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NLEAP model simulation of climate and management effects on N leaching for corn grown on sandy soil

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Abstract

The Nitrate Leaching and Economic Analysis Package (NLEAP) model was used to evaluate effects of climate and N fertility on nitrate leaching from a 3-yr field experiment of continuous corn (*Zea mays* L.). Half of the plots were randomly chosen to be either nonirrigated or irrigated (based upon calculated potential evapotranspiration). Three replications of nitrogen (N) fertility (56, 112 and 224 kg ha^{-1}) were used. Soil was a Hecla sandy loam to loamy sand (Pachic Udic Haploboroll). Soil and climate data were from the upper Midwest U.S.A. database for NLEAP. On-site data were used in the model when available.

This study shows that NLEAP is capable of integrating data collected for nonirrigated and irrigated conditions on sandy soil for a wide range of N treatments and predicting the nitrate available for leaching (NAL). Precipitation distribution and amount were different in each year. Calculated NAL provided an excellent indicator of potential nitrate leaching hazard. NLEAP output showed that leaching of residual N on this sandy soil is very sensitive to early-spring precipitation. The NLEAP model provided valuable insights concerning effects of climate and N and irrigation management on N leaching. To obtain optimum yields while minimizing nitrate leaching, this study indicates the need to use soil and plant-tissue testing, post-emergence N-fertilizer application, and modern irrigation-scheduling technology. Also, use of the NLEAP model along with field-plot experiments provide additional important information concerning timing of N-leaching events relative to climate and an additional assessment of the effectiveness of fertilizer-N management decisions.

1. Introduction

The objective of nitrogen (N) fertilization is to provide the optimum amount of N in the root zone at the proper time for crop uptake. Properly applied irrigation should result

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in more efficient N uptake by the crop. However, excess water may leach nitrate-N (NO_3-N) below the crop-root zone, especially on sandy soils. Large areas of moderately coarse- to coarse-textured soils exist in North and South Dakota, Minnesota, Michigan and in other Midwest U.S.A. states. These soils are often underlain by a shallow water table that may be easily contaminated by NO_3-N leached from overlying crop root-zones. Thus, optimum management of both N and water are especially important for these soils. Field experimentation has helped define approaches to optimize management of N and water, but computer models can provide additional valuable insights and are often easily used.

A new computer model called NLEAP (Nitrate Leaching and Economic Analysis Package) was developed to implement theories, methods and equations (Follett et al., 1991) that relate to NO_3-N leaching (Shaffer et al., 1991). Assessment of NLEAP under many climatic, soil, crop and management conditions is needed to test and improve its usefulness. Other assessments of NLEAP, in addition to that reported here, include those for data collected in Ohio and Iowa (Shaffer et al., 1991), Minnesota (Khahural and Robert, 1991), Colorado (Shaffer, 1990) and North Dakota (Follett et al., 1994). Such assessments allow model developers to test the model under a range of field conditions, while allowing users to evaluate different management strategies quickly and cheaply. Data sets from experimental plots can provide necessary information to perform such tests while also representing major agricultural areas.

The objective of this study was to use the NLEAP model to simulate climate and management effects on leaching of N during 3 yr for irrigated and nonirrigated corn grown on sandy soils of the upper Midwestern U.S.A.

2. Materials and methods

2.1. Field experiment

The research was conducted on a Hecla soil (Pachic Udic Haploboroll), that is representative of sandy-soil areas in the upper Midwest states of the U.S.A. Texture ranged from sandy loam to loamy sand. Depth to the saturated water table was measured at weekly intervals using a network of shallow observation wells in and around the plot areas. As reported previously (Follett et al., 1994), the experimental site had a 3-yr average water table (time weighted from May to September) of 2.3 m.

Two levels of water management were used; half of the plots were randomly selected as nonirrigated treatments. The other half were irrigated at weekly intervals with irrigation need based upon calculated potential evapotranspiration (ET_p) using the modified Jensen–Haise equation (Follett et al., 1973; Jensen et al., 1990; Martin et al., 1991). The general form of the modified Jensen–Haise equation used was:

$$ET_p = C_t(T - T_x)R_s \tag{1}$$

where C_t is an air temperature coefficient; T is mean daily temperature; T_x is the temperature axis intercept when T is plotted against ET_p/R_s; and R_s is solar radiation.

Amount of irrigation water (IW) applied was decided by:

$$IW = (ET_p * K_c) - P_r + D \quad (2)$$

where K_c is a crop coefficient (Pair, 1969; Jensen et al., 1990; Martin et al., 1991); P_r is measured precipitation; and D is the soil water deficit. Calculated IW amounts less than 7.6 mm were not applied and became the soil-water deficit (D) for the following week. Precipitation events less than 2.5 mm were ignored. Assuming that soil profile drainage was rapid, precipitation exceeding $[(ET_p * K_c) + D]$ was ignored for calculation of the amount of irrigation water to apply the week following the precipitation event(s).

The precipitation and applied irrigation amounts for each of the three years are shown in Fig. 1. Irrigation water was provided by a pumped well located between about 10 and 100 m from the opposite corners of the plot area. Besides helping to provide drainage, as a result of drawdown of the water table, the pumped well served as the source of irrigation water. An overhead rotating-boom plot-irrigation machine (Bond et al., 1970) was used to irrigate the research plots.

A minimum of three soil cores of 3.8-cm diameter at 30-cm depth intervals to a depth of 152 cm were collected across each plot before planting and after final harvest each of the three years. Samples were frozen and stored until extracted with 2 *M* KCl. Extracts were analyzed for available NO_3-N and ammonium (NH_4-N) by a Technicon® Autoanalyzer (Technicon Inc., Tarryton, New York, U.S.A.) [1].

Plots were planted to continuous corn, including the year before beginning the study. Treatments were replicated three times. Each replication had a randomized factorial arrangement of the two water management treatments and three levels of N fertilization. The first year of the study, ammonium nitrate (33–0–0) was broadcast at 56, 112 and 224 kg ha^{-1} N. The second and third year, sufficient ammonium nitrate was broadcast at planting to provide fertilizer N plus residual soil inorganic N (NO_3-N plus NH_4-N) amounts of 56, 112 and 224 kg ha^{-1} N in the top 91 cm of soil based upon soil samples collected on April 26 (day of the year, 116) and April 3 (day of the year, 93), respectively.

Based upon soil test results, concentrated superphosphate (0–46–0) and potassium sulfate (0–0–50) were broadcast uniformly the first year at 56 and 112 kg ha^{-1} of P and K, respectively. The second and third year, concentrated superphosphate was banded 5 cm deep and 5 cm to the side of the seed at 33 kg ha^{-1} P at planting. Zinc sulfate (36% Zn) was similarly banded below and beside the seed at 5.6 kg ha^{-1} Zn the first year and 4.4 kg ha^{-1} Zn the second and third year.

Corn cultivar Pioneer® hybrid 3935, was planted the first two years and Northrup King® hybrid PX-20 was planted the third year. Planting and harvest dates were May 25 and September 20 (days of the year, 145 and 263), May 9 and September 18 (days of the year, 129 and 261) and May 8 and September 18 (days of the year, 128 and 261) the first, second and third years, respectively. Respective corn populations for the three

[1] Trade and company names are given for the reader's benefit and do not imply endorsement or preferential treatment of any product by the authors or the USDA.

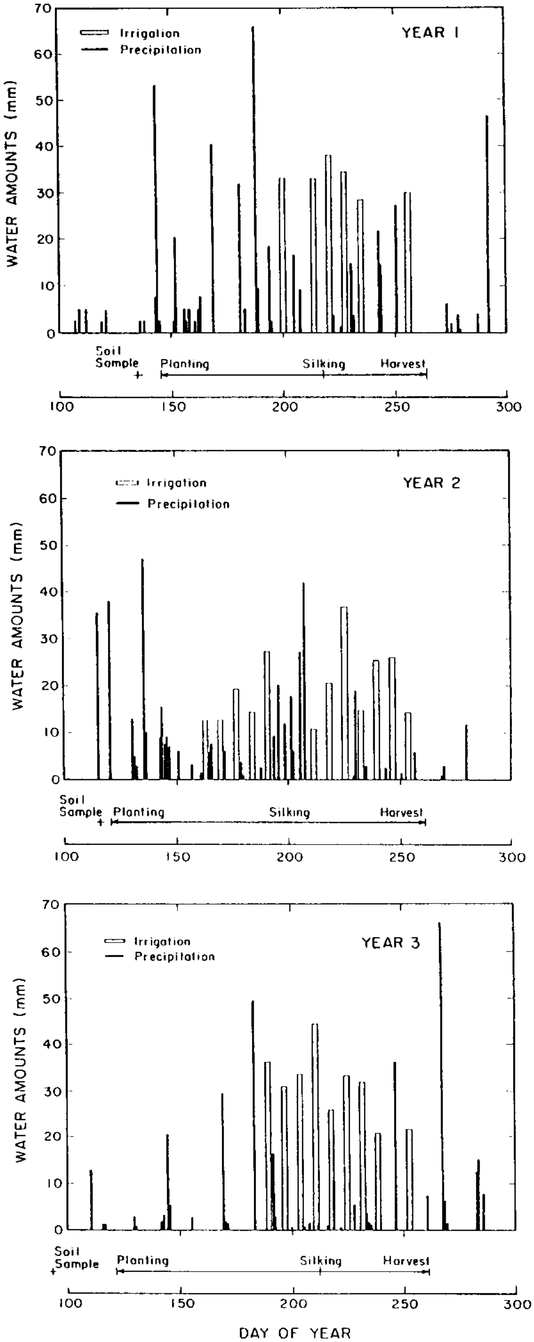

Fig. 1. Daily precipitation and irrigation for each of the three experimental years.

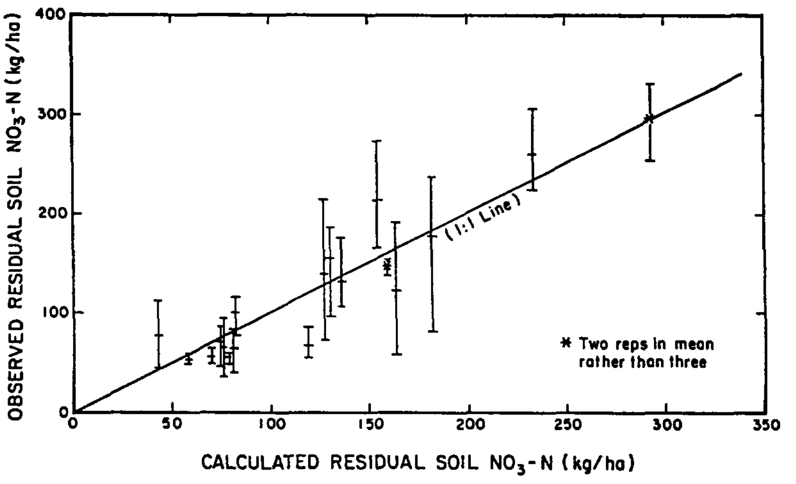

Fig. 2. Three years of observed- and calculated-residual soil NO_3-N content to a depth of 1.52 m. *Vertical lines* indicate the range of observed data (3 replications) around the mean.

years were 66,600, 57,500 and 56,000 plants ha^{-1}. Yield was determined by harvesting a total of 13.7 m of row from the center 4 rows in each plot. Total N concentrations in the stover and grain were determined by Kjeldahl procedure (Bremner and Mulvaney, 1982).

2.2. Model runs

The NLEAP software program was loaded into an IBM®-compatible personal computer (Compaq® LTE 386s/20) as described by Brodahl et al. (1991). Soil and climate data for model input were obtained from the North Dakota portion of the Region 1 (upper Midwest) database (Shaffer et al., 1991). Because daily precipitation data were available, the "Event-by-Event" analysis option was chosen. This option provides the most detailed analysis available in the model of NO_3-N available for leaching (NAL), water leached and NO_3-N leached (NL). Soil data and daily precipitation, pan evaporation and temperature data were collected at the experimental site and were substituted for database values whenever available. Calibration of the model was conducted to estimate residual soil NO_3-N against 3 yr of data from these replicated corn plots. Correlation analysis of observed vs. calculated values for residual soil NO_3-N to 1.52 m following harvest for 3 yr is shown in Fig. 2 (Follett et al., 1994). The 1:1 line in Fig. 2 indicates perfect agreement of observed and calculated values. Because observed data was used to calibrate the NLEAP model parameters, a close fit of the calculated values was expected:

$$(\text{residual } NO_3\text{-N})_{calc} = 0.83 * (\text{residual } NO_3\text{-N})_{obs} + 21$$

The coefficient of determination (r^2) was 0.87; t-testing showed that the intercept is not significantly different from 0 and the slope is not significantly different from 1, both at the 95% confidence interval. Two observations were deleted from the data set because of mistakes in irrigation.

Planting dates, crop yields, N fertilizer applied, crop residues returned from the previous crop and soil NO_3-N amounts to 1.52 m at spring soil sampling (see Fig. 1) were used as management inputs into NLEAP for individual research plots. Statistics used were analysis of variance, correlation and *t*-test procedures (SAS, 1989).

3. Results

3.1. Grain yield

Sources of variance and their significance for corn grain yields show a highly significant interaction of irrigation by year ($I \times Y$) (Table 1). Response to irrigation was highly significant in years 1 and 3, but there was no significant response to irrigation in year 2 (Fig. 3). Finally, there was an even larger yield response to irrigation in year 3 than was observed during year 1. Relative to each other, years 1 and 2 had about the same amount of total growing-season precipitation and year 3 was much drier. Growing-season precipitation (planting to harvest) amounted to 348, 329 and 209 mm in years 1, 2 and 3, respectively (Fig. 1). For the nonirrigated treatment, the largest grain yield was observed during year 2 (Fig. 3). However, for the irrigated treatment, the smallest grain yield was also observed during year 2. Although it is possible to imply that a reason for the decreased irrigated yield during year 2 was lack of N, fertilizer-N rate was not a significant treatment effect for grain yield (Table 1). The causes for grain yield differences among year and treatment are not readily apparent. More complete information about the relation of N leaching to climate is necessary to understand grain yield differences between years. Thus, use of the NLEAP model to help evaluate climatic and management effects on N and water budgets for irrigated and nonirrigated corn during this 3-yr experiment is discussed in the following sections.

Table 1
Significance of treatment effects upon grain yield, nitrate-N available for leaching (NAL), water leached and nitrate-N leached (NL)

	Significance for:				
Source	d.f.	grain yield	NAL	water leached	nitrate-N leached
Irrigation (I)	1	* *	n.s.	* *	n.s.
Nitrogen (N)	2	n.s.	* * *	n.s.	n.s.
$I \times N$	2	n.s.	n.s.	n.s.	n.s.
Year (Y)	2	n.s.	* * *	* * *	* * *
$I \times Y$	2	* * *	n.s.	* *	n.s.
$N \times Y$	4	n.s.	n.s.	n.s.	n.s.
$I \times N \times Y$	4	n.s.	n.s.	n.s.	*
Replications (R)	2	n.s.	* *	n.s.	n.s.

d.f. = degrees of freedom; * * *, * *, * = significant at the 0.01, 0.05 and 0.10 levels, respectively; n.s. = not significant.

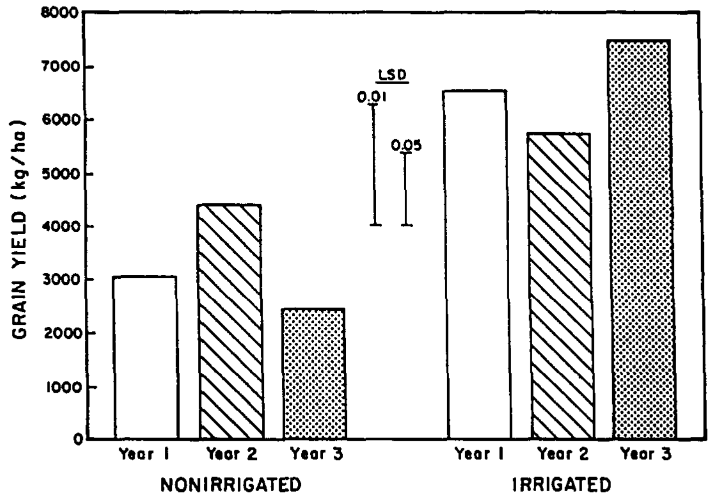

Fig. 3. Corn grain yield as a function of nonirrigated and irrigated treatments for each of the three experimental years.

3.2. *Nitrate-N available for leaching* (NAL)

A mass-balance approach is used by the NLEAP model to calculate the kg ha^{-1} of NO_3-N available for leaching from the crop-root zone, where NAL is calculated as:

$$NAL = (N_{in} - N_{out})$$

N_{in} includes inputs of NO_3-N from all sources, including nitrification of soil NH_4-N, fertilizer-N, residual NO_3-N, N mineralized from soil organic matter (net mineralization), crop-residue N, N in precipitation and irrigation water, biologically fixed N, added N from organic wastes and minor inorganic-N sources. N_{out} includes outputs of all types, including NO_3-N uptake by the crop, inorganic NO_3-N that is lost with water runoff and soil erosion, NO_3-N losses by denitrification and other N losses (Pierce et al., 1991; Shaffer et al., 1991). Important to remember is that, even though NO_3-N may be available for leaching, it is not necessarily leached from the crop-root zone during some years. The NAL responded significantly to fertilizer-N (Table 1) and averaged 144, 182 and 265 kg ha^{-1} N at the 56-, 112- and 224-kg-ha^{-1}-N rates, respectively. Response of NAL was also significantly affected by year, NAL averaged 232, 242 and 116 kg ha^{-1} N during years 1, 2 and 3, respectively. The significant effect of replicate on NAL (Table 1) resulted from an initially lower level of residual NO_3-N present in the plot area occupied by the third replication.

3.3. *Water leached*

Data input for computation of a water budget by the NLEAP model includes precipitation, number of wet days, irrigation amount, run-on, air temperature, pan evaporation, pan coefficient and crop coefficient (Shaffer et al., 1991). Computations by

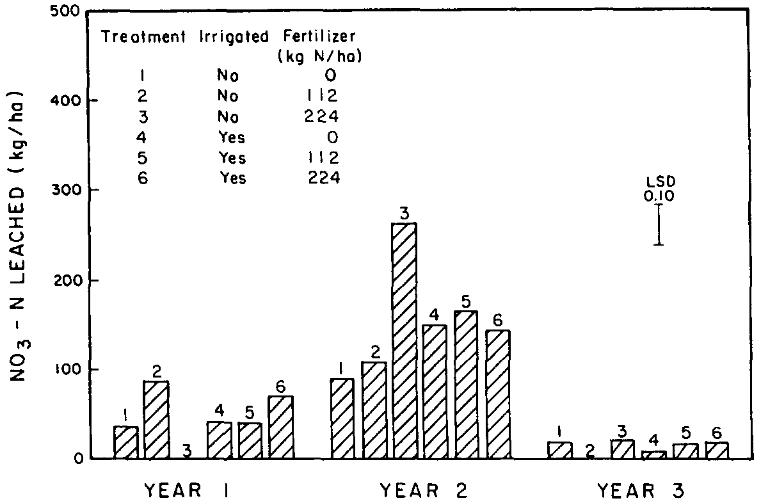

Fig. 4. Calculated NO_3-N leached as a function of irrigation and fertilizer-N treatment for each of the three experimental years.

NLEAP of water leached (or leachate volume) shows a significant irrigation by year interaction (Table 1). The simulated amount of water leached was very low (12–22 mm) during years 1 and 3 and not significantly different between the nonirrigated and irrigated treatment during either year individually. However, during year 2 the calculated amount of water leached was 100 and 143 mm for the nonirrigated and irrigated treatments, respectively. The difference in water leached during each of the experimental years was due in part to distribution of precipitation. For example, May precipitation amounted to 26%, 40% and 16% of growing season precipitation for years 1, 2 and 3, respectively. Crop water use was still small during May, so more of the growing season precipitation was lost through leaching in year 2.

3.4. *Nitrate-N leached* (NL)

Year was a highly significant source of variation for NL which averaged 46, 152 and 14 kg ha^{-1} N for years 1, 2 and 3, respectively. The irrigation by N by year ($I * N * Y$) interaction was significant at the 0.10 confidence level (Table 1). During year 1, referring to the treatment numbers shown in Fig. 4, the NL of treatments 2 and 6 were both larger than for treatments 1, 4 and 5; and all treatments were larger than treatment 3. During year 2, NL for treatment 3 was larger than all other treatments, likely as a result of carryover of residual N from year 1; treatments 4, 5 and 6 were larger than treatments 1 and 2, likely as a result of irrigation. During year 3, none of the treatments were different from each other. Treatments 2 and 6 of year 1 and all year-2 treatments were larger than all year-3 treatments. Treatment 1 of year 2 was larger than the NL measured for treatments 1, 3, 4 and 5 of year 1; all other year-2 treatments were larger than all year-1 treatments.

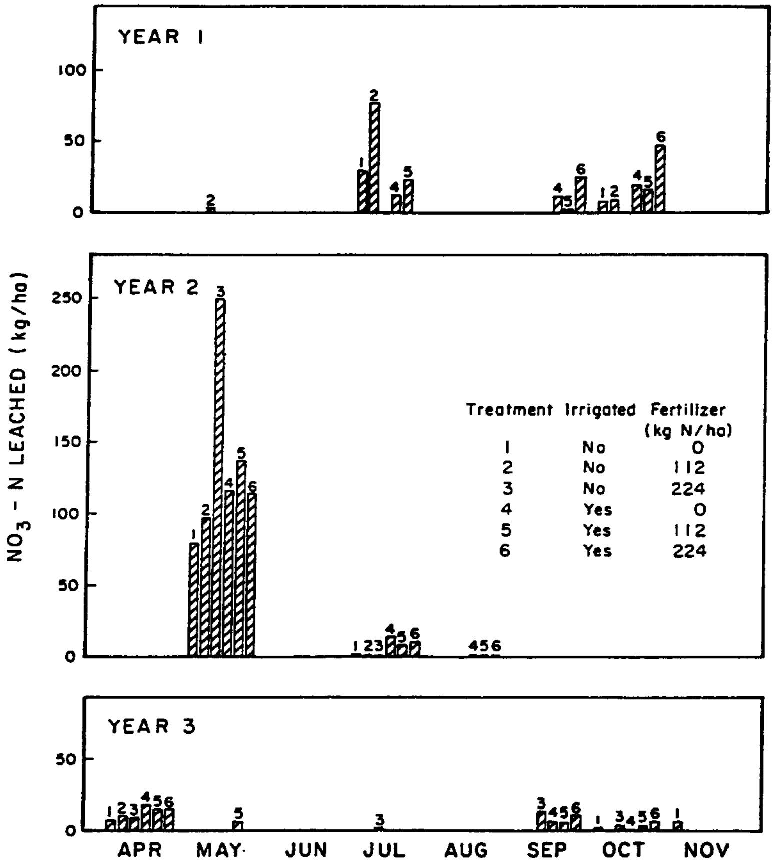

Fig. 5. Calculated NO_3-N leached by month from April to November as a function of irrigation and fertilizer-N treatment for each of the three experimental years.

Further insight is provided by considering NL on a monthly basis (Fig. 5). During year 1, there was intermittent NO_3-N leaching, especially during July (days 182 to 212) when some rather large precipitation events were recorded (Fig. 1) and also around or following corn harvest on September 20 (day 263) and into October. During year 2, NLEAP calculations showed that nearly all of the NO_3-N leaching occurred during May (days 121 to 151) with some minor leaching also occurring in July and August. Corn planting was on May 8 (day 128); however, root system and canopy development would have been too small to effectively utilize the amount of May precipitation that fell. Also during year 2, spring soil samples to determine the amount of fertilizer-N to apply were collected on April 26 (day 116); however, the year-2 spring soil samples failed to predict the extent of the decrease in residual soil-N levels resulting from NO_3-N leaching that occurred in May. Therefore, especially for the irrigated treatment, the crop would have had insufficient plant-available N during the growing season to produce optimum grain yield, compared to years 1 and 3 (Fig. 3). For year 3, early-season NO_3-N leaching

(April) was again observed. Spring soil sampling (Fig. 1) to determine the amount of fertilizer-N to apply was done on April 3 (day 93). As was the case during year 2, soil samples for fertilizer-N recommendation were again collected before early-spring leaching events of year 3 (Fig. 5). However, the amounts of precipitation and NO_3-N leaching that occurred during May of year 3 was much less than during year 2 and NAL also was significantly smaller than it had been for years 1 and 2. During year 3, some NO_3-N leaching was again seen during September and October (days 244 to 304) that was likely associated with late-season precipitation (Fig. 1).

4. Discussion and conclusions

Results of this study show that the NLEAP model is adaptable to data collected for nonirrigated and irrigated conditions on sandy soil for a wide range of N fertilizer rates. Use of the NLEAP model can help evaluate possible climatic and management effects on N leaching. Field-plot experiments provide much useful information concerning crop N uptake. However, field plot experiments may not provide definitive information about the timing of N-leaching events relative to seasonal precipitation or an adequate assessment of the effectiveness of fertilizer-N management decisions, especially when such assessments are made based only upon spring soil testing.

The results from this study indicate that calculation of NAL provides an excellent indicator of potential N-leaching hazards. A high NAL occurred for this study during years 1 and 2. Soil testing was not used to determine fertilizer-N requirements for year 1. Because residual soil-N was already higher than the desired fertilizer rates, fertilizer-N applied during year 1 resulted in excessive amounts of soil-N that eventually could be leached. During year 2, residual N carried over from year 1 was readily identified with soil testing and by NLEAP calculation of NAL; NLEAP showed that much of the residual soil-N was leached by May rainfall events. Soil testing was used to determine fertilizer-N application for year 2. However, these soil test samples could not predict the major effect of the May rainfall on the amount of residual N that was leached from the crop-root zone. Consequently, the amounts of available soil-N were lower than they should have been for optimum yields. Additionally, application of N fertilizer (NH_4NO_3) in mid-May likely resulted in leaching of at least some of the applied N fertilizer. Soil-test samples were also collected in early April in year 3 followed by N-fertilizer application in early May. However, NLEAP simulation showed essentially no leaching of either residual NO_3-N or applied N fertilizer from the crop-root zone during May of year 3. A much larger corn grain yield response to irrigation also was observed during year 3 than for year 2, likely because plant-available N level were more favorable.

Results from this study indicate that residual soil-N is easily leached by early-spring rainfall on sandy soil. Significant amounts of spring precipitation occur frequently enough in the upper Midwestern U.S.A. that special attention must be given to minimizing the leaching of NO_3-N during that period of the year. These results indicate that, for preplant N-fertilizer application, soil samples need to be collected and analyzed just before planting and N-fertilizer application. However, for those years where precipitation in May results in significant amounts of NO_3-N leaching, this precaution may not satisfactorily predict crop fertilizer-N needs. Sidedressing of N fertilizer for irrigated corn should benefit yields significantly on these sandy soils, especially during years when significant amounts of early-spring precipitation occur, while also helping to minimize N leaching.

In addition, emerging technologies for managing fertilizer-N appear to offer a major opportunity to minimize NO_3-N leaching and to maximize crop N use efficiency. For example, the presidedress soil-N test (PSNT) technology is showing considerable promise. Use of the PSNT was first reported by Magdoff et al. (1984) in Vermont and is based on monitoring of in situ soil NO_3-N at 1–2 weeks before normal sidedressing; its use was more recently described by Meisinger et al. (1992). Another approach that is showing considerable promise and is being tested for Midwestern soils of the U.S.A. is the Minolta® SPAD 502 chlorophyll meter (Schepers et al., 1992) which monitors plant N status by measuring the relative "greenness" of selected leaves. The strength of the chlorophyll meter approach lies in its ability to detect N deficiencies in growing crops. Results from this study indicate that an additional technology that may need to be used, is the application of fertilizer-N with the irrigation water. Plant-tissue testing for N status, such as by chlorophyll meter, shows promise for determining when corn needs to have N applied with the irrigation water during the growing season.

In conclusion, insights with use of the NLEAP model concerning relationships among climate, N leaching, and N and irrigation management, can be readily provided by analyses of appropriate data collected from research plots. Use of the NLEAP model can be an especially important approach to evaluate possible climatic and management effects on N leaching. Field plot experiments can provide much useful information concerning crop N uptake. However, use of the NLEAP model in conjunction with field plot experiments provides additional important information concerning timing of N-leaching events relative to climate and an additional assessment of the effectiveness of N-fertilizer management decisions.

References

Bond, J.J., Power, J.F. and Olson, H.M., 1970. Rotating-boom plot irrigator with offset mounting. Trans. Am. Soc. Agron. Eng., 13: 143–144; 147.

Bremner, J.M. and Mulvaney, C.S., 1982. Nitrogen-total. In: A.L. Page (Editor), Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties. Am. Soc. Agron.–Soil Sci. Soc. Am., Madison, WI, Agron. Monogr. No. 9, pp. 595–624.

Brodahl, M.K., Bartling, P.N.S. and Shaffer, M.J., 1991. NLEAP software package installation and startup. In: R.F. Follett, D.R. Keeney and R.M. Cruse (Editors), Managing Nitrogen for Groundwater Quality and Farm Profitability. Soil Sci. Soc. Am., Madison, WI, pp. 343–348.

Follett, R.F., Reichman, G.A., Doering, E.J. and Benz, L.C., 1973. A nomograph for estimating evapotranspiration. J. Soil Water Conserv., 28(2): 90–92.

Follett, R.F., Keeney, D.R. and Cruse, R.M. (Editors), 1991. Managing Nitrogen for Groundwater Quality and Farm Profitability. Soil Sci. Soc. Am., Madison, WI, 357 pp.

Follett, R.F., Shaffer, M.J., Brodahl, M.K. and Reichman, G.A., 1994. NLEAP simulation of residual soil nitrate for irrigated and nonirrigated corn. J. Soil Water Conserv., 49: 375–382.

Jensen, M.E., Burman, R.D. and Allen, R.G. (Editors), 1990. In: Evapotranspiration and Irrigation Water Requirements. Am. Soc. Civ. Eng., Manuals Rep. Eng. Pract. No. 70, pp. 80–163.

Khahural, B.R. and Robert, P.C., 1991. Soil nitrate leaching potential indices. Agronomy, 83: 314 (abstract).

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

Martin, D.L., Gilley, J.R. and Skaggs, R.W., 1991. Soil water balance and management. In: R.F. Follett, D.R. Keeney and R.M. Cruse (Editors), Managing Nitrogen for Groundwater Quality and Farm Profitability. Soil Sci. Soc. Am., Madison, WI, pp. 199–235

Meisinger, J.J., Bandel, V.A., Angle, J.S., O'Keefe, B.E. and Reynolds, C.M., 1992. Presidedress soil nitrate test evaluation in Maryland. Soil Sci. Soc. Am. J., 56: 1527–1532.

Pair, C.H. (Editor), 1969. Sprinkler irrigation. Sprinkler Irrig. Assoc., Washington, DC, 3rd ed., pp. 109–111.

Pierce, F.J., Shaffer, M.J. and Halvorson, A.D., 1991. Screening procedure for estimating potentially leachable nitrate-nitrogen below the root zone. In: R.F. Follett, D.R. Keeney and R.M. Cruse (Editors), Managing Nitrogen for Groundwater Quality and Farm Profitability. Soil Sci. Soc. Am., Madison, WI, pp. 259–283.

SAS (Statistical Analysis Systems), 1989. SAS/STAT User's Guide, Version 6, 4th ed., vols. 1 and 2. SAS Institute, Inc., Cary, NC, 943 and 846 pp., respectively

Schepers, J.S., Blackmer, T.M. and Francis, D.D., 1992. Predicting N fertilizer needs for corn in humid regions: Using chlorophyll meters. In: B.R. Bock and K.R. Kelly (Editors), Predicting N Fertilizer Needs for Corn in Humid Regions. Natl. Fert. Environ. Res. Cent., Tenn. Valley Auth., Muscle Shoals, AL, Bull. Y-226, pp. 105-114.

Shaffer, M.J., 1990. Computer model for predicting nitrate leaching. Proc. Nonpoint Water Qual. Symp., March 22–23, 1990, Colorado Springs, CO, Soil Water Conserv. Soc., Ankeny, IA, pp. 145–157.

Shaffer, M.J., Halvorson, A.D. and Pierce, F.J., 1991. Nitrate leaching and economic analysis package (NLEAP): model description and application. In: R.F. Follett, D.R. Keeney and R.M. Cruse (Editors), Managing Nitrogen for Groundwater Quality and Farm Profitability. Soil Sci. Soc. Am., Madison, WI, pp. 285–322.