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Identification and mitigation of nitrate leaching hot spots using NLEAP–GIS technology

M.J. Shaffer [a,*], B.K. Wylie [a,1], M.D. Hall [b]

[a] *U.S. Department of Agriculture, Agricultural Research Service, Great Plains Systems Research Unit, Fort Collins, CO 80522, USA*

[b] *Department of Earth Resources, Colorado State University, Fort Collins, CO 80523, USA*

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Abstract

Leaching of NO_3-N from agricultural lands often occurs in well-defined hot spot areas when viewed across geographical regions of hundreds or thousands of km^2 and often appears as areas of high NO_3-N concentrations in shallow underlying aquifers. Delineation of high-NO_3-N zones can be achieved by combining models such the Nitrate Leaching and Economic Analysis Package (NLEAP) with Geographical Information System (GIS) technology to calculate the long-term potential mass of NO_3-N leached from the crop root zone. Once identified, the hot spots can be further analyzed with the model to evaluate and rank appropriate alternative management techniques. A simulation analysis using the NLEAP model showed that long-term NO_3-N leaching from corn (*Zea mays* L.) grown under furrow irrigation on a coarse-textured soil could be reduced by 53% with N management alone, while an 84% reduction in leached NO_3-N was achieved for combined N and water management (sprinkler irrigation). This type of modeling analysis can be completed after a few weeks of effort, while comparable field studies would take several years to finish.

1. Introduction

Recent studies have shown that leaching of agricultural non-point NO_3-N sources to shallow groundwater does not occur uniformly across farmed areas, but rather tends to occur in well-defined hot spots up to several km across that are a function of soil texture

* Corresponding author.

[1] Currently located at Augustana College/EROS Data Center, Sioux Falls, SD 57198, USA.

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and management (Pierce et al., 1991; Wylie et al., 1994). Producers, regulators, extension agents and the Natural Resources Conservation Service (NRCS) are interested in knowing the specific locations and sizes of these hot spots and the relative contributions of various potential sources of N that may have contributed to these problem areas. Producers want to know if they are located in hot spot areas and, if so, how their management practices contribute to the problem and what Best Management Practices (BMP's) are available to minimize NO_3-N leaching on their farms. Action agencies and regulators realize that identification of NO_3-N hot spot areas would allow direction of limited resources to areas with the greatest need and potential payoff.

Most models capable of simulating the movement of nutrients and pesticides from soil profiles to groundwater are point (soil) or field specific, and were not originally designed for use across landscapes, regions, drainage basins, or counties. Examples include NLEAP (Shaffer et al., 1991), NTRM (Shaffer and Larson, 1987), RZWQM (USDA–ARS, 1992), EPIC (Williams et al., 1984) and GLEAMS (Leonard et al., 1986). Field testing of these models has been generally limited to small-scale research plots and farm fields.

In general, regional assessments of agricultural impacts on groundwater quality have been receiving increased attention in the literature. This has been especially true since the development of GIS and remote sensing technology. These studies range from combination remote sensing–GIS studies (Bishop et al., 1992) and combination empirical vulnerability models and GIS (Christy, 1992) to approaches involving remote sensing, GIS and mechanistic modeling (Wylie et al., 1994). The use of a GIS in combination with pesticide leaching models has been demonstrated using LEACHM (Bleecker et al., 1990; Petach et al., 1991). Pickus and Hewit (1992) used a decision–support tool (PUMPS) which integrated modeling techniques and GIS to map pesticide leaching vulnerability. Models such as AGNPS (Young et al., 1989) have been used within a GIS to evaluate runoff characteristics and transport processes.

The NLEAP model (Shaffer et al., 1991) was developed as part of a national effort to consolidate knowledge about managing N in agriculture, provide a screening tool to assess potential NO_3-N leaching, and suggest alternative management techniques (Follett et al., 1991). NLEAP estimates NO_3-N leaching indices at the field scale. However, recent research efforts (Pierce et al., 1991; Wylie et al., 1994) have suggested that NLEAP leaching indices can be extended to a watershed or regional scale by combining NLEAP simulations with GIS technology. In particular, Pierce et al. (1991) and Wylie et al. (1994) have shown that an NLEAP–GIS combination can be used to predict NO_3-N leaching hot spots across broad geographical areas. Wylie et al. (1994, 1995) completed a pilot study that evaluated the use of the NLEAP NO_3-N leached index (NL) for identifying NO_3-N distributions and hot spots across a shallow regional aquifer under irrigated agriculture in eastern Colorado, U.S.A.

Identification of sources of NO_3-N leaching to shallow aquifers is difficult, but separation of fertilizer and manure sources has been successful in some cases by using natural ^{15}N enrichment as a tracer (Gormly and Spalding, 1982; Spalding et al., 1982). This technique takes advantage of the observation that enrichment in ^{15}N is significantly less for commercial fertilizers than for animal manures, with native soil N^{15} enrichment falling somewhere in the middle. In cases where clear identification of NO_3-N source is

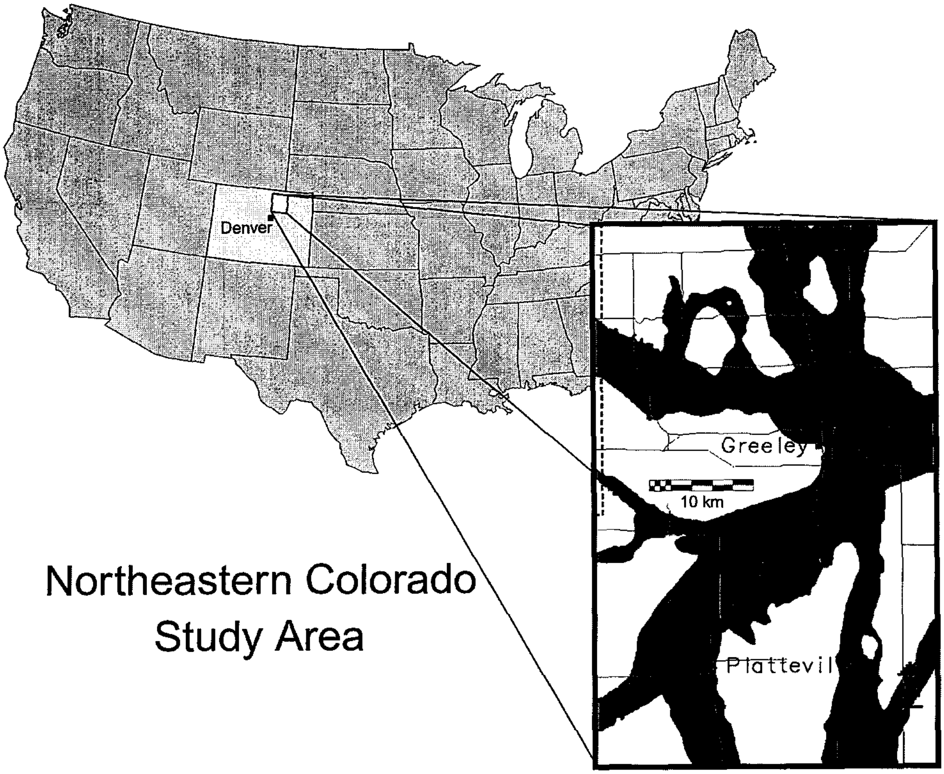

Fig. 1. South Platte study area location in the western U.S.A.

possible, the tracer information may be useful in testing source separation techniques based on models such as NLEAP.

This paper describes a case study that illustrates the use of the NLEAP model in conjunction with a GIS to identify potential NO_3-N leaching hot spots across regional areas. The paper also shows how NLEAP can be used to help identify and test management practices that show promise in controlling NO_3-N leaching.

2. South Platte case study

A regional study was completed for a 642-km^2 irrigated area along the South Platte River and its tributaries in northeastern Colorado (Wylie et al., 1994; Fig. 1). This study represents a direct test of a combined NLEAP–GIS approach on a regional scale and involved extensive GIS mapping of aquifer, soil, irrigated agriculture and agricultural management data layers over the pilot area.

The South Platte alluvial aquifer and associated irrigated agriculture present an excellent opportunity to test the NLEAP model for several reasons. The region is typical

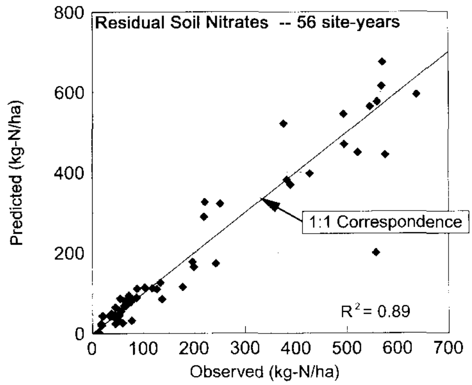

Fig. 2. NLEAP validation studies: simulated vs. measured residual NO_3-N under various crops in northeastern Colorado.

of many irrigated areas in the western U.S.A. that are underlain with shallow aquifers subject to leaching from agricultural non-point sources. The South Platte alluvial aquifer is known to have high NO_3-N concentrations dating back to the 1970's with increasing problems reported in a recent sampling of irrigation and municipal wells (NFRWQPA, 1989–1991). Mapping of groundwater NO_3-N concentrations indicated that 70% of the South Platte River alluvial aquifer in a 642-km^2 area near Greeley, Colorado, exceeded the 10-mg-L^{-1} EPA standard (Wylie et al., 1994). Municipalities along the river have either piped in surface water or installed expensive reverse osmosis filtering systems to solve this problem (Schuff, 1990, 1992).

Previous and on-going studies and surveys by several U.S. Federal and State agencies and local water districts have provided extensive information on aquifer water quality and properties, soil properties, climate history, cropping patterns, and agricultural management. The NLEAP pilot project included close collaboration with the Natural Resources Conservation Service (NRCS), the North Front Range Water Quality Planning Association (NFRWQPA), Colorado State University (CSU) and the Northern Colorado Water Conservancy District (NCWCD).

Initially, residual soil NO_3-N data from irrigated research plots in Fort Collins and farm fields within the study area were used to field validate the NLEAP model under furrow, surge and center-pivot irrigation (Shaffer et al., 1994; Crookston and Hoffner, 1992b). A regression of observed vs. predicted residual soil NO_3-N gave an R^2-value of 0.89 for 56 site-years (Fig. 2). A t-test on the slope and intercept of the regression showed that they were not different from 1.0 and 0.0, respectively ($P < 0.05$).

GIS data mapping layers were prepared for location of the alluvial aquifer, soils, irrigated areas, crops, irrigation practices and feedlots. Determination was made that the dominant crop in the study area was corn (*Zea mays* L.), and continuous corn was selected as the reference cropping practice. The NLEAP–GIS model then was used to compute the long-term steady-state NL index across the region for an average climate year. Direct comparison of NLEAP results with groundwater NO_3-N concentrations in the shallow alluvial aquifer produced an R-value of 0.59, and indicated that the NL index shows promise for identification of regional NO_3-N leaching distributions and hot spots (Fig. 3).

Further analysis of NLEAP results suggested that the occurrence of coarse-textured soils combined with agricultural management practices such as over-fertilization of crops with chemical fertilizers, manures and other N sources, application of excess irrigation water, and improper timing of N and water applications can all contribute to excess NO_3-N loading and the formation of the hot spots shown in Fig. 3.

Use of the NLEAP–GIS technique to identify potential NO_3-N hot spots in aquifers should be used with caution and supported with other techniques such as dating of groundwater and ^{15}N isotope discrimination. For example, the management conditions that created the hot spots may have changed — a good example is conversion of irrigation practices from furrow to sprinkler. Also, evaluating the impact of NO_3-N loading on groundwater NO_3-N concentrations in shallow aquifers is sometimes made difficult by poorly defined aquifer processes such as NO_3-N removal by riparian vegetation, dilution, mixing and NO_3-N losses by denitrification.

However, in many cases a strong positive correlation exists between the long-term (steady state) annual mass of NO_3-N leached below the root zone and groundwater NO_3-N concentrations when the correlations are made across areas on the order of hundreds or thousands of km^2. This means that hot spot or potential hot spot areas for shallow aquifers often can be mapped across large geographical areas without knowing all the details of the aquifer or the initial conditions (e.g., soil NO_3-N and water contents) of the soils. Better results would be expected when good estimates of actual management practices are available.

Mass of NO_3-N leached is the end result of a number of interrelated biological, physical and chemical processes in the root zone. Calculations of NO_3-N leached must be repeated across the geographical area and continued until steady-state (time invariant) conditions are approximated. The use of a computer model such as NLEAP is essential, because of the complex system and the large number of calculations involved.

3. Mitigation of hot spot areas

By identifying the areas prone to agricultural NO_3-N leaching, farmers together with consultants, extension agents and NRCS personnel can determine where water and N management are critical. However, development of site-specific management alternatives suitable for control of leaching in problem areas is not always an easy task. Models such as NLEAP can be used to quickly test a range for management alternatives and identify methods that are the most promising.

For example, in rain-fed agricultural areas, water management is often difficult and attention is generally focused on N management. The NLEAP model can be used to estimate NO_3-N available for leaching (NAL) and NL during each month of the year. This information can be used to help design N management schemes such as scavenger crops, split fertilizer applications, crop rotations and nitrification inhibitors, all of which help minimize NAL during critical periods of the year when deep percolation is the most

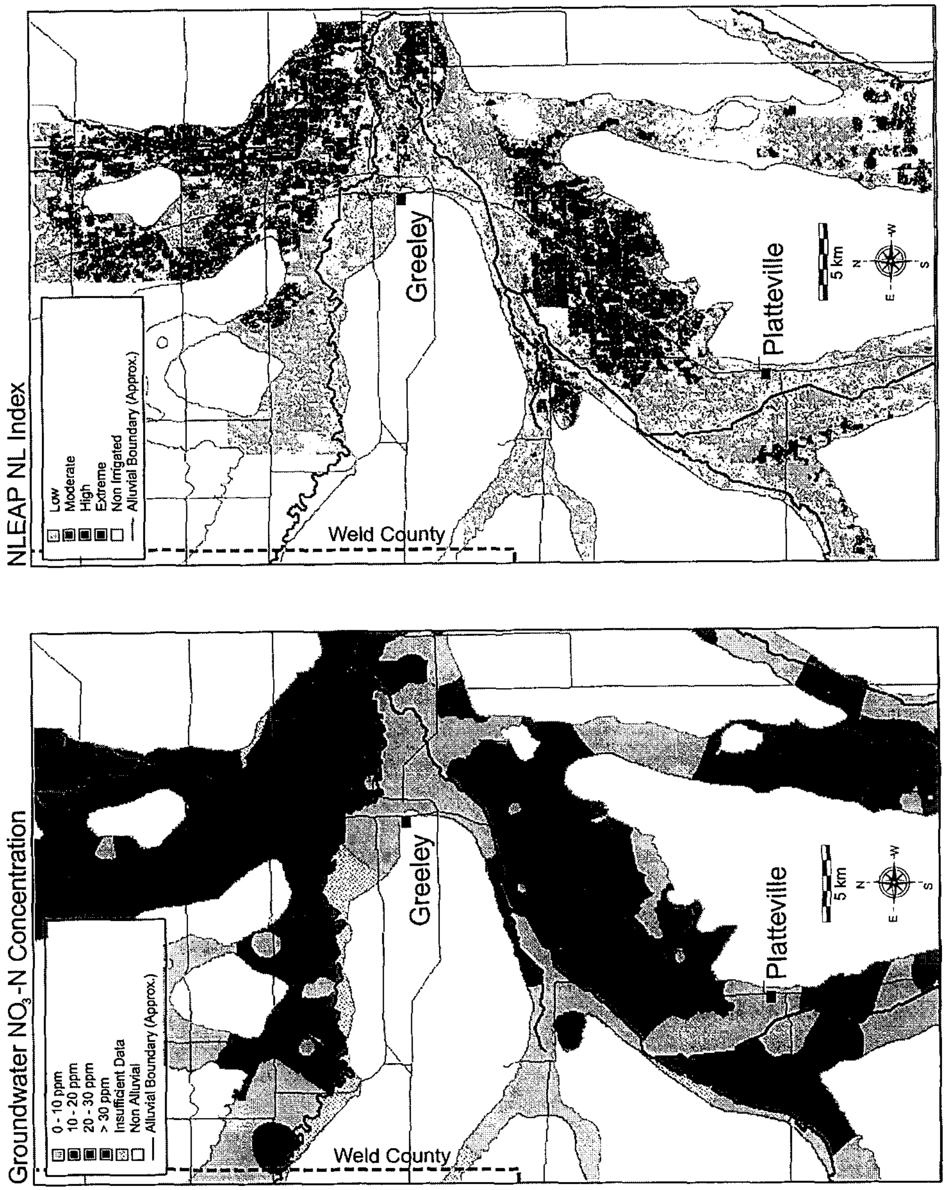

Fig. 3. Regional spatial patterns for observed groundwater NO_3-N (mg L^{-1}) vs. the NLEAP NO_3-N leached index (NL). Adapted from figs. 2 and 4 in Wylie et al. (1994).

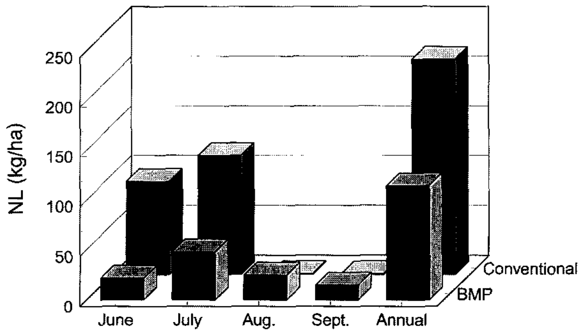

Fig. 4. NLEAP NO_3-N leached index (NL) for simulated conventional and best management practices (BMP) for nitrogen management on an irrigated sandy loam soil (average climate year, continuous corn, steady-state conditions).

likely. NLEAP can then be used to quickly test the relative effectiveness of these techniques at each site.

In irrigated areas, water management is closely tied to NO_3-N leaching. This means that deep percolation generally must first be brought under control before N management can be effective. However, this is often not an easy task. In the western U.S.A., historical irrigation water supply projects have provided large volumes of water to the farmers at low fixed costs. Many farmers feel that their water allocation may be threatened by other demands for water and that they need to "use it or lose it". Water policy plays a role in NO_3-N leaching in these areas and may require revision as part of comprehensive water quality plans.

One soil water management strategy that can promote NO_3-N leaching is furrow irrigation on coarse-textured soils. Large volumes of water are required for water to reach the end of long furrow runs (Ferguson et al., 1991). Combine this with a heavy preplant application of N fertilizer and the low plant uptake of N early in the irrigation season and the result can be major NO_3-N leaching events. This is often typical of irrigated agriculture and is illustrated in Fig. 4 by the conventional system simulated using the NLEAP model. In this case, the conventional management was 115 kg ha^{-1} fertilizer N as urea–ammonium nitrate (UAN) applied preplant to corn on May 3 followed by a 115-kg-ha^{-1}-N sidedress on June 15 for a total N application of 230 kg ha^{-1}. The BMP N treatment, also simulated using the NLEAP model, represents an attempt to manage the N applications without changing water management. Fertilizer N as UAN was applied at rates of 20-kg-ha^{-1}-N preplant and 36-kg-ha^{-1}-N sidedress on June 8, and 30 kg ha^{-1} N as calcium nitrate applied with selected irrigation events (fertigation) for a total of 150 kg ha^{-1} N applied during July and August. Total N application for the year was 206 kg ha^{-1}. Based on the BMP N management scenario, annual NO_3-N leached was reduced from 200 to 95 kg ha^{-1}, a reduction of 53%.

Irrigators have water management options available that can help reduce NO_3-N leaching events. For the long term, reduction of deep percolation should be accompanied with N management. Otherwise, excess NO_3-N will tend to accumulate in the soil profile and be subject to leaching during occasional large precipitation or irrigation

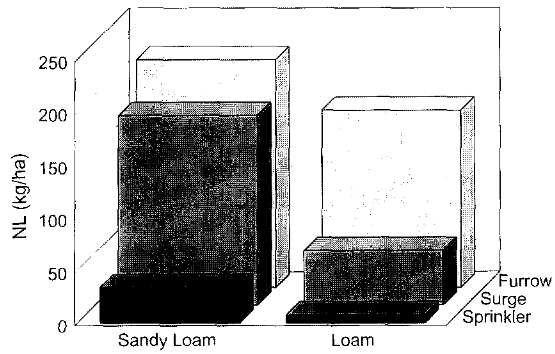

Fig. 5. NLEAP NO_3-N leached index (NL) for simulated furrow, surge and sprinkler irrigation on sandy loam and loam soils (average climate year, continuous corn, steady-state conditions).

events. Water management scenarios were simulated using NLEAP as a management assistance tool (Fig. 5). Comparable field plot analyses would take several years to accomplish. Field studies in eastern Colorado by the NCWCD (Crookston and Hoffner, 1992a) suggest that surge irrigation can reduce infiltration by ~ 40% and also reduce tail water runoff. Surge-furrow irrigation uses a computerized control to send pulses of water down the furrows, allowing the upper reaches of the furrow to "seal" between pulses, and thus reducing the infiltration rate in these areas.

Using these reduced water applications and Colorado State University fertilizer recommendations [these take into account yield goals, residual soil NO_3-N and soil organic matter (SOM) levels], simulated annual leaching of NO_3-N at steady state under surge irrigation was reduced by 17% for the sandy loam soil and 67% for the loam soil (Fig. 5). Sprinkler irrigation, though more expensive than furrow or surge methods, provides a more uniform application of water and is less prone to leaching. In our example, infiltration amounts were assumed to be reduced by 73% relative to conventional furrow irrigation. This reduction is similar to field observations reported by the NCWCD in eastern Colorado (Crookston and Hoffner, 1992a). As shown in Fig. 5, simulated NO_3-N leaching on the sandy loam soil was reduced from 216 to 34 kg ha^{-1}, a reduction of 84%. Simulated annual losses on the loam soil were reduced 95% from 168 to 8 kg ha^{-1} N.

A comparison of major N sources and sinks for furrow, sprinkler and surge treatments shown in Fig. 5 is detailed in Table 1. The fertilizer recommendations for furrow and surge irrigation on the sandy loam were the same because of similar residual N and SOM levels. For both the furrow and surge treatments on the sandy loam, crop N uptake was less than the crop requirement for the assumed yield goal of 11,800 kg ha^{-1} (190 bu ac^{-1}). This illustrates a problem common to coarse-textured soils and furrow irrigation — excess leaching of NO_3-N demands extra N fertilizer to insure crop yields.

Sprinkler irrigation resulted in a reduced fertilizer requirement for both soils (Table 1). This coupled with the reduced deep percolation volumes resulted in significant reduction in the mass of NL. Note, however, the trend to increased residual soil NO_3-N levels with improved soil water management. This was caused primarily by accumula-

Table 1
Major N sources and sinks at steady state for combined water and N management (NLEAP simulations for average climate year and continuous corn)

	Sources (kg ha^{-1})				Sinks (kg ha^{-1})		
	fertilizer N	residual N	N mineralization		crop N uptake	N denitrified	NL
			SOM	crop residues			
Sandy loam							
furrow	275	24	99	27	183	8	216
surge	275	24	93	27	205	11	180
sprinkler	195	138	114	28	242	29	34
Loam							
furrow	276	35	105	44	241	6	168
surge	156	191	110	45	242	5	55
sprinkler	121	186	115	47	242	30	8

SOM = soil organic matter; NL = NLEAP NO_3-N leached index.

tion of NO_3-N near the bottom of the root zone, where extraction by roots was not efficient and less water was available for leaching. Control of this problem may be possible with even tighter management of N inputs to the soil and/or the use of deep rooted scavenger crops to remove accumulations of NO_3-N.

Sensitivity analyses performed using NLEAP for manure applications vs. commercial fertilizers suggested that the model may be able to separate the relative contributions to NO_3-N leached from these sources. Also, direct comparisons with field plot and farm field data suggested that NLEAP may be able to evaluate the relative contributions to NO_3-N leaching from irrigation practices, commercial fertilizer practices and cropping practices. A cooperative pilot project is underway to assess the feasibility of using ^{15}N isotope techniques in conjunction with the NLEAP model to help separate manure and commercial fertilizer source contributions to groundwater NO_3-N in the Greeley, Colorado, area.

4. Conclusions

Leaching of soil NO_3-N from agricultural lands tends to occur in hot spots that are related to soil texture and management. Long-term leaching of NO_3-N from agriculture expressed as mass of NO_3-N leached per year is often well correlated with concentrations of NO_3-N in underlying, shallow unconfined aquifers. The use of models such as NLEAP in conjunction with a GIS can be helpful in determining the locations of regional NO_3-N leaching hot spots and the relative effectiveness of management techniques in minimizing NO_3-N leaching for cropping sequences, soil series, irrigation practices and climate. NLEAP can aid in the comparison of long-term (steady-state) N budgets for various proposed management schemes. This allows relative contributions from N sources and losses to N sinks to be summarized and evaluated without field plot studies lasting many years.

5. Availability of the NLEAP model

The NLEAP model and associated regional databases are available from the Soil Science Society of America (SSSA), 677 S. Segoe Road, Madison, WI 53711, tel. (608)-273-8080. The model is being sold in conjunction with an SSSA book entitled *Managing Nitrogen for Groundwater Quality and Farm Profitability*, by R.F. Follett, D.R. Keeney and R.M. Cruse (Editors) (Follett et al., 1991). Information about NLEAP and user support is available from USDA–ARS, P.O. Box E, Fort Collins, CO 80522: M.J. Shaffer, M.K. Brodahl and P.N.S. Bartling. Phone: (970)-490-8338, Fax: (970)-490 -8310, E-mail: brodahl@gpsrv1.gpsr.colostate.edu.

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