subbasins ranged from 1 to 25 mg N L^{-1} (Fig. 3). Nitrate concentrations exhibited marked seasonal patterns from 1995 through 2000 with concentrations rising from late fall to mid-summer and then dropping to lows in late summer. This pattern has been reported for watershed data across the Midwest (Fene-

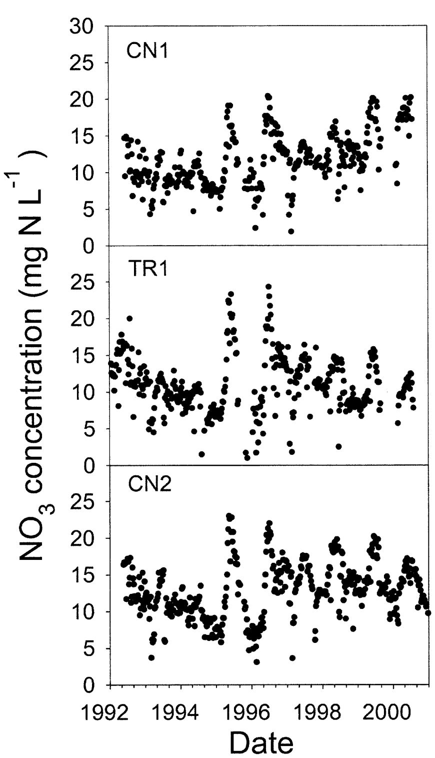

Fig. 3. Nitrate concentration in drainage from the control (CN1 and CN2) and treated (TR1) subbasins.

lon and Moore, 1998; Moog and Whiting, 2002). Increasing concentrations are probably due to the flushing by snow melt and spring rains of NO_3 mineralized from organic matter and from N fertilizer. Decreasing concentrations in late summer are probably due to removal of NO_3 from soil by growing crops. The seasonal pattern is not as obvious in the 1993 and 1994 data. In 1993, the excessive rain and runoff probably diluted the NO_3, lowering the concentration. In 1994, little springtime leaching occurred because of low rainfall and because much of the soil NO_3 had been flushed from the system in 1993. The high concentrations in 1995 and 1996 may reflect leaching of soil NO_3 that accumulated in the soil from fertilizer application and mineralization in 1994 but had not leached that year due to low rainfall. Higher concentrations in tile drainage in years following dry years have been observed elsewhere in the Midwest (Randall and Iragavarapu, 1995).

The effect of the 1993 wet season and the 1994 dry season are reflected also in the flow-weighted annual NO_3 concentrations in the drainage leaving the three subbasins (Table 3). In general, NO_3 concentrations during the pretreatment period followed the trend CN1 $<$ TR1 $<$ CN2. Flow-weighted annual average NO_3 concentrations during this period were close to or exceeded the MCL for NO_3 in drinking water (10 mg N L^{-1}).

During the treatment period of 1997–2000, the NO_3 concentrations tended to be higher in both of the control subbasins (CN1 and CN2) compared with the LSNT-treated subbasin (TR1). This was particularly true for the last two years of the treatment period when we would expect the full effect of the LSNT treatment to be exhibited. The flow-weighted annual mean NO_3 concentration exceeded the 10 mg N L^{-1} MCL in every year and subbasin during the treatment period other than in CN1 in 1997.

To compare the three subbasins during the pretreatment period, a combined trend and AR model was fitted to the time series of the paired differences in weekly measured NO_3 concentrations in each subbasin. Using the criterion that there was no significant difference in NO_3 concentrations if the 95% confidence limits for the fitted model included 0, there were no significant differences between NO_3 concentrations in Subbasins TR1 and CN1 other than a 2-mo period in the fall of 1995 and a week in the fall of 1996 (data not shown). Likewise, the 95% confidence limits for the model fitted to the time series for the difference in NO_3 concentration between Subbasin CN2 and TR1 showed no time period when the difference was significantly different than 0 (data not shown). Thus, the NO_3 concentrations in the drainage water leaving the three subbasins were consistent and not significantly different during the pretreatment period.

Table 3. Flow-weighted average annual NO_3 concentration in the discharge from the control (CN1 and CN2) and treated (TR1) subbasins.

Subbasin	1992	1993	1994	1995	1996	1997	1998	1999	2000
	mg N L^{-1}								
CN1	9.9	8.2	9.2	13.1	14.0	8.4	11.1	15.8	16.5
TR1	12.5	9.2	8.9	16.0	15.6	10.8	10.2	11.7	11.0
CN2	13.7	9.7	10.2	16.7	15.4	13.1	14.0	16.5	15.1

Conversely, the time series of paired NO_3 concentration differences exhibited markedly different behavior during the LSNT treatment years. Comparing Subbasins TR1 to CN1, the NO_3 concentration difference time series exhibited an initial period when the concentrations were higher in TR1 than CN1. This was followed by a period of increasingly greater NO_3 concentrations in CN1 that continued to the end of the treatment period (Fig. 4). A rational quadratic polynomial model with an AR residual component was fitted to the concentration difference series giving:

$$\Delta_{TR1-CN1} = 0.96 - 0.00055i^2/(1 + 0.000036i^2) - 0.02\varepsilon_{i-1} + \varepsilon_i \quad [2]$$

where $\Delta_{TR1-CN1}$ is the NO_3 concentration in Subbasin TR1 minus the concentration in Subbasin CN1 (mg N L^{-1}), ε is the residual or error, and i is an index representing the number of weeks from 1 Jan. 1997. The model fit the data well ($R^2 = 0.86$) and describes a nearly constant period in the NO_3 concentration difference for about 33 weeks or until mid-August 1997 after which the NO_3 concentration in the water coming from the LSNT-treated subbasin started to decrease in relation to the water coming from Subbasin CN1. This decrease continued, with the mean difference being about 8 mg L^{-1} by the end of 2000. In the later half of 1998, the 95% confidence bands for the model no longer included the null hypothesis that the concentration difference was zero and thus, the NO_3 concentration coming from LSNT-treated subbasin can be considered significantly lower than the NO_3 concentration coming from the control subbasin after this time.

A logistic model with an AR residual component was fitted to the time series of the NO_3 concentration

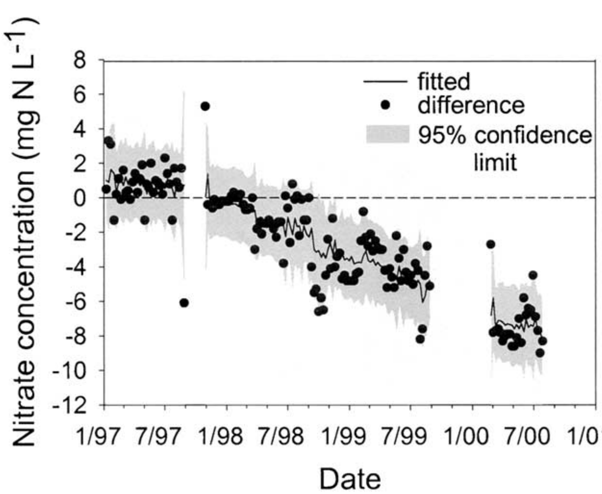

Fig. 4. Nitrate concentrations in the treated subbasin (TR1) minus the concentrations in the control subbasin (CN1) during the late spring nitrate test (LSNT) treatment period and the fitted quadratic model with a Lag 1 residual component and its 95% confidence limits. Concentrations from the two subbasins are significantly different when the confidence limits do not include the 0 difference line.

difference between Subbasins TR1 and CN2 (Fig. 5). The resulting model fit the data well ($R^2 = 0.62$) and was:

$$\Delta_{TR1-CN2} = -4.73 + 2.66/[1 + \exp(i - 60.6)] + 0.198\varepsilon_{i-1} + \varepsilon_i \quad [3]$$

where $\Delta_{TR1-CN2}$ is the difference between the weekly NO_3 concentrations coming from Subbasins TR1 and CN2 (mg N L^{-1}). The NO_3 concentration in Subbasin TR1 was initially lower than that in Subbasin CN2 and, similar to the Subbasin CN1 comparison, remained constant through much of 1997. The logistic model showed the NO_3 concentration difference to become increasingly negative starting about week 50 (mid-December 1997) but then leveling off early in 1998 to an average difference of about 4.5 mg N L^{-1}. Using the 95% confidence limits of the model as the criteria, the NO_3 concentration in Subbasin TR1 was significantly lower than that in Subbasin CN2 by early 1998.

Thus, the concentration difference time series for two subbasin pairings showed a significant decrease in the NO_3 concentration coming from the LSNT-treated watershed about 10 to 14 mo after ceasing fall N fertilizer application. However, the two time series were different in that the NO_3 concentrations in Subbasins TR1 and CN1 continued to diverge to the end of 2000, whereas the NO_3 concentrations in Subbasins TR1 and CN2 showed a constant difference by 1998 that was maintained throughout 1999 and 2000. These differences were probably due to different farming practices on the two control subbasins during this time. These practices were uncontrolled in this experiment, with the many farmers of the various fields within the subbasins free to follow and change their farming practices as they chose. These differences are reflected by the small changes in area of each watershed dedicated to corn and soybean production during the study and the change in N fertilizer rates used by the farmer-cooperators on their fields within and adjacent to the control subbasins

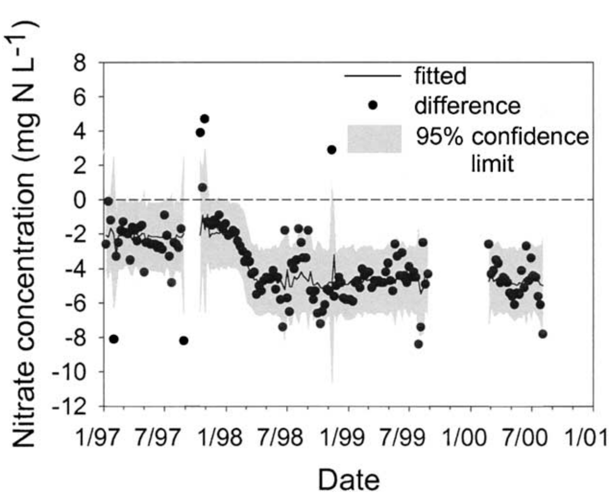

Fig. 5. Nitrate concentrations in the treated subbasin (TR1) minus concentrations in the control subbasin (CN2) during the late spring nitrate test (LSNT) treatment period and the fitted quadratic model with a Lag 1 residual component at its 95% confidence limits. Concentrations from the two subbasins are significantly different when the confidence limits do not include the 0 difference line.

(Table 2). Regardless of comparison, the LSNT resulted in a significant and substantial decrease in NO_3 concentrations in the drainage from the treated subbasin relative to the control subbasins. Annual average flow-weighted NO_3 concentrations for the last two years of the study were 11.3 mg N L^{-1} for the LSNT subbasin and 16.0 mg N L^{-1} for the control subbasins. Based on these values and the concentration difference models (Eq. [2] and [3]), adopting the LSNT program at a watershed scale resulted in a 30% or greater decrease in NO_3 concentration in the drainage water.

Examining Table 3 and Fig. 3 it is apparent that much of the difference in NO_3 concentrations between the LSNT and control subbasins was not because of decreases in NO_3 concentration coming from the LSNT subbasin. The flow-weighted annual average NO_3 concentration in the LSNT-treated subbasin decreased about 1 mg N L^{-1} during the treatment period compared with the pretreatment period. Conversely, the NO_3 concentration coming from the control subbasins tended to increase during the four years and be at or above the highest concentrations observed during the pretreatment years. Whether the increases in NO_3 concentrations in the control watershed were due to variations in weather, increases in N fertilization rates, or changes in other cultural practices in the control subbasins cannot be determined from this study. Nevertheless, if the LSNT program had been adopted throughout the Walnut Creek watershed, a considerable reduction in NO_3 concentration leaving the watershed would have been realized.

CONCLUSIONS

One of the potential benefits of using the LSNT for N fertilizer management is delaying application from the fall to the spring, thus decreasing the opportunity for soil N loss due to leaching or denitrification. Another benefit may be that by splitting N fertilizer application between a preplant and a sidedress operation, more N is applied closer to the time of peak N demand by the growing crop, which may increase N fertilizer use efficiency. Finally, by adjusting the amount of N fertilizer applied based on measured soil NO_3 levels, the LSNT approach may result in less N fertilizer being applied in a given year. Adoption of the LSNT for N fertilizer management of corn resulted in a relative decrease of at least 30% in NO_3 concentration in the water leaving a 400-ha subbasin of Walnut Creek. However, we failed in our goal of keeping either the weekly or annual averaged flow-weighted NO_3 concentrations below the MCL of 10 mg N L^{-1}. Greater reductions in NO_3 concentrations to meet our goal may require increasing cropping diversity (Randall et al., 1997) or incorporating edge-of-field practices to trap and denitrify excess NO_3 (Lowrance et al., 1985).

Despite the water quality advantages, there are drawbacks to using the LSNT approach. The test is often unable to identify soils not responsive to N fertilizer (Bundy et al., 1999). The factor of 8 used in Eq. [1] is at best an approximation and should be modified as additional information for specific fields is acquired. Also, crop yields may suffer when using the LSNT approach depending on the timing between sidedressing and rainfall. Adopting the LSNT approach also increases the risk to the farmer. The window of opportunity for sidedressing N using standard equipment is fairly short and coincides with typically rainy weather in the Midwest. Wet soil conditions could potentially delay sidedressing and prevent timely application of needed N. Development of high-clearance application equipment may help reduce this risk in the future. For these reasons, the LSNT approach used here should be considered only an initial start, to be replaced or refined as new research emerges.

The ≥30% relative reduction in NO_3 concentration observed at the end of this study is comparable with the suggested decrease for N discharges from the Mississippi River to manage hypoxia in the northern Gulf of Mexico (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, 2001). The reduction was achieved by reducing the application of N fertilizer within the subbasin by 23% as compared with the cooperating farmers' N program in the last 2 yr. This gives a ratio for the percent reduction in NO_3 concentration to percent reduction in fertilizer N of about 1.3. Randall and Mulla (2001), working with small continuous-corn plots, also found a ratio of 1.3 when N fertilizer rates were reduced and application was switched from fall to spring. The similar ratios found at the two different spatial scales gives us encouragement that similar responses could be realized by applying the LSNT approach at even larger spatial scales.

In the past, criticisms have been directed at best management practices promoted by public institutions that have not been proven to function adequately on an applied scale such as a farm or watershed. This project extended over 400 ha comprising eight different farmers' production fields and 11 different soil types. Our results show that implementing an intensive N management strategy across this agricultural watershed resulted in lower NO_3 concentrations leading to improved water quality.

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REFERENCES

Baker, J.L., and H.P. Johnson. 1981. Nitrate-nitrogen in tile drainage as affected by fertilization. J. Environ. Qual. 10:519–522.

Bakhsh, A., R.S. Kanwar, T.B. Bailey, C.A. Cambardella, D.L. Karlen, and T.S. Colvin. 2002. Cropping system effects on NO_3–N loss with subsurface drainage water. Trans. ASAE 45:1789–1797.

Bjorneberg, D.L., D.L. Karlen, R.S. Kanwar, and C.A. Cambardella. 1998. Alternative N fertilizer management strategies effects on subsurface drain effluent and N uptake. Appl. Eng. Agric. 14:469–473.

Blackmer, A.M., D. Pottker, M.E. Cerrato, and J. Webb. 1989. Correlations between soil nitrate concentrations in late spring and corn yields in Iowa. J. Prod. Agric. 2:103–109.

Blackmer, A.M., R.D. Voss, and A.P. Mallarino. 1997. Nitrogen fertilizer recommendations for corn in Iowa. PM-1714. Iowa State Coop. Ext., Iowa State Univ., Ames.

Bundy, L.G., D.T. Walters, and A.E. Olness. 1999. Evaluation of soil nitrate tests for predicting corn nitrogen response in the north central region. North Central Reg. Res. Publ. 342. Wisconsin Agric. Exp. Stn., Madison.

Clausen, J.C.W.E., F.I. Jokela, I.I.I. Potter, and J.W. Williams. 1996. Paired watershed comparison of tillage effects on runoff, sediment, and pesticide losses. J. Environ. Qual. 25:1000–1007.

David, M.B., and L.E. Gentry. 2000. Anthropogenic inputs of nitrogen and phosphorus and riverine export for Illinois, USA. J. Environ. Qual. 29:494–508.

David, M.B., L.E. Gentry, D.A. Kovacic, and K.M. Smith. 1997. Nitrogen balance in and export from an agricultural watershed. J. Environ. Qual. 26:1038–1048.

Dinnes, D.L., D.L. Karlen, D.B. Jaynes, T.C. Kaspar, J.L. Hatfield, T.S. Colvin, and C.A. Cambardella. 2002. Nitrogen management strategies to reduce nitrate leaching in tile-drained Midwestern soils. Agron. J. 94:153–171.

Durieux, R.P., H.J. Brown, E.J. Stewart, J.Q. Zhao, W.E. Jokela, and F.R. Magdoff. 1995. Implications of nitrogen management strategies for nitrate leaching potential: Roles of nitrogen source and fertilizer recommendation system. Agron. J. 87:884–887.

Economic Research Service. 1999. Agricultural chemicals and production technology: Questions and answers [Online]. Available at http://www.ers.usda.gov/Briefing/AgChemicals/Data/2000ARMS%20updated%20%20fertilizer%20data.xls (verified 3 Dec. 2003). USDA-ERS, Washington, DC.

Eidem, J.M., W.W. Simpkins, and M.R. Burkart. 1999. Geology, groundwater flow, and water quality in the Walnut Creek watershed. J. Environ. Qual. 28:60–69.

ESRI. 2002. ArcView. ESRI, Redlands, CA.

Fenelon, J.M., and R.C. Moore. 1998. Transport of agrichemicals to ground and surface water in a small central Indiana watershed. J. Environ. Qual. 27:884–894.

Goolsby, D.A., W.A. Battaglin, B.T. Aulenbach, and R.P. Hooper. 2001. Nitrogen input to the Gulf of Mexico. J. Environ. Qual. 30:329–336.

Goolsby, E.A., W.A. Battaglin, G.B. Lawrence, R.S. Artz, B.T. Aulenbach, R.P. Hooper, D.R. Keeney, and F.J. Stensland. 1999. Flux and sources of nutrients in the Mississippi-Atchafalaya River basin. Topic 3 report for the integrated assessment of hypoxia in the Gulf of Mexico. NOAA Coastal Ocean Program Decision Analysis Ser. 17. NOAA Coastal Ocean Program, Silver Spring, MD.

Grabow, G.L., J. Spooner, L.A. Lombardo, and D.E. Line. 1998. Detecting water quality changes before and after BMP implementation: Use of a spreadsheet for statistical analysis. p. 1–9. *In* NWQEP notes. The NCSU Water Quality Group Newsletter. November 1998. North Carolina State Univ. Coop. Ext., Raleigh.

Grabow, G.L., J. Spooner, L.A. Lombardo, and D.E. Line. 1999a. Detecting water quality changes before and after BMP implementation: Use of SAS for statistical analysis. p. 1–11. *In* NWQEP notes. The NCSU Water Quality Group Newsletter. January 1999. North Carolina State Univ. Coop. Ext., Raleigh.

Grabow, G.L., J. Spooner, L.A. Lombardo, and D.E. Line. 1999b. Detecting water quality changes before and after BMP implementation: Use of SAS for trend analysis. p. 1–8. *In* NWQEP notes. The NCSU Water Quality Group Newsletter. July 1999. North Carolina State Univ. Coop. Ext., Raleigh.

Guillard, K., T.F. Morris, and K.L. Kopp. 1999. The pre-sidedress soil nitrate test and nitrate leaching from corn. J. Environ. Qual. 28:1845–1852.

Hatfield, J.L., D.B. Jaynes, M.R. Burkart, C.A. Cambardella, T.B. Moorman, J.H. Prueger, and M.A. Smith. 1999. Water quality in

Walnut Creek watershed: Setting and farming practices. J. Environ. Qual. 28:11–24.

Heathwaite, A.L., T.P. Burt, and S.T. Trudgill. 1993. Overview—The nitrate issue. p. 3–21. *In* T.P. Burt et al. (ed.) Nitrate: Processes, patterns and management. John Wiley & Sons, New York.

Hewes, L., and P.E. Frandson. 1952. Occupying the wet prairie: The role of artificial drainage in Story County, Iowa. Ann. Assoc. Am. Geogr. 42:24–50.

Jaynes, D.B., T.S. Colvin, D.L. Karlen, C.A. Cambardella, and D.W. Meek. 2001. Nitrate loss in subsurface drainage as affected by nitrogen fertilizer rate. J. Environ. Qual. 30:1305–1314.

Jaynes, D.B., J.L. Hatfield, and D.W. Meek. 1999. Water quality in Walnut Creek watershed: Herbicides and nitrate in surface waters. J. Environ. Qual. 28:45–59.

Jaynes, D.B., R.C. Rice, and D.J. Hunsaker. 1992. Solute transport during chemigation of a level basin. Trans. ASAE 35:1809–1815.

Klausner, S.D., W.S. Reid, and D.R. Bouldin. 1993. Relationship between later spring soil nitrate concentrations and corn yields in New York. J. Prod. Agric. 6:350–354.

Kluitenberg, G.J., and R. Horton. 1990. Effect of solute application method on preferential transport of solutes in soil. Geoderma 46: 283–297.

Lowrance, R.R., R. Leonard, and J. Sheridan. 1985. Managing riparian ecosystems to control nonpoint pollution. J. Soil Water Conserv. 40:87–97.

Magdoff, F.R., D. Ross, and J. Amadon. 1984. A soil test for nitrogen availability to corn. Soil Sci. Soc. Am. J. 48:1301–1304.

Meek, D., D. Dinnes, D. Jaynes, C. Cambardella, T. Colvin, J. Hatfield, and D. Karlen. 2001. An autoregression model for a paired watershed comparison. p. 223–231. *In* G. Milliken (ed.) Proc. 12th Appl. Stat. Agric. Conf., Manhattan, KS. 1–2 May 2000. Stat. Dep., Kansas State Univ., Manhattan, KS.

Mississippi River/Gulf of Mexico Watershed Nutrient Task Force. 2001. Action plan for reducing, mitigating, and controlling hypoxia in the northern Gulf of Mexico. Office of Wetlands, Oceans, and Watersheds, USEPA, Washington, DC.

Montgomery, D.C., and E.A. Peck. 1982. Introduction to linear regression. John Wiley & Sons, New York.

Moog, D.B., and P.J. Whiting. 2002. Climatic and agricultural factors in nutrient exports from two watershed in Ohio. J. Environ. Qual. 31:72–83.

Ocean Studies Board and Water Science and Technology Board, Commission on Geosciences, Environment, and Resources, National Research Council. 2000. Clean coastal waters: Understanding and reducing the effects of nutrient pollution. Natl. Academy Press, Washington, DC.

Onstad, C.A., M.R. Burkart, and G.D. Bubenzer. 1991. Agricultural research to improve water quality. J. Soil Water Conserv. 46:184–188.

Rabalais, N.N., W.J. Wiseman, R.E. Turner, B.K. Sen Gupta, and Q. Dortch. 1996. Nutrient changes in the Mississippi River and system responses on the adjacent continental shelf. Estuaries 19:386–407.

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 CRP, alfalfa, and row crop systems. J. Environ. Qual. 26:1240–1247.

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. 24:360–366.

Randall, G.W., and D.J. Mulla. 2001. Nitrate nitrogen in surface waters as influenced by climatic conditions and agricultural practices. J. Environ. Qual. 30:337–344.

Randall, G.W., J.A. Vetsch, and J.R. Huffman. 2003. Nitrate losses in subsurface drainage from a corn–soybean rotation as affected by time of nitrogen application and use of nitrapyrin. J. Environ. Qual. 32:1764–1772.

Roth, G.W., D.B. Beegle, and P.J. Bohn. 1992. Field evaluation of a presidedress soil nitrate test and quicktest for corn in Pennsylvania. J. Prod. Agric. 5:476–481.

Salas, J.D. 1993. Analysis and modelling of hydrologic time series. p. 19.1–19.72. *In* D.R. Maidment (ed.) Handbook of hydrology. McGraw-Hill, New York.

SAS Institute. 1990. SAS/STAT user's guide. Version 6. 4th ed. SAS Inst., Cary, NC.

Shankar, B., E.A. DeVuyst, D.C. White, J.B. Braden, and R.H. Hornbaker. 2000. Nitrate abatement practices, farm profits, and lake water quality: A central Illinois case study. J. Soil Water Conserv. 55:296–303.

Sims, J.T., B.L. Vasilas, K.L. Gartley, B. Milliken, and V. Green. 1995. Evaluation of soil and plant nitrogen tests for maize on manured soils of the Atlantic coastal plain. Agron. J. 87:213–222.

Tufte, E.R. 1983. The visual display of quantitative information. Graphics Press, Cheshire, CT.